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DARPA TECHNICAL ACCOMPLISHMENTS

AN HISTORICAL REVIEW OF SELECTED DARPA PROJECTS

Volume I

Sidney G. Reed
Richard H. Van Atta
Seymour J. Deitchman

February 1990

Prepared for
Defense Advanced Research Projects Agency

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This volume describes the genesis of the study, the approach that was taken in carrying it out, and program histories of 28 DARPA projects. Each history describes the genesis of the project or program, the major participants and events in its lifetime, and contains a flow diagram illustrating the complex of interactions among organizations over time that characterize the project. Each project review ends with observations about the project's success and the nature of its impact. Volume II, due in June 1990, will present 27 additional histories, in the same format, and will synthesize the observations about success and influence in such a way that DARPA can apply the results to future program management.

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PART ONE: STUDY OVERVIEW

PART ONE: STUDY OVERVIEW

PURPOSE AND SCOPE

DARPA began in 1958 as the Advanced Research Projects Agency (ARPA) with the mission of creating a U.S. capability to launch and use spacecraft, after the Soviet Sputnik launch. Subsequently it was given a broader charter, to advance defense technology in many critical areas and to help the DoD create military capabilities of a character that the Military Services and Departments were not able or willing to develop for any of several reasons: because the risks could not be accepted within the limits of Service R&D and procurement budgets; because those budgets did not allow timely enough response to newly appearing needs; because the feasibility or military values of the new capabilities were not apparent at the beginning, so that the Services declined to invest in them; or because the capabilities did not fall obviously into the mission structure of any one Service, so that there was no eager, *ab initio* source of support for development and operational trials.

ARPA's charter, therefore, came to include several means by which the agency, whose name was changed to the *Defense* Advanced Research Projects Agency (DARPA) in 1972, could undertake new projects and programs. These included assignment by the President, the Secretary of Defense or his senior technical subordinates, requests by Congress or by the Services, or work undertaken on DARPA initiative (ratified by the Secretary of Defense and the Congress in the budget approval process if by no other means) if the agency saw that a military need could be met with a technological advance that was not being explored or exploited. In all the cases related to Service missions, even those where there was initial Service opposition to an idea, the agency established some appropriate relationship with the Services and Military Departments, as a matter of stimulating their support, capitalizing on their knowledge and often on their personnel and facilities, and ultimately of interesting them in using the results of the projects and transferring the products to them for exploitation and use. In other cases, such as the broad DARPA program on nuclear test monitoring, DARPA has established similar relations to appropriate non-defense agencies.

In these modes DARPA undertook, over the years until now, hundreds of projects and programs,[1] some large and some small, in areas such as Ballistic Missile Defense, Nuclear Test Monitoring, counterinsurgency warfare in Southeast Asia, advanced information processing, advanced naval technologies, advanced technologies applicable to tactical and strategic land and air warfare systems, and basic research in such areas as materials, underwater phenomenology and the phenomenology associated with observation from space, to mention just a partial list. The output from these efforts has been prodigious, and it has had a profound impact on the world of defense technology and often on civilian technology as well.

One purpose of this task has been to trace that impact. It has sought to learn how a representative sampling of projects interacted with the world of "users" to affect the technology available to them and how they applied that technology in systems and equipment.

In some cases the output of DARPA projects was accepted directly. In others, the influence of DARPA projects that were not transferred explicitly for use may nevertheless have been felt indirectly in changing the direction of an area of military R&D or the form of military systems as articulated in industry's systems design concepts and implementation. In still other cases technological advances that were clear and apparent improvements over earlier approaches emerged from DARPA projects and were adopted because they did represent such advances. Finally, even some projects that appeared initially to have been failures have been found on deeper exploration to have made themselves felt over time in many indirect ways.

In all cases there were complex interactions among DARPA, the Services, the academic world and defense as well as civilian industry. Given the multifaceted nature of the influence DARPA can have in the course of these interactions, the tracing of influence of DARPA work is not a straightforward task. Views of influence vary with participating individuals, many related efforts outside DARPA interacted with the DARPA efforts themselves, and only in some cases is there a clear path from genesis of an idea to its direct and apparent use.

From this, a second purpose of this task has been to delineate the nature of DARPA's influence and to draw from that lessons that can help DARPA consciously

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[1] A program is a collection of interrelated projects in a single subject area.

manage the formulation of its program and the guidance of projects so as to maximize the acceptance and use of the program's results. Thus, the overall report will describe the histories of the individual projects selected for review, and it will draw from the histories some lessons that might be learned about success, impact and scientific and technological influence. It will then aggregate those lessons into a more complete overview that attempts to answer the questions regarding the second objective.

This is the first of two volumes presenting the histories of specific projects and programs, from the point of view of learning how the DARPA efforts influenced the defense and civilian technological worlds. This volume describes 28 projects, grouped to correspond to the larger program areas of which they were part, drawn mainly, but not exclusively, from the first two thirds or so of the 1958-1988 period. Thus, many of the projects reviewed have been completed and the outcome of their impact is mostly apparent. The projects in this volume are listed in Table I. Each project history describes the genesis of the project, the major participants and events in its evolution and its applications or adaptation into other technical work, to the extent they are known. Each includes an organization/time flow chart that illustrates the environment and the complex interchanges in the project's genesis, execution and influence on other efforts. Each history ends with brief observations about its "success."

Volume II, to be published in June 1990, will present 27 additional project histories, listed in Table II, in the same format and will also include brief accounts of the broader programs' histories, and a comprehensive analysis of the lessons about the extent and success of technology transfer, and the influence of DARPA, that have been learned from reviewing the histories of all the individual projects.

STUDY APPROACH

The projects studied were selected by the IDA project team and DARPA management working together, based on two criteria: (a) their importance, judged on the basis of evidence in attestation and documentation; and (b) the expected availability of data. The data available would have to contain sufficient information to permit elucidation of DARPA's role and contribution, tracing the paths of technical events through ultimate use, assessment of the impact and spin-offs of the output, and clear enough records to permit evaluation of lessons learned from the outcome. The lists shown in Tables I and II resulted

Table 1. DARPA Projects Reviewed in Volume I

SECTION A - SPACE

I. ARGUS
II. TIROS
III. TRANSIT
IV. CENTAUR
V. SATURN

SECTION B - DEFENDER: ANTI-BALLISTIC MISSILE

VI. ESAR
VII. TABSTONE
VIII. HIGH ENERGY LASERS
IX. OTH
X. AMOS

SECTION C - NUCLEAR TEST MONITORING

XI. VELA HOTEL
XII. WWNSS
XIII. LASA

SECTION D - AGILE: VIETNAM WAR PROGRAMS

XIV. M-16 RIFLE
XV. CAMP SENTINEL
XVI. QT-2 AIRCRAFT
XVII. POCKET VETO

SECTION E - INFORMATION PROCESSING

XVIII. ILLIAC IV
XIX. MAC
XX. ARPANET
XXI. ARTIFICIAL INTELLIGENCE
XXII. MORSE CODE ANALYZER
XXIII. ACCAT

SECTION F - NAVAL TECHNOLOGIES

XXIV. LAMBDA
XXV. SLCSAT

SECTION G - TACTICAL TECHNOLOGIES

XXVI. TANK BREAKER
XXVII. HIMAG
XXVIII. MINI-RPV

Table 2. DARPA Projects to be Reviewed in Volume II

ANTI-BALLISTIC MISSILE

PRESS
HIBEX
MINITRACK
REENTRY PENETRATION AIDS

TACTICAL WEAPONS

ASSAULT BREAKER
COPPERHEAD
ARMOR / ANTIARMOR
SIAM
ROCKET BELT
STEALTH
X-29
ADVANCED CRUISE MISSILE

MATERIALS and COMPONENTS

CARBON - CARBON
METAL MATRIX COMPOSITES
CERAMIC TURBINE BLADES
RAPID SOLIDIFICATION
VLSI PROCESSING
GaAs INTEGRATED CIRCUITS

INFORMATION PROCESSING

INTERACTIVE GRAPHICS
SIMNET
IMAGE PROCESSING
ADA
STRATEGIC COMPUTING
ROBOTICS

SENSORS & SURVEILLANCE

ADVANCED SURVEILLANCE (w/ TEAL RUBY-HIGH CAMP)
ACOUSTIC RESEARCH CENTER
ARECIBO

from several iterations to ensure that the selection criteria, especially the second, could be met.

The starting point was a list of accomplishments that DARPA had prepared for the Agency's 25th anniversary celebration. Most topics on this list are single projects, but some are groups of projects, constituting sub-programs under a broader program area (such as DEFENDER). This list, which had inputs from former DARPA Directors and current and former program managers, formed the working basis for discussions between the IDA project leader and DARPA management. DARPA was amenable to changes that either added to or subtracted from the list, depending on what preliminary explorations showed about data availability and revised perspectives on the value of the programs' outputs. The resulting list was then divided into those entries that could easily be described from data that were mainly available, and others for which extensive research would be necessary to elicit the factual histories. Both kinds of descriptions are included in this volume; the division simply meant that some of the project reviews on the agreed list had to be postponed until the next volume of this report could be completed.

The factual histories of the selected projects or programs were elicited from a combination of sources: interviews with participants, reference to DARPA records, review of the technical literature, congressional hearings, and interviews with other individuals who had first-hand knowledge about at least some aspects of the projects. After the relevant facts and judgments were obtained from these various sources, the flow charts and the histories were prepared.

Available data included a list, prepared by Mr. A. Van Avery, a former ARPA program manager, of ARPA or DARPA Orders up to 1975,[2] and a compilation by DARPA of the actual ARPA or DARPA orders that had been issued from 1975 through 1988. There were also compilations by the Battelle Memorial Institute of one-page project descriptions for the projects in the DEFENDER and AGILE programs, prepared under DARPA contract. Battelle had also prepared a categorization and listing of all the DARPA programs for several years in the mid 1970s. Other documentary sources included Service program histories, a book about the VELA program;[3] a book by Dr. H. York, the Chief

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[2] ARPA or DARPA Orders are documents signed by the Director that convey agency funds to contracting agencies of the Services who support DARPA administratively.

[3] A. Kerr, ed., *The VELA Program*, Defense Advanced Research Projects Agency, 1985.

Scientist of ARPA at its inception;[4] a history of ARPA up to 1974;[5] Congressional hearings for the relevant years; and access to the DARPA and IDA archives.

Interviews with participants in or observers of the projects or programs being described, and of follow-on or related Service or commercial impacts, were undertaken wherever the documentary record was not clear and complete. The interviews were used to gain insights and clues as to where to seek further data, but the ensuing written descriptions of the projects were based to the greatest extent possible on the written record. The interviews furnished valuable information for corroboration or illumination of documentary data, and in such cases the resulting interviews were used and appropriately footnoted (as were the documentary sources). Interviews were often most useful in gaining insights on the subsequent impact or transfer of DARPA technology in both the military and commercial arena. Therefore, we make a explicit effort to obtain the perceptions of those outside of DARPA who were knowledgeable about the program, its origins and related research supported by others.

DARPA history and DARPA-related individuals were not the only sources for the descriptions, since ARPA or DARPA influence on events and systems elsewhere in the DoD and commercial worlds was also being sought. Influence works in two directions, including that exerted *upon* DARPA as well as that exerted *by* DARPA, and appropriate data from outside sources were gathered and used in the same manner as the DARPA or DARPA-related data. A good example is the description of the development of Over-The-Horizon radar, where the Australians have written their own history of their work in this area and participation in the joint U.S.-Australian program.

An attempt was made to estimate the costs of the ARPA or DARPA projects for comparison with dollar figures relating to their impacts. Congressional hearings and DARPA records were the information sources for costs. This information was used where it was readily available and appeared credible.

While we believe that the accounts resulting from the process described are as accurate as the overall project-based approach, available time and information permit, experience has shown that new insights and information are discovered continually on these topics, at unpredictable times after work on them begins. Often the unearthing of information on the evolution and subsequent effects of a project is akin to sleuthing or

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[4] Herbert F. York, *Making Weapons, Talking Peace*, Basic Books, New York, 1987.

[5] *The Advanced Research Projects Agency, 1958-1974*, Richard A. Barber Associates, 1975.

prospecting with leads playing out or becoming blind alleys. Frequently the sources of information are obscure conference papers or documents that may take several weeks to obtain. Moreover, more than once important information on the impact of a DARPA project was gleaned from documents being reviewed for assessing another DARPA project. Additionally, the more recent efforts have not yet fully run their course. Thus, Volume II may contain additional information that appears after publication, about the project and program discussions in this volume, and the sponsor may wish to update the entire report every few years as the outputs of the program are used more and insights about their importance change.

Every attempt has been made to keep the project or sub-program discussions unclassified. While omission of classified information necessarily makes the account of events incomplete, it was believed that technical detail, which tends to constitute the classified component of a project, was less important than scientific and engineering principle and the simple flow of ideas, events and technical interactions among different programs and groups; the latter set of concerns shaped the main avenues of investigation.

The results of the effort to date are given in the program assessments of Volume I for the 28 projects listed in Table I, in the order and in the program groupings shown in the table. The list is organized by program categories, with projects listed under them, in rough historical order. Some of the projects and sub-programs to be described in Volume II will predate some of those in this volume, and the order will be rearranged as appropriate for the final history.

It should be noted that this volume, and the one to follow, do not constitute histories in the true sense of the word, nor do they, together, constitute a complete and balanced history of the agency. Moreover, while we have grouped the projects under the broad program headings to which they mainly belonged, it is important to note that a description of some of the projects in a broad DARPA program area may not convey an adequate sense of the overall strategy and impact of the programs. However, the individual narratives describe a selected set of projects and programs chosen because it was believed that they were important in the relationship of the agency with the development of technical capabilities in the "outside world," and because it was believed that their importance could be traced and documented. Many important gaps remain to be filled--for example, the materials area, some major aspects of the DEFENDER program, and others. Many of these will be filled by the added project and program descriptions planned for Volume II.

Thus, we do not represent this document as a definitive account of all ARPA and DARPA activities or of the overall impact of the broader programs since the agency's inception. But we believe it constitutes a useful working document that the sponsor can apply to current and planned activities and update as new information arrives.

We have made a special attempt, in the time available, to have Volume I reviewed by knowledgeable individuals who could judge its accuracy overall or in part. The entire document was reviewed by R. Sproull, C. Herzfeld, E. Rechtin, G. Heilmeier, S. Lukasik, and R. Cooper, all ex-ARPA or DARPA directors, and also by F. Koether and A. Flax. Parts of Volume I were reviewed by H. York, C.W. Cook, MGen. J. Toomay, T. Bartee, R. Finkler, J. Kreis, Capt. H. Cox, O.G. Villard, T. Croft, R. Schindler and H. Wolfhard and R. Collins. We thank the reviewers for their comments and insights, which have greatly benefited the document. Any persistent errors remain the responsibility of the authors.

VOLUME II - Proposed Approach and Outline

Based on the work done to date, we have developed some preliminary ideas for assessing the overall impact of the identified DARPA projects. Our major concern is that any such assessment appreciate (1) the complexity of the research undertaken by DARPA and (2) the range of potential impact this research might have. Our experience on this subject is that individuals, within DoD as well as elsewhere in government and industry, frequently define DARPA's role very explicitly and narrowly and define "success" based on such interpretations of DARPA's role. Given the history and charter of DARPA, the multifaceted nature of the work that it has been assigned as well as initiated itself, such narrow concepts are not apt. Sometimes they lead to misplaced criticism or self-flagellation for programs not directly leading to a fielded weapon system. We contend that technology transfer, while an important issue and an important basis for judging DARPA's accomplishments, must not be conceived too narrowly. On the other hand, it is inherent to sound management principles, even in an advanced research enterprise, to demand that programs be conceived, overseen, and ultimately judged on the degree to which they will make a difference to the accomplishment of the overall organization's objectives and missions. It is in this sense that we will review and assess the accomplishments of DARPA.

PART ONE: OVERVIEW AND ASSESSMENT OF DARPA ACCOMPLISHMENTS

A. ASSESSMENT OF SUCCESS -- Will assess and aggregate across DARPA programs to determine factors that differentiate degree and type of success based upon the following:

1. Origin of Program -- How did it get to DARPA and did its origins have any implications for success? e.g., "Project was White House initiative of highest priority," or "Project was brought to DARPA by Service research office after failing to get funding from Service."
2. Objective of Project -- What was the initial objective? Was it to develop a military system? Assess the potential of a new technology for improving a military capability? Was it aimed at improving a technology base for potential defense application?

   Did it stay the same? If it changed, why? Was objective clear, specific? Was it broad, general?
3. Type of Program
   - Mission or Operational Program (type: Nuclear Detection, Space Payload, etc.)
   - Weapons Research and Development (Strategic & Tactical)
   - Information Systems R&D (type: C^3I, etc.)
   - Technology Base stimulation/exploration (assess new technology to guard against surprise and identify potential, push technology application for defense use, overcome obstacles to technology development)
4. Status of Technology
   - U.S. leadership position relative to adversaries
   - U.S. falling behind or trailing relative to others
5. Political-Organizational Climate/Environment
   - Defense Transfer -- Competing with other approaches or applications of user versus cooperating with or supported by user
   - External factors -- Create resistance versus facilitate development/implementation

6. Type of Success -- The results and impact of the DARPA programs will be characterized according to the following categories (these are not mutually exclusive and are subject to revision):

   - DARPA-developed system itself actually fielded for military, defense, or national security mission. Still used? If not, why? Obsolete and replaced. Threat changed. Superseded by another technology (DARPA role?)
   - DARPA-developed system transferred to military service or agency and fielded, etc.
   - DARPA-developed system concept transferred to Service (or Agency) for further development and subsequent fielding
   - DARPA-developed system concept transferred to Service (or Agency) for further development (and subsequent fielding?)
   - DARPA-developed technology used, adapted, by Service or Agency in development of weapon system or defense application (subsequently fielded?)
   - DARPA development achieved quantum jump in fundamental scientific or technical knowledge of use to defense or broader applications
   - DARPA research stimulated or explored nascent, high potential (or unknown potential) technology and related technology base to determine military worth and/or degree of adversarial threat
   - DARPA sped up the development of a technology (by several years) for meeting defense application
   - DARPA research led to substantial spin-offs/spill-overs to other military systems, commercial applications, and/or overall technology base significant for defense or national security
   - DARPA research caused fundamental rethinking, redefinition of defense mission or approach to a mission (with major impact on alternative systems)
   - DARPA research had widespread indirect, but identifiable payoffs, e.g., pervasive impact on technology area; established new technology base which has led to many, perhaps unforeseen, improvements in national defense and economic capabilities

B. LESSONS LEARNED

Will summarize aspects of DARPA's successful accomplishments that can be useful for selecting and conducting programs in the future. Can such "successes" be repeated in today's environment? Are there differences in types of programs that lead to differing kinds and degrees of success? Are there indications of precursors, minimum requirements, ideal conditions for success? Given DARPA's mission (high risk-high potential), how assured should success be? (Does analysis show examples of "success" that were aimed too low?)

PART TWO: ASSESSMENT OF DARPA PROGRAMS

For Volume II, 27 DARPA projects will be reviewed and organized as listed in Table II above.

PART TWO: PROGRAM ASSESSMENTS

A. SPACE

I. ARGUS

A. BRIEF OVERVIEW

The ARGUS experiment was one of the earliest major ARPA space projects, involving nuclear explosions at altitudes in the hundreds of kilometers, with a coordinated set of measurements by satellites, rockets and ground stations. It was a test of the concept that large numbers of electrons might be injected into the earth's magnetic fields, be trapped there, and affect ballistic missile warheads, satellites, and jamming of radio and radar systems. The experiment was accomplished in six months in response to a Presidential order. ARGUS was a very risky,very large scale, and quite successful project, getting ARPA off to a good start.

B. TECHNICAL HISTORY

The ARGUS concept was suggested by the late Nicholas C. Christofilos, then at AEC's Livermore Laboratory, in reaction to the advantage in space the Soviets had shown by their launch of the Sputniks in late 1957. At Livermore, Christofilos was involved in the ASTRON project to trap and heat hydrogen ions in a magnetic field formed by a toroidal current of electrons, for controlled thermonuclear fusion. According to a recent account,[1] Christofilos' suggestion was:

> an Astrodome-like defensive shield made up of high-energy electrons trapped in the earth's magnetic field .... in essence, he proposed to explode a large number of nuclear weapons, thousands per year, in the lower part of the earth's magnetosphere, just above the upper reaches of the atmosphere. These explosions would produce huge quantities of reactive atoms and these in turn would emit high-energy electrons (beta particles) and inject them into a region of space where the earth's magnetic field would trap and hold on to them for a long time ... months or longer.
>
> The number of trapped electrons, he believed, would be enough to cause severe radiation damage--and even heat damage--to anything, man or nuclear weapon, that tried to fly through the region. He expected that this region would extend over the whole planet, save only a relatively small region, around each pole. Nick had, in effect, invented a version of the

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[1] H. York, in *Making Weapons, Talking Peace*, Basic Books, New York, 1987, p. 130.

> neutrally occurring Van Allen belt, before it was discovered. He proposed an experiment, named Argus, ... in it we would explode a nuclear bomb high above the atmosphere, after first placing in orbit a satellite with instruments on board suitable for observing the predicted injection of high energy electrons in the magnetosphere.

Christofilos' idea was brought to the attention of the then recently formed President's Science Advisory Committee (PSAC) by Dr. H. York, then director of the Livermore Laboratory and a member of PSAC. According to James Killian, Jr., then the President's Science Advisor:[2]

> PSAC strongly supported a test of this theory. It felt that the test would yield important new scientific knowledge about the earth's magnetic field and the behavior of radiation in space. The test might provide data and help answer questions that were under debate. Would such an interjection of electrons interfere with radar and radio, might the man-induced curtain suggest any possibilities for an antiballistic missile system? What would be the effects of such an explosion on our early-warning and global communications systems? Clearly there might be important military results achieved by such a test....PSAC recommended that the great experiment be undertaken. Apparently for security purposes the President preferred not to have the matter discussed at an NSC meeting. I presented the PSAC recommendation to him on 1 May 1958 and he made the decision himself that the experiment be undertaken.

At the time Christofilos presented his ideas and proposals, it was not at all clear how these could be carried out. York[3] says:

> The experiment he wanted was on a grand scale and necessarily involved satellites. Such devices were coming along, but we had not yet flown any. Argus, to say the least, was a collection of far out interesting ideas but it seemed there was simply no place to take an invention like Nick's. Before such an invention and the experiments that supported it could be acted upon, a wholly new organization had to be created, one that could deal with projects of this grand scope and great novelty, projects that had to be taken seriously but did not fit into any existing niche.

ARPA was this new organization, and York became its Chief Scientist in March 1958. Once there he had:

> both the responsibility and authority for carrying out the experiment Nick Christofilos and I had first discussed four months earlier. With the help of Nick himself, we were able to elaborate ARPA Order #4,[4] conveying fiscal

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[2] James R. Killian, Jr. "Sputnik, Scientists and Eisenhower;" MIT Press 1977, p. 187.

[3] York, ibid., p. 131.

[4] Dated 4/28/58.

authority and instructions to the Armed Forces Special Weapons Project, and thus to set in motion Project Argus.

Regarding the scale and plans for the project Killian says:[5]

> Obviously the test would require immense resources and facilities involving both the Atomic Energy Commission and the Department of Defense and a group of other organizations. As finally organized, the operational and technological management of the project was vested in the Advanced Research Projects Agency (ARPA) of the DoD. The nuclear explosions would be provided by the AEC, the Explorer rocket by the Army Center in Huntsville, and the Navy would provide the task force. The Air Force Special Weapons Center undertook the preparation of a series of high-altitude sounding rockets for the study of the lower fringes of the expected effects--at altitudes of about 500 miles using a five-stage solid-propellant rocket vehicle that had been developed by the NACA. The Air Force Cambridge Research Center and the Stanford Research Institute developed, located, and prepared to operate a variety of equipment at suitable ground stations and aboard aircraft and ships. In his capacity as Chief Scientist of ARPA, Dr. York directed the program and provided a link with the Science Advisory Committee. The Navy was entrusted with the execution of the experiment ... three rockets were launched from the rolling, pitching base of the Norton Sound and all these were successful in delivering the nuclear test devices.

The detailed organization was handled efficiently by an informal group consisting of Dr. Frank Shelton, Chief Scientist of the Armed Forces Special Weapons Project (AFSWP), and Col. Dent Lay of ARPA (ex-deputy chief of AFSWP). Since AFSWP was occupied in the conduct of the TEAK and ORANGE tests (megaton level and high altitudes < 100 km) in the Pacific in July, a new ARGUS task force was formed by the Navy, and it rendezvoused with the U.S.S. Norton Sound (which had sailed from the Pacific Coast) in the South Atlantic on August 25.[6]

About what happened, York says[7]:

> Between August 27 and September 6, 1958 three nuclear weapons were exploded above the atmosphere at an altitude of three hundred miles above the South Atlantic at a point approximately longitude ten degrees west and latitude forty degrees south. A satellite, Explorer 4, suitable for observing the high energy electrons produced by the explosion and trapped by the earth's field, was in place... The bombs had been lofted by a rocket

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[5] Killian, ibid., p. 188.

[6] "Testing Moratorium Years 1958-61," unpublished manuscript by Dr. F. Shelton. Discussion with Dr. Shelton 7/88.

[7] York, ibid., p. 149.

> launched from a ship in the lee of Gough Island,[8] an uninhabited British possession located in just the right place in the South Atlantic, for reasons having to do with the imperfect symmetry of the earth's (magnetic) field.

More scientific detail, as well as an interesting account of the scientific background at this time and of his own personal involvement, has been published recently by Dr. James Van Allen.[9] From data gathered earlier from their Explorer I and III satellites, Van Allen and his group had concluded that there was trapped radiation in the magnetic field of the earth giving a radiation intensity at least a thousand times greater than the cosmic radiation, in what is now known as the "Van Allen belt". Figures 1 and 2, from Van Allen,[10] give 2- and 3-dimensional pictures of the Van Allen belt regions. Van Allen states:

> In mid April 1958 I informed Pickering and Panofsky of my by then reasonably firm interpretation of the observations by Explorers I and III, namely that there was a huge population of electrically charged particles already present in trapped, Stormerian orbits in the earth's external magnetic field. In the context of our earlier studies of the primary auroral radiation, I considered it likely that these particles had a natural origin.

Some of those who knew of Christofilos' ideas suggested, at the time, that this trapped radiation might have been due to insertion of electrons by earlier nuclear explosions conducted by the Soviet Union.[11]

For the ARGUS experiments, Van Allen's group designed and constructed Explorers IV and V. These Explorer satellites were also sponsored by the International Geophysical year (IGY). Explorer IV (IGY-designated 1958e) was launched in July 1958, by an Army Jupiter C. Explorer V did not achieve orbit. Van Allen[12] also makes it clearer why the Navy was so involved, and in the South Atlantic:

> From a geomagnetic point of view the best site for the injection of electrons into durable orbits was near the geomagnetic equator in the South Atlantic.

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[8] In the scientific account of the experiment only the first of the three explosions is given as occurring in the vicinity of Gough Island (12° W, 38° S). The second and third locations are said to have been 8° W, 50° and 10° W, 50° S. The lee of Gough Island was also used to avoid large ships' motions in the heavy seas. The two other locations were selected to separate the artificial electron "belts" and improve the measurements at the conjugate points near the Azores.

[9] James A. Van Allen, *Origins of Magnetospheric Physics*, Smithsonian Institution Press, Washington, D.C., 1983, Chapter VIII.

[10] "The Argus Test," Van Allen, ibid., p. 66.

[11] Van Allen states that the Soviet scientists had the same idea about the U.S., ibid., p. 83.

[12] Van Allen, ibid., p. 74.

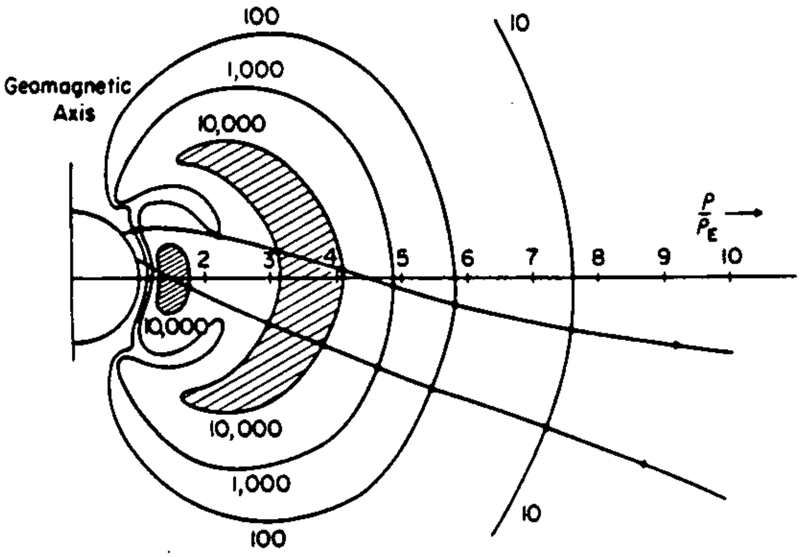

Figure 1. A meridian cross-section of contours of equal intensity of geomagnetically trapped radiation based on data from Explorers I, III, and IV and Pioneer III. *The semicircle at the left represents the earth, and the two undulating curves that traverse the diagram represent the outbound (upper curve) and inbound (lower curve) trajectories of Pioneer III. The labels on the contours are counts per second of a heavy shielded miniature Geiger-Mueller tube. The linear scale of the diagram is in units of the earth's equatorial radius (6,378 km). The two distinct regions of high intensity (cross-hatched) are the inner and outer radiation belts, separated by a region of lesser intensity called the slot. From Van Allen, ibid.*

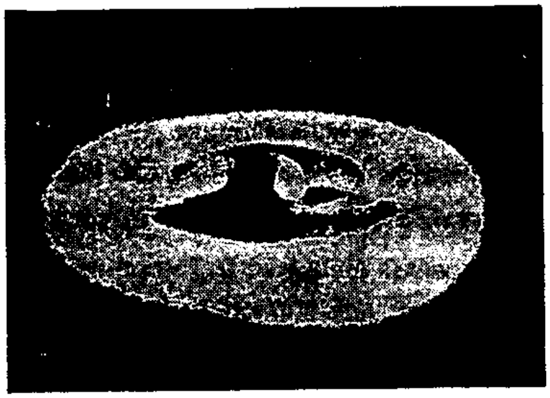

Figure 2. An artist's three-dimensional conception of the earth and the inner and outer radiation belts. From Van Allen, ibid.

> Because of the eccentricity of the earth's magnetic field, a site at that longitude could minimize the altitude at which injection had to occur, while an equatorial site could maximize the efficiency for injection in order to produce durably trapped orbits. Launching from a ship in an isolated site was desirable because it allowed the secrecy of the operation to be safeguarded. Two satellite launchers and three bomb injections were judged to be the minimum effort to give reasonable assurance of success. The Navy's guided missile ship, the U.S.S. Norton Sound, which we had "initiated" with Aerobee rocket launchers in 1949, was selected to launch the rockets.

The Norton Sound had been used in previous rocket launchings and had an on-board computer system to control launch at minimum pitch and roll conditions.

Important information for closer determination of the desirable test location was generated from Explorer IV.[13]

> On the basis of the first few weeks of data from Explorer IV, we had advised ARPA of a discovery of a minimum in the previously present radiation when intensity was plotted against latitude. This finding was utilized in helping select the latitude for the ARGUS bursts so that the artificial radiation belts would enjoy the optimum prospects of detection. This choice of latitude turned out to be the best possible choice within the latitude range of Explorer IV., i.e., in the "slot" between the previously observed 'inner' radiation belt and the newly discovered 'outer' radiation belt.

Besides the general atmosphere of urgency and desire to "catch up" with the Russians, there were more definite time constraints. Killian says:[14] "The whole program was under great pressure to meet deadlines, particularly the deadline for the voluntary one-year cessation of nuclear tests that the United States had committed itself to as of Oct. 31, 1958."

The problems of such a tight schedule and remote location of launch desired for the experiment did not seem at all attractive to those in the Air Force and Army associated with the major rocket development projects at the time. Despite the difficulties of launch at sea, and with a strong desire to become involved, the Navy took on the launch task. Dr. Willis Hawkins, of Lockheed, has described the rockets used on the Norton Sound, which were modifications of the Lockheed X-17 used in previous reentry body experiments, in an

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[13] Van Allen, ibid., p. 78.

[14] Killian, ibid., p. 189.

interesting account of ARGUS which gives the flavor of some of the risks involved.[15] Three X-17's were put on the Norton Sound for the launches, in the hope that at least one would be successful. Under way, however, three different altitudes were ordered for the explosions. To comply, each X-17 had to be launched successfully at a different angle; remarkably, each was successful.

Van Allen also compares the other nuclear tests in the Pacific shortly before ARGUS, with the altitudes of the ARGUS explosions.[16]

> The AEC/DoD tests group successfully produced two bursts of (in the megaton yield range) bombs, called Teak and Orange, on August 1 and August 12 at approximate altitude of 75 and 45 km, respectively, above Johnston Atoll in the Central Pacific: The three Argus bursts (1-2 kiloton yield range) were produced successfully on August 27, August 30 and Sept 6 at altitudes of about 200, 250, and 480 km.[17]

The Air Force Weapons Center rocket measurements at Wallops Island, Puerto Rico and Cape Canaveral were also able to determine the difference in injection altitudes very shortly after the explosions from their measurements and theoretical work.[18]

Regarding the outcome: Killian says[19]: "Staggering in scale and complexity, it was a beautifully managed and highly successful experiment from beginning to end." York says:[20] "Ten months from the germ of an idea to its actual execution in outer space was nothing short of fantastic even then; today, with more complex rules and regulations, it would be utterly impossible." However, mainly because of the time schedule, scientific instrumentation involved was quite limited.[21]

A comprehensive review of all the ARGUS results took place at Livermore in February 1959. The New York Times "broke" the previously classified story in March

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[15] Willis Hawkins; Annex to this chapter. Another detailed and flavorful account of the Air Force's Weapons Laboratories ARGUS rocket project, which was conducted with NASA assistance, is given in "A New Dimension--Wallops Island Test Range, the First 15 Years," by J.A. Shortal, NASA Reference Publication 1028, 1978 pp. 573-580.

[16] Van Allen, ibid., p. 78.

[17] Hawkins, Appendix A, however, indicates that some of these altitudes may be in question.

[18] Discussion with Dr. Lew Allen, 8/88.

[19] Killian, ibid., p. 189.

[20] York, ibid., p. 149

[21] Some later critics stated that ARGUS was poorly instrumented. Cf. "United States High Altitude Test Experiments," Los Alamos Report LA 6405, by H. Hoerlin, Oct. 1976, p. 46.

1959, and an unclassified seminar was held at the National Academy of Sciences at the end of April 1959.[22] The public statement by the Academy said [23]

> A fascinating sequence of observations was obtained. The brilliant initial flash of the burst was succeeded by a fainter but persistent auroral luminescence in the atmosphere extending upwards and downwards along the magnetic line of force through the burst point. Almost simultaneously at the point where this line of force returns to the earth's atmosphere in the northern hemisphere--the so-called conjugate point--near the Azores Island, a bright auroral glow appeared in the sky and was observed from aircraft previously stationed there in anticipation of the event, and the complex series of recordings began. For the first time in history measured geophysical phenomena on a world-wide scale were being related to a quantitatively known cause--namely, the injection into the earth's magnetic field of a known quantity of electrons of known energies at a known position and at a known time.
>
> The diverse radiation instruments in Explorer IV recorded and reported to ground stations the absolute intensity and position of this shell of high energy electrons on its passes through the shell shortly after the bursts. The satellite continued to lace back and forth through the man-made shell of trapped radiation hour after hour and day after day. The physical shape and position of the shell were accurately plotted out and the decay of intensity was observed. Moreover, the angular distribution of the radiation was measured at each point. The shape and form of a selected magnetic shell of the earth's magnetic field were being plotted out for the first time by experimental means. In their helical excursions within this shell the trapped electrons were traveling vast distances and were following the magnetic field pattern out to altitude of over 40,000 miles.

York says, briefly, "We found that electrons were trapped as Nick had predicted but that they did not persist for as long as he had hoped."[24]

Van Allen gives more scientific detail and outlines the impact on magnetospheric physics:[25]

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[22] Quoted by Killian, ibid., p. 190. Proceedings of this symposium were published in the Proceeding of the National Academy and in the Journal of Geophysical Research, Vol. 64, 659, pp. 869-957. Discussion of the security "leak" occurred in Hearings of the House of Representatives Committee on Science and Astronautics, 10 April 1959, and in "A Scientist at the White House," by G.B. Kistiakowsky, Harvard U. Press, 1976, p. 72.

[23] Quoted by Killian, ibid., p. 190.

[24] York, ibid., p. 149.

[25] Van Allen, ibid., p. 78.

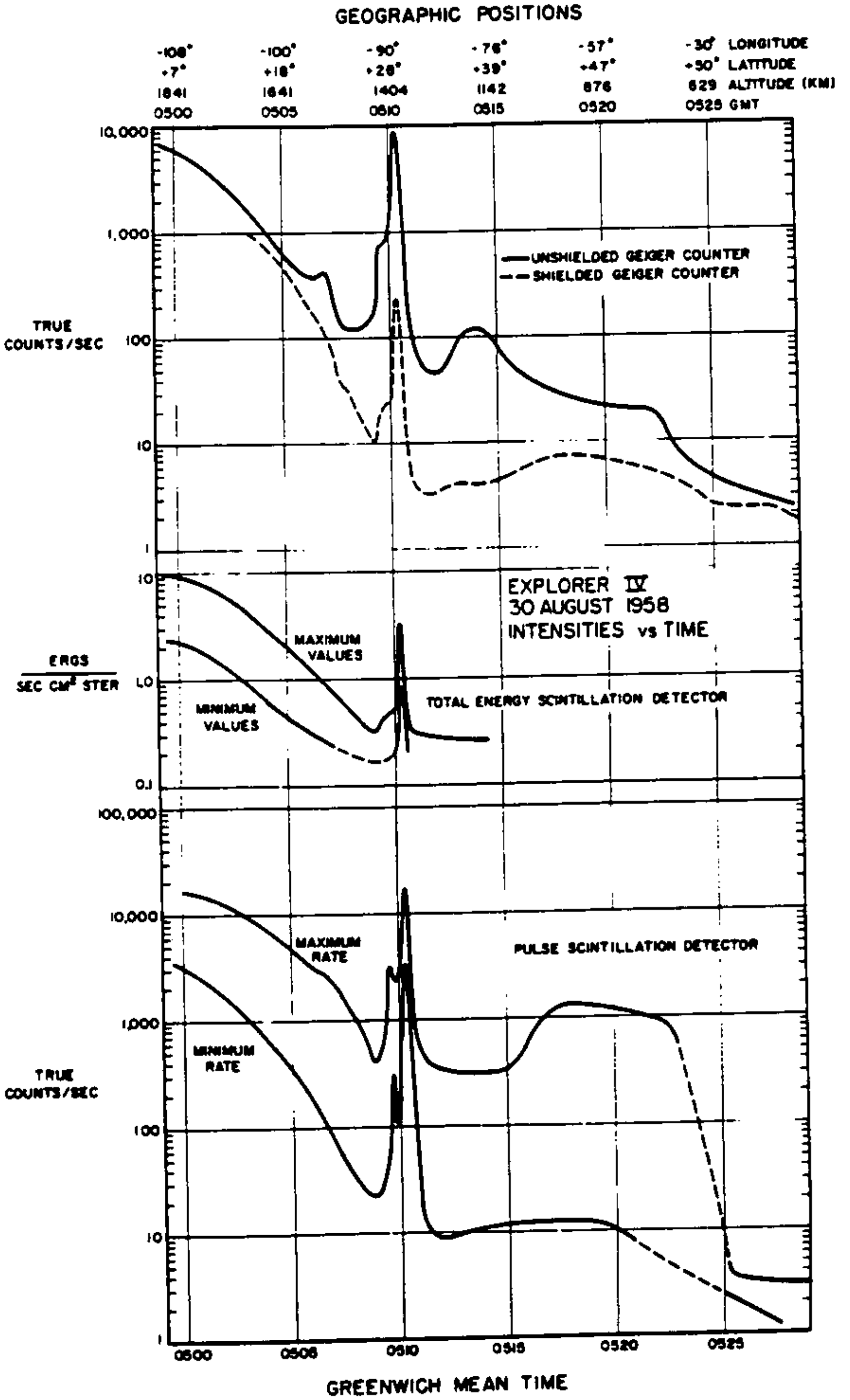

Figure 3. The narrow double spikes in the responses of the four radiation detectors were observed at about 0510 GMT on August 30, 1958, as Explorer IV traversed the shells of energetic electrons injected into trapped orbits by the Argus I burst on August 27 and the ARGUS II burst about three hours earlier on August 30 (From Van Allen, ibid., p. 79).

We observed with Explorer IV the effects of all five of the bursts in populating the geomagnetic field with energetic electrons. Despite the large yields of Teak and Orange, the incremental effects on the existing population of trapped particles were small and of only a few days lifetime because of the atmospheric absorption corresponding to the low altitudes of injection.

The three higher-altitude ARGUS bursts produced clear and well-observed effects (see our Fig. 3) and gave a great impetus to understanding geomagnetic trapping. About 3% of the available electrons were injected into durably trapped orbits. The apparent mean lifetime of the first two of these artificial radiation belts was about three weeks and of the third, about a month. In all three cases a well-defined Stormerian shell of artificially injected electrons was produced. Worldwide study of these shells provided a result of basic importance--a full geometrical description of the locus of trapping by "labeled" particles. Also, we found that the physical nature of the ARGUS radiation, as characterized by our four Explorer IV detectors, was quite different than that of the pre-ARGUS radiation, thus dispelling the suspicion that the radiation observed by Explorers I and III had originated from Soviet nuclear bomb bursts.

During the approximate month of clear presence of the three artificial radiation belts, there was no discernible radial diffusion of the trapped electrons, thus permitting determination of an upper limit on the radial diffusion coefficient for such electrons. The gradual decay in intensity was approximately explicable in terms of pitch angle scattering in the tenuous atmosphere and consequent loss into the lower atmosphere.

A comprehensive ten-day workshop on interpretation of the ARGUS observations was conducted at Livermore in February 1959. The physical principles of geomagnetic trapping were greatly clarified at this workshop. To us, one of the principal puzzles had been the durable integrity of a thin radial shell of electrons despite the irregular nature of the real geomagnetic field and the existence of both radial and longitudinal drift forces resulting from gradients in the magnetic field intensity. We had previously understood the importance of the first adiabatic invariant of Alfven in governing trapping along a given magnetic line of force and the effects to the radial component of the gradient of the magnetic field intensity B in causing longitudinal drift in an axially symmetric field. But the longitudinal component of the gradient of B seemed to imply irregular drift in radial distance and hence in radial spreading, contrary to observation. The puzzle was immediately solved by Northrop and Teller who invoked the second and third adiabatic invariants of cyclic motion to account for the observations. These theorems had been proven previously by Rosenbluth and Longmire [1957] and applied to plasma confined by a laboratory magnetic field. A specific application of these principles was McIlwain's [1961] concept of the L-shell parameter for the reduction of three-dimensional particle distributions to two-dimensional ones--a concept that has permeated the entire subsequent literature of magnetospheric physics.

The adiabatic conservation and nonadiabatic violation of these three invariants have proved to be central to understanding trapped particle motion

> and to play a basic role in all of magnetospheric physics. In effect, they supplant the rigorous integral of motion found by Stormer for an axisymmetric magnetic field and make it possible to understand trapped particle motion and the diffusion of particles when the conditions for conservation of the three invariants are violated by time-varying magnetic and electric fields. The three invariants correspond to the three forms of cyclic motion, with quite different periods, into which the Stormerian motion of a charge particle in an approximate dipolar magnetic field can be analyzed. The first is the gyro motion of the particle around a field line; the second is the latitudinal oscillation of the guiding center (the center of the cylinder on which the helical motion of the particle occurs) of the particle's gryo motion; and the third is the time-averaged cyclic drift of the guiding center through 360° of longitude.
>
> The Kirtland rocket measurements were generally consistent with our Explorer IV measurements but added important detail on particle identification and energy spectra. Also, atmospheric luminescence of auroral character was observed along the lines of force on which the bursts occurred; an artificial auroral display was observed at the northern geomagnetic conjugate point of the third burst; radar reflections from the auroral tubes of forces were observed in all three cases; and a variety of transient ionospheric effects were detected. No electromagnetic (cyclotron) emission from the trapped electrons was observed by ground stations, a result consistent with estimates of the intensity relative to cosmic background.

The Livermore meeting recommended further research, particularly on methods of achieving higher efficiency of injection of electrons into trapped belts. This led to plans for a follow-on test, WILLOW, and some further laboratory and theoretical work,[26] but this area was not pursued intensively after the test moratorium in 1958. There were no further nuclear explosions between 1958 and 1961. However, four high altitude nuclear explosions, one U.S. and three Soviet, occurred in 1962. The U.S. "STARFISH" event, a 1.4 megaton detonation at an altitude of 400 km near Johnston Island, led to an intense artificial radiation belt with the longest "mean lifetime," nearly 1.5 years.[27] The intensity and lifetime of this "STARFISH" belt seems to have been somewhat unexpected.[28] This effect has been partially attributed to magnetohydrodynamic migration outward of the bomb

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[26] F. Shelton, ibid., and AO 6 Tasks 37-41 of 5/59.

[27] "Spatial distributions and time delay of the intensities of geomagnetically trapped electrons from the high altitude nuclear burst of July 1962," J.A. Van Allen, in "Radiation Trapped in The Earth's Magnetic Field," B.M. McCormac, Ed., Reidel, 1966, p. 577. The decay is apparently not exponential, and the "Lifetime" somewhat ambiguous.

[28] "Kennedy, Khruschev and the Test Ban," Glenn T. Seaborg, U. Cal. Press, 1981, p. 156. See also H. Hoerlin, Ref. 21.

debris.[29] "STARFISH" effectively disabled or depressed operations of several satellites, indicating the importance of accurate information on the intensity and distribution of trapped radiation for durable satellite electronics design. Information of this type on natural and artificial radiation has been compiled in the DARPA "Trapped Radiation Handbook," which first appeared in 1971.[30] The dual mission global positioning system (GPS) and nuclear detonation detection system (NDS) satellites, now used for detection of nuclear tests in the atmosphere or in space, include a dosimeter to measure radiation in order to be able to estimate degradation of on-board and other systems as well as to detect possible trapped radiation from high-altitude nuclear tests.[31]

C. OBSERVATIONS ON SUCCESS

The ARGUS concept was brought to ARPA via PSAC, as a presidential-level assignment, and by H.York as its first Chief Scientist. York states that ARPA was the only place to handle the ARGUS project, and that the ARGUS idea was one of only two truly unique concepts in early ARPA projects.

ARGUS was the first man-made large scale geophysical experiment in the earth's magnetosphere. Because of the nuclear test treaty, it is not likely that another geophysical experiment like ARGUS will be conducted again.

A unique feature also was the role of York himself, due to his own background and connections with AEC, PSAC, and the DoD groups involved in nuclear testing. PSAC provided assistance through its leverage and many scientific subgroups. York played the key role in ARPA's coordination of the entire effort; decisions were made quickly with a smoothly operating working group of two consisting of ARPA liaison, Col. Dent Lay, who had come to ARPA from AFSWP, and the executive agent, AFSWP Chief Scientist, Dr. F. Shelton.[32]

AFSWP, as the DoD unit concerned with nuclear effects, had previously conducted several large-scale, successful nuclear test operations, but none had been of the remote, "task force underway" type of ARGUS. In fact, AFSWP had just completed the

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[29] "The Motion of Bomb Debris Following the Starfish Test," J. Zinn, H. Hoerlin, and A.G. Petschek, B.M. McCormac, ibid., p. 671-692.

[30] "The Trapped Radiation Handbook," DNA Report 2524 H, 1971, Rev. 1973.

[31] "Satellite Verification of Arms Control Agreements," Chapter by Harold V. Argo in *Arms Control Verification*, Ed. Tsipsis, Pergamon 1985.

[32] F. Shelton, ibid., footnote 6.

HARDTACK Pacific Johnston Island tests in mid-August, and sent a new task force directly from the East Coast to conduct ARGUS in the South Atlantic at the end of August.[33] Also, many of the physical measurements involved in ARGUS, from satellites and remote sites, were new. AFSWP deserves much credit for ARGUS success.[34]

The IGY, predominantly an academic and laboratory activity, provided an important assist: many preparations had already been made, including the Explorer satellites series, which provided essential and timely information on the Van Allen Belt and its characteristics, and many other large-scale, ground-based and rocket measurements that probably made the operation more acceptable and feasible than at another time. However, it was delicate to manage the relations between the open IGY and the classified effort.

The recorded ARPA outlay for ARGUS is about $9 million. There appears to be two reasons for this low figure: the AFSWP major costs were handled as part of those for operation HARD TACK, and the Explorer satellites built at the University of Iowa by Van Allen and his graduate students were very cheap. The industry involvement was mainly in modification of the existing X-17 rockets, and supply of some others of a type already available. NASA also provided considerable assistance to AFWAL for its rocket project.

During the course of the project, and before the actual explosions, it also became recognized theoretically that some of the initial concern about the synchrotron radiation from the artificial belts may have been exaggerated, since the geometric distribution of that radiation was limited to the high angles of the planes perpendicular to the trapped belt and could only affect sidelobes of missile defense and most other radars. However, the major concern was the potential damage to reentry vehicles,[35] and to determine the injection and trapping efficiencies from an nuclear explosion required an experiment.

The technical and operational risks, both intrinsic and due to the extraordinarily tight schedule, were very high indeed, and as indicated in Hawkins' account, even increased substantially by ARPA during the operation. The success can be credited partly

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[33] See Annex by W. Hawkins for a key participant's view.

[34] A unclassified AFSWP movie "Project ARGUS" can be obtained from DNA. Made shortly after the explosions, the results given there represent an uncertain early stage of the analysis of results.

[35] Discussion with H. York, 5/88.

to many factors such as the high quality of technical effort, and the incentive of clear top level interest, but largely must be described as just very good luck.[36]

ARGUS' impact was mainly answering, in a timely fashion, a top policy-level set of questions then considered highly important. Also, even though ARGUS was conducted with a limited scientific instrumentation, it has left technological data of enduring value regarding trapped electrons in the earth's magnetosphere injected by nuclear explosions. These data have been used in design and assessment of manned and unmanned space vehicle vulnerability, in the design of the GPS/NDS system, and in recent SDI studies. However, the U.S. high-altitude explosion STARFISH appears to have been conducted without enough preparation, due partly to the lack of a strong follow-on program after ARGUS.

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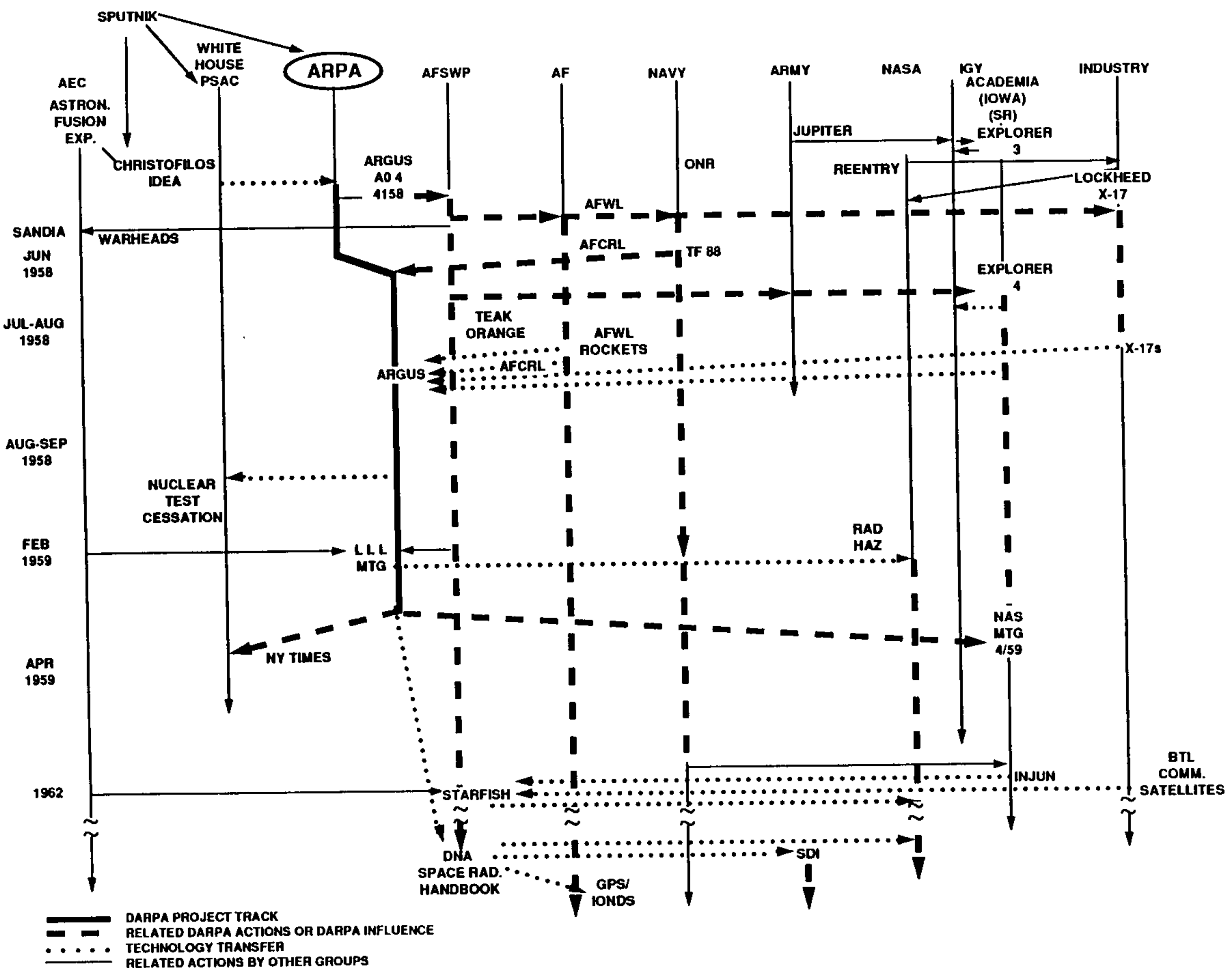
[36] Dr. Shelton states that ARGUS' success was due to the "right people being in the right place at the right time," Cf. footnote 6.

ARGUS



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ANNEX (ARGUS)

THE ARGUS PROGRAM

Willis M. Hawkins
Lockheed Company, Burbank, CA

ANNEX (ARGUS)

Willis M. Hawkins

With some detailed exploration I can pinpoint the dates of the Argus Adventure. It was late 1958. Lockheed's fledging "Missile Systems Division" had emerged four years earlier to continue the development of pilotless aircraft exemplified by the X-7 Ramjet test vehicle and the Q-5 Mach 3 target drone, both of which were originated in the advanced design department of the California Aircraft Division. It should be remembered that the start of the Missile Systems Division paralleled the beginnings of the Air Force and Navy ballistic missile programs.

This fresh, new MSD organization had made unsuccessful proposals to the Air Force for both ICBMs and IRBMs but in the process had suggested a means for doing research on reentry phenomena which was successful. This program produced a reentry test vehicle--the X-17. This was an ingenious device, a 3-stage rocket with a large size (for its day), the first stage with fixed fins, a second stage, with conical skirt, made up of a cluster of three 9-in. dia. specially-developed rockets, and a third stage using one of these new rockets, also with a conical aft skirt, and on the nose a 9-in. simulated reentry body heavily instrumented (see Fig. A-1). The tests consisted of launching the vehicle leaning out to sea (Pt. Mugu) a bare few degrees. After first-stage burnout the complete vehicle reached apogee at approximately 600,000 ft. and started falling back to earth, stabilized by the fixed fins as the atmosphere became dense enough. From this stabilized position the 2nd and 3rd stages were fired reaching Mach numbers near 15 at altitudes not much over 10,000 to 20,000 ft., simulating heat input of a reentry body. Data were transmitted to shore before and after the "blackout." The Air Force fired about fifteen of these test vehicles (called the FTV-3 Series) and the Navy fired approximately 20. These programs were pertinent to the Argus because there were five of these test vehicles left over from the Air Force and Navy programs when ARPA, under Herb York at the time, decided to confirm the trapped radiation theories of Dr. Christofolis.

The total program was conceived to fire a nuclear device at high altitude in the South Atlantic and to measure the characteristics and propagating paths of the resulting radiation with approximately 20-30 sounding rockets and a satellite. Although the program was held in the tightest security, various instrumentation stations were alerted around the work to record perturbations from nuclear events.

Lockheed first started on the program approximately May 8th of 1958 and the team set out to prepare for the nuclear devices, modify the X-17's to be stable when all three stages were fired in an upward direction, create instrumentation for the sounding probes, and prepare the launching ship to be deployed in the South Atlantic off Tierra Del Fuego. ARPA contracted for the probes through the Air Force Weapons Lab (a young officer, to become General Lew Allen, was the Scientific Director) for the AFWL project and ARPA contracted directly with Lockheed (I think) for the nuclear launch vehicle.[1] Lockheed responded with a combination of Dr's. Martin Walt and George Taylor for the science aspects and Tom Anderson supported by Tom Dudley with Irv Culver (the designer of the X-17) for the engineering and hardware.

ARPA and the science community were told that it would take three launches to guarantee one success and we were off and running with the five spare X-17s as a resource. The test vehicle was long and slender and would have to be spun to be stable after its first stage fins were lost at separation, so one of the vehicles was prepared for a test of strap-on spin rockets and the structural beef-up calculated to strengthen the attachments between stages to make the bird withstand spinning. The fins were also canted to produce spin.

Thanks to the schedule, the launch stand for the three vehicles on the ship fantail (The U.S.S. Norton Sound) had to be tackled first so the ship could leave to reach its launch station. Dudley tackled this while Anderson and Culver tackled the spin and structural integrity. The Air Force was charged with the transport of test vehicles and nuclear devices to rendezvous with the ship. Simultaneously, probe rockets were being assembled from where ever they were available and instrumented by Walt while Taylor worried about the nuclear device furnished by Sandia. The momentum built instantly and our first flight from near Port Hueneme was hoped to be just a confirmation. Not so! The bird (long and slender) spun up just right so that its rpm matched first bending frequency and we scattered hardware all over the Pacific. We had one spare left so we attempted to

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[1] Actually, the contract was through ONR's field project branch.

avoid disaster by additional beef-up and reducing the fin cant. With our last spare we fired from the fan tail of the ship to test one of the launchers and the structure at the same time. Disaster again, and no more birds and no time--the ship had to leave. In the time for the Norton Sound to reach the South Atlantic we scoured the country--tried to find smaller spin rockets--designed and built new strap-on fittings, etc. We had to get a special courier flight from the Air Force to take the new hardware to match up with test vehicles and ship. We also prayed a bit.

At this point the scientific community, forgetting that the reason for three test vehicles was to get one success, then asked for three different altitudes. Some hard words were said by Tom Dudley who was in charge of launch details on the ship, supported by Dr. Taylor, who then thought about it and decided to use some Kentucky windage (his hobby was building and firing ancient Kentucky rifles) so he launched, or attempted to, on the roll of the ship (which was substantial in the weather encountered) in order to vary the altitude. The vehicle without spin rockets (final configuration) performed adequately from a mechanical and structural standpoint, but its stability left something to be desired.

Miscellaneous other victories and problems ensued, but the first launch on Aug. 27, 1958 reached a still arguable altitude with a successful nuclear event. On Aug. 30 the second launch reached a different altitude and also fired. Finally, the maximum desired altitude was reached on Sept. 6 with the third nuclear event. The multiple teams at Wallops, Puerto Rico and Cape Canaveral launched probes, the Air Force read out experimental packages on coordinated Atlas launches and Dr. Van Allen, who had monitored everything, obtained further information from Explorer 4. All told, it was a triumph for science, a remarkably successful engineering accomplishment and a monumental logistics miracle. Science, industry and government all did it right under ARPA--this is the way we need to do it today.

There are two amusing postscripts. Communications were necessary to alert everyone when the launch took place (under high security) so coded messages were relayed via miscellaneous foreign and U.S. commercial ships to the United States.[2] It appears to be a fact that the launch trigger for the probes was via a Greek ships captain.

The second postscript involved security. The day after the last shot, Bob Bailey, the P2V Program Manager from the Lockheed Aircraft Division, called me from Tahiti

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[2] The Navy Task Force had been shadowed by Russian trawlers, but these were "lost" during a storm in the Caribbean.

where he was on vacation. His words were "Willy -- what the hell are you blowing up in the South Atlantic?" I was stunned and asked him what he meant. The circumstances he described involved a group of instrumentation specialists alerted by the Air Force Geophysical Organization to listen for potential signals from the shots. They were discussing the whole affair in a bar where Bob and his wife were having a cocktail and someone mentioned Lockheed, which alerted Bob. He couldn't resist calling me. I was at the time Assistant General Manager for the Missile Systems Division so he surmised that I was involved. So much for security.

The whole operation started in May and was over early in September--approximately 90 days. I hope DARPA can guide us through many more miracles like this.

II. TIROS WEATHER SATELLITES

A. BRIEF OVERVIEW

The TIROS (Television and Infrared Observation Satellites) project involved active orchestration by ARPA of concepts and capabilities into the design of a meteorological satellite experimental system, the funding of the first such system together with its launch, and provision for follow-on analysis, before transfer to NASA. TIROS, the first dedicated meteorological satellite, opened up a new meteorological era. There has been a lasting impact since TIROS and its successors: TOS (TIROS Operational System) ITOS (Improved TIROS Operational System) and, more recently, TIROS N, 30 satellites in all, have been the principal global operational meteorological systems for the U.S. While used primarily for weather forecasting and climate research projects by NOAA and NASA, TIROS data and technology have been useful for the design of the Defense Meteorological Satellite System (DMSP). TIROS also provides data directly to military meteorological stations.

B. TECHNICAL HISTORY

By the spring of 1958 there was considerable evidence that technology had advanced to the point where it appeared possible to develop and construct a meteorological satellite, and a lot of enthusiasm to actually do it. The concept of using satellites for meteorology had been discussed in the U.S. since the late 1940's, and developed in some detail in a 1951 RAND report by Greenfield and Kellogg.[1] The International Geophysical Year (IGY) included plans for a meteorological satellite. Several payloads, brought to high altitudes by rockets, had taken large-scale pictures of cloud patterns. "Introduction to Outer Space," a publication issued by the President's Science Advisory Committee (PSAC) in March 1958, summarized current views:[2]

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[1] S.M. Greenfield and W.W. Kellogg, "Inquiry Into the Feasibility of Weather Reconnaissance From a Satellite Vehicle," Rand report 1951, reissued (unclassified) as Rand Report R-365, Aug. 1960.

[2] Quoted in J. R. Killian, *Sputnik Scientists and Eisenhower*, MIT Press 1977, p. 94.

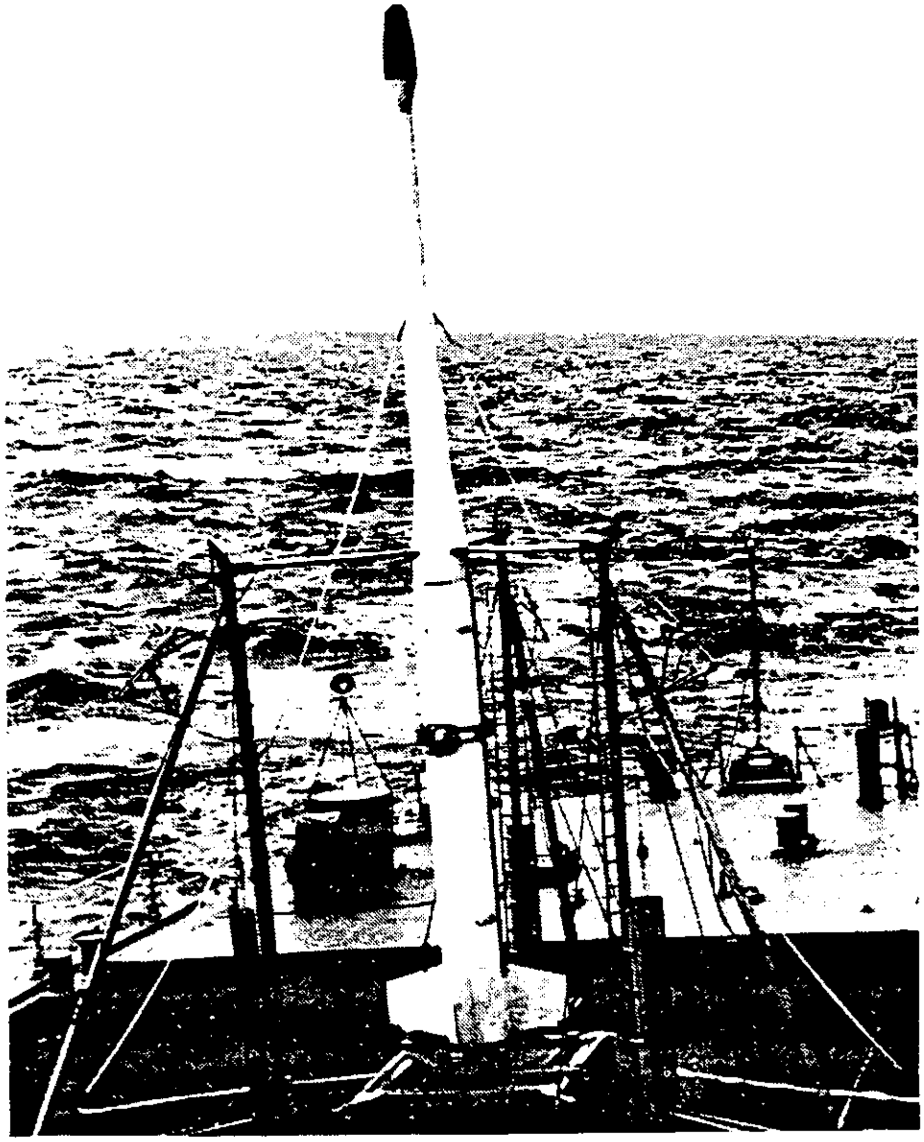

Figure A-1. Nuclear Warheads Were Launched Into Space by X-17s Under the Auspices of "Project Argus." These Missions Were Carried Out Aboard the U.S.S. Norton Sound.

> The satellite that will turn its attention downward holds great promise for meteorology and the eventual improvement of weather forecasting. Present weather stations on land and sea can keep only about 10 percent of the atmosphere under surveillance. Two or three weather satellites could include a cloud inventory of the whole globe every few hours. From this inventory meteorologists believe they could spot large storms (including hurricanes) in their early stages and chart their directions of movement with much more accuracy than at present. Other instruments in the satellites will measure for the first time how much solar energy is falling on the earth's atmosphere and how much is refracted and reflected back into space by clouds, oceans, the continents, and by the great polar ice fields.

These predictions were largely fulfilled with the first few TIROS satellites. In May 1958 Roger Warner, of the ARPA/IDA staff, set up a committee on meteorological satellites, chaired by W.W. Kellogg of RAND and including representatives of the three military services, the Weather Bureau, NACA[3] and RCA. This committee went to work to define a satellite meteorological system and develop solutions to the many associated problems. The program objective was:[4]

> To test experimental television techniques leading to a worldwide meteorological information system; to test sun angle and horizon sensor systems for spacecraft orientation; to obtain meteorological data for research and development analysis.

The committee recommended cloud cover observations using cameras of high, medium, and low resolution, and measurements of the earth's radiation in the infrared. RCA had participated in the early RAND study and Air Force surveillance satellite studies, and since 1956 had been working for the Army to develop a system (JANUS) to be launched by an Army rocket to provide a reconnaissance capability.[5] A prototype satellite, JANUS II, was constructed, but was long and thin, without directional stability. About this time, however, the Air Force was given responsibility by H. York, then DDR&E, for all DoD satellite surveillance systems. ARPA also had requested the Army to develop a booster, JUNO II based on the JUPITER, to put larger satellites in orbit. This allowed RCA to modify its design to a spin-stabilized "hatbox" shape. The TIROS project and the name originated in the ARPA meteorological committee. Invoking an urgent requirement for a meteorological satellite to assist operations of optical surveillance satellites, ARPA felt

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[3] NASA was established later, in July 1958.

[4] In "Meteorological Satellites," Library of Congress Staff Report for the Committee on Aeronautical and Space Sciences, U.S. Senate, March 29, 1962.

[5] "A Preliminary History of the Evolution of the TIROS Weather Satellite Systems," by John H. Ashby, NASA, 1964, p. 10.

that TIROS offered a timely opportunity to reorient the RCA effort toward meteorology, which would not have as stringent optical resolution requirements as demanded by targeting/surveillance systems, and so could be accomplished with systems that were considerably smaller and lighter.

This also allowed the TIROS project to be unclassified, which for a number of reasons was considered highly desirable at the time.[6] By July 28 ARPA Order # 10 was issued for a "Meteorological Payload" TIROS, providing nearly $8 million to the Army Material Command, under which the Army Signal Corps R&D labs were responsible for the payloads, with RCA the contractor.[7] Only one payload launch was called for in the RCA contract. The Air Force Cambridge Research Laboratory was given nearly $1M for data analysis in ARPA Order # 26 of September 29, 1958. The Air Force Systems Command was provided $3.6 million for Thor vehicles for the TIROS launch, on April 10, 1959. Originally TIROS was to include an optical television system, the top priority, to be built by RCA under Signal Corps supervision, and an infrared scanning (IR) system built by W.G. Stroud, of the Signal Corps laboratory, but this IR system was not included in the first payload.

When the TIROS project was transferred to NASA on April 13, 1959, the project plans and funding for initial payload construction, launch, and data analysis were in place, as well as apportionment of responsibility in each of these areas. According to a 1962 staff report for the Committee on Aeronautical and Space Science of the U.S. Senate on meteorological satellites:[8]

> The TIROS program, originated by the Advanced Research Projects Agency of the Department of Defense, was transferred to NASA on April 13, 1959. Basic responsibility was apportioned as follows: U.S. Army (USASRDL and contractors from industry--primarily RCA); development of payload and selected ground equipment, data acquisition, and data transmission; U.S. Air Force (BMD and contractors from industry--Space Technology Laboratories, Douglas and Lockheed); development of launch vehicle, mating of vehicle and payload, launch data acquisition. Air Force Cambridge Research Center assists with data analysis and interpretation.

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[6] There were strong pressures to define systems to be taken over by NASA, and TIROS, a weather satellite, offered much public appeal, and international goodwill opportunity. The transfer to NASA included provision to supply TIROS data to DoD.

[7] RCA has built TIROS systems ever since.

[8] "Meteorological Satellites," ibid., footnote 4.

> U.S. Navy (Naval Photographic Interpretation Center) assists the Weather Bureau in locating photographed areas by identifying landmarks and other geographical features. NASA (Goddard Space Flight Center), overall direction and coordination, tracking and orbit prediction, operation of the control center, data analysis, and interpretation. U.S. Weather Bureau (largely Meteorological Satellite Laboratory, which is supported by NASA): Data analysis and interpretation, data dissemination, and historical storage of data.

The same staff report gives a chronology of related events which occurred rapidly in this period. For example, Vanguard II, carrying a dual photocell system for earth albedo measurement designed by the Signal Corps R&D Lab, was launched in February 1959 to fulfill U.S. IGY commitments. IGYstudies leading to the Vanguard payload had explored many of the aspects of a meteorological satellite system. ARPA was aware of these studies and the Signal Corps lab's capability through this project. Explorer VI was launched in August 1959, carrying a payload which transmitted a rough picture of the earth's surface and its clouds. Also, in August of 1959 an Atlas missile carried a camera which took pictures of clouds over the Caribbean and the South Atlantic. And in October 1989, Explorer VII carried IGY instruments to measure the earth's radiation balance.[9]

TIROS 1, however, was the first dedicated meteorological satellite. A description is given by the same staff report:[10]

> **TIROS I (Television Infrared Observation Satellite)**
>
> Date of launching
>
> April 1, 1960.
>
> Launching vehicle
>
> Three-stage Thor-Able adapted. Liftoff weight, over 105,000 pounds; total height, 90 feet; basic diameter, 8 feet.
>
> General shape, weight, and dimensions of spacecraft
>
> A "pillbox," 42 inches in diameter and 19 inches high, covered by solar cells with three pairs of solid-propellant spin rockets mounted on baseplate. Shell composition: aluminum alloy and stainless steel. Total spacecraft weight, 270 pounds.

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[9] "Meteorological Satellites," ibid.

[10] ibid.

Spacecraft Payload:

Instrumentation: Two television cameras that are identical except for lens equipment -- a low resolution and a high-resolution camera -- both with 500 lines per frame and a video bandwidth of 62.5 kilocycles; a magnetic tape recorder for each camera with maximum capacity of 32 photographs taken at 30-second intervals (while out of ground-station range); two timer systems for programming future camera operations as set by a program command from either Fort Monmouth or Kaena Point stations; sensing devices for measuring spacecraft attitude, environment, and equipment operation. Antennas: four rods from baseplate for transmitters and one vertical rod from top center for receiver. Transmitters: TIROS broadcasted its picture on two FM radios at 235 megacycles with 2 watts each and tracking information on 108 and 108.03 megacycles, with 30 milliwatts. Power supply: nickel/cadmium batteries continuously charged by 9,200 solar cells. Power output average about 19 watts.

The TIROS orbit was nearly circular, at about 500 km and with an inclination of 48 deg. Ground command of the cameras allowed control power savings; readout was also commanded from the ground.

TIROS I was an instant success. Designed for 90 days operation, in 78 days it provided approximately 19,389 pictures of the cloud cover which were considered useable, and also some pictures of the sea ice useful to ice reconnaissance.[11] The TIROS low resolution, wide-angle camera TV system provided most of the data. The infrared scanning system was not included in TIROS I,[12] but infrared horizon sensors were employed. Some of these pictures showed features which were immediately identified as hurricanes and tornados. While routine daily worldwide data without interruptions was achieved only in 1966, TIROS has been considered semi-operational from the first launch.[13] Teams of meteorologists were involved in analysis of TIROS data, which were used to correct weather maps (see Fig. 1) for control of missile firings at test ranges, and for hurricane tracking. The comparison of vortical cloud images and of predicted vortical structures on weather maps was particularly striking.[14] That the payloads of the subsequent TIROS II, III and IV, between November 1960 and February 1962, included only minor changes of the television system indicated soundness of basic design. These later TIROS systems also included infrared scanners, radiometric and earth radiation balance measurement systems. Figure 2 shows the evolution of the TIROS system to 1978. The 30 satellites of the

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[11] "Meteorological Satellites," William K. Widger, Jr. Holt, N.Y. 1966, p. 136.

[12] Ashby, Ref. 4, p. 37. Infrared Sensors were used to determine the horizon.

[13] Footnote 5, p. 126.

[14] "TIROS Meteorology," by Arnold H. Glaser, AFCRL Report 613, 31 Mar. 1961.

TIROS, TOS and ITOS and NOAA series launched in 1985 all included vidicon TV systems similar to that of the first TIROS. The TIROS series has been the principal global operational meteorological system for the U.S. Weather Service.[15] Beginning with TIROS IX, the subsequent operational meteorological satellites, other than the GOES geoschronous weather satellite, have all had polar orbits.

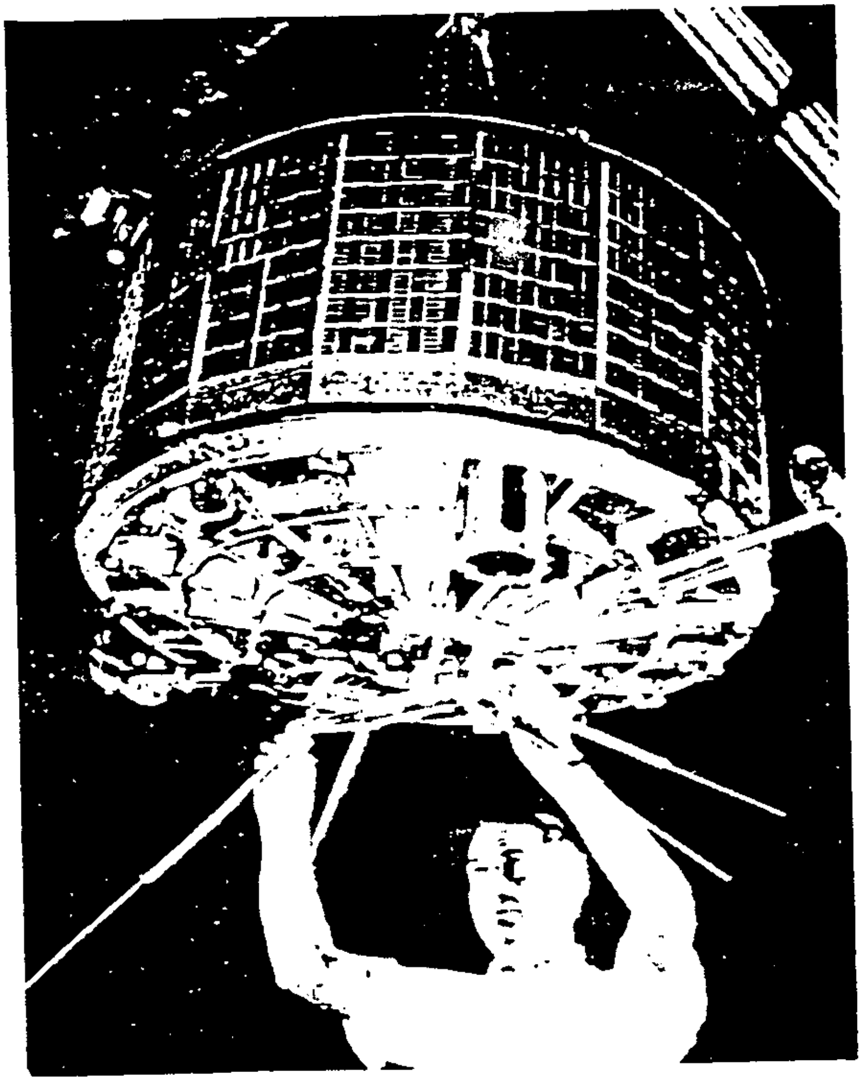

Figure 1. Tiros Weather Satellite (from "Advances in Space Science and Technology," Vol. 7, 1965, p. 369)

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[15] A. Schnapf, "Global Weather Satellites--Two Decades of Accomplishment," presented at the Aviation Space Writers Conference, Atlanta, 1978, and "25 Years of Weather Satellites," *RCA Engineer*, Vol. 30, August 1985, p. 23.

As the TIROS data began to be assimilated, the limitations of TIROS coverage due to its fixed spin axis, dependence on solar illumination, and the location of ground command stations began to be appreciated. In fact, TIROS was able to produce images of less than 25 percent of the earth's cloud cover. However, this was far more than available before.

It was soon clear that military requirements for detailed cloud conditions at specific times and locations would not, generally, be met by TIROS or any civilian system. Designs began for a military meteorological satellite system.[16] The statistics of cloud cover provided by TIROS and its follow-ons, as well as the TIROS system technology, have been important inputs to the design of the military system.[17]

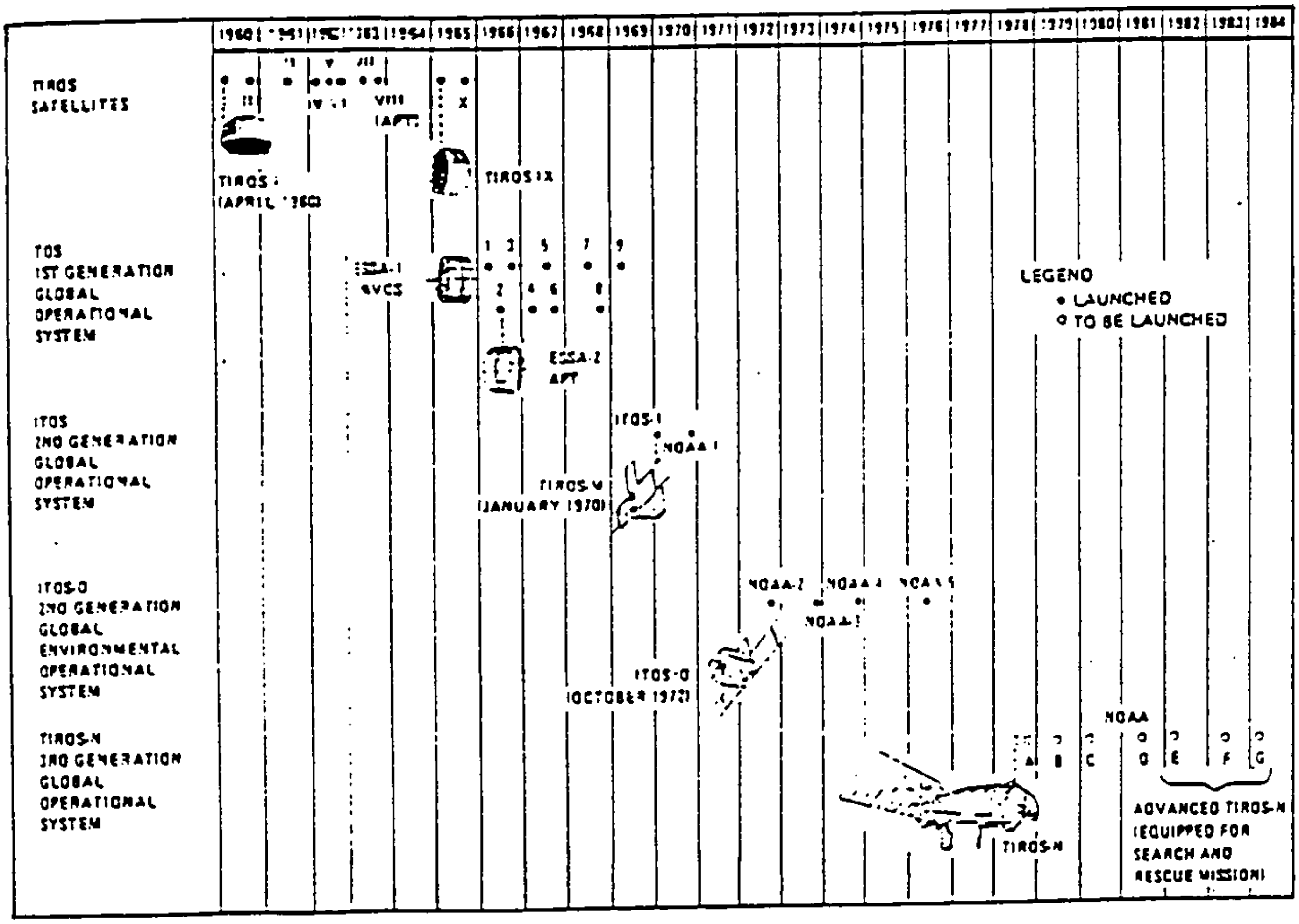

Figure 2. From A. J. Schnapf, Ibid.

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[16] IDA TE-214, by R.S. Warner, Jr., Dec. 15, 1959.

[17] Discussion with C. Cook, 12/79.

The resulting Defense Meteorological Satellite Program (DMSP), in operation since the mid-1960s (and also built by RCA), employs two spaced satellites in polar orbits at about the same altitude as the early TIROS, with sensors covering the visible and infrared spectral regions, and radiometric infrared systems at different wavelengths to measure atmospheric structure.[18] The primary emphasis of DMSP has been on cloud cover. Because of technology similarities and rising costs in the TIROS satellites and DMSP, Congress has questioned the need for both TIROS and DMSP. OMB and the National Security Council have studied the possibilities of commonality, some of which has proved feasible. Also, TIROS' orbits were lowered, in the early 1970's, to more nearly that of DMSP.[19] However, the military and civilian requirements are different, and the two separate systems have continued to be launched and to operate.

Data from the TIROS-type satellite are integrated with DMSP and other information in the Air Force Global Weather Central at Offutt AFB. Since 1972 DMSP data have been available to civilian weather services.

C. OBSERVATIONS ON SUCCESS

The TIROS idea was formed in an ARPA committee convened to define a satellite system to meet an urgent meteorological requirement related to the efficient use of surveillance satellites. TIROS drew on previous Air Force studies and Army technology developed originally for surveillance purposes. The top-level decision that surveillance would be an Air Force responsibility made the Army-developed technology available for meteorology.

Roger Warner, a gifted member of ARPA's staff, pulled together, in the agency's TIROS steering committee, a group of experts from RAND, government labs and agencies, academia and industry who in fact were both uniquely qualified to define the system and in a position both to share and carry out the responsibility for constructing it and making it work.

No new component technology needed to be developed, and the experts on the committee had been anxious to get going for some time. The IGY had also recommended such a project. It would have been inefficient and unwise not to take quick advantage of

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[18] "What's The Weather Down There," by M.D. Spangler, Westinghouse Engineer, Vol. 34, No. 4, Oct. 1974, and "Evolution of the Operational Satellite Service 1958-84" by A. Schnapf, RCA, 1979, p. 13.

[19] "Weather Satellite Costs Have Increased...," GAO Report RCED 86/28 Oct. 31, 1985, p. 97

this capability and enthusiasm. RCA, the industrial payload contractor involved, has continued to construct the TIROS payloads to date as well as the military DMSP satellites. The objective to quickly obtain and use an experimental system was achieved very efficiently and quickly. After TIROS was transferred to NASA, arrangements continued to ensure availability of data to the military. ARPA can be credited with getting U.S. weather satellite technology under way, which transformed meteorology, as well as producing, even while in an initial experimental phase, useful information for military operations.

Probably TIROS, or something similar, would have gotten under way eventually as a NASA program had not ARPA undertaken it. However, ARPA's actions were on a scale and quality to get TIROS off to a very good start. Timeliness for military users, and the existence and nature of the accomplishment as a international interest item, evidenced by Presidential level announcements, were very important factors for U.S. posture in the early space days, and very helpful to NASA's early image.

TIROS, however, could not be depended on to provide specific data for military requirements. This, plus TIROS' success, led to the development of the Air Force DMSP satellites with primary emphasis on cloud cover, as was that of the first TIROS. Negative lessons, such as TIROS limitations in coverage due to fixed orientation, scan angle and the location of ground stations, and the positive contributions of statistical information produced by TIROS on cloud distributions, were also essential to design the DMSP system. Again, this information would have been available, presumably, if NASA and not ARPA had undertaken TIROS, but again timeliness would have been an important factor. Later versions of TIROS added IR sensors. The DMSP design also incorporated similar technology, and DMSP data became available for civilian use in 1972.

As a result of a 1973 study mandated by Congress, NOAA and the Air Force were directed to coordinate future efforts for new polar satellite designs. However, the different requirements for the military and civilian users have so far justified separate systems.[20]

The recorded ARPA outlay for the first TIROS was about $14 million--$9 million for payload, $4M for a booster, and $1M for analysis. Much of the development of the satellite package had already been accomplished in the previous Army-funded work, and the Air Force also paid for some of the expense of the ground stations involved. Costs of

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[20] GAO, ibid.

the civilian TIROS and follow-ons are estimated as approaching one-half billion. The DMSP system cost to date is estimated also as about one-half billion.[21]

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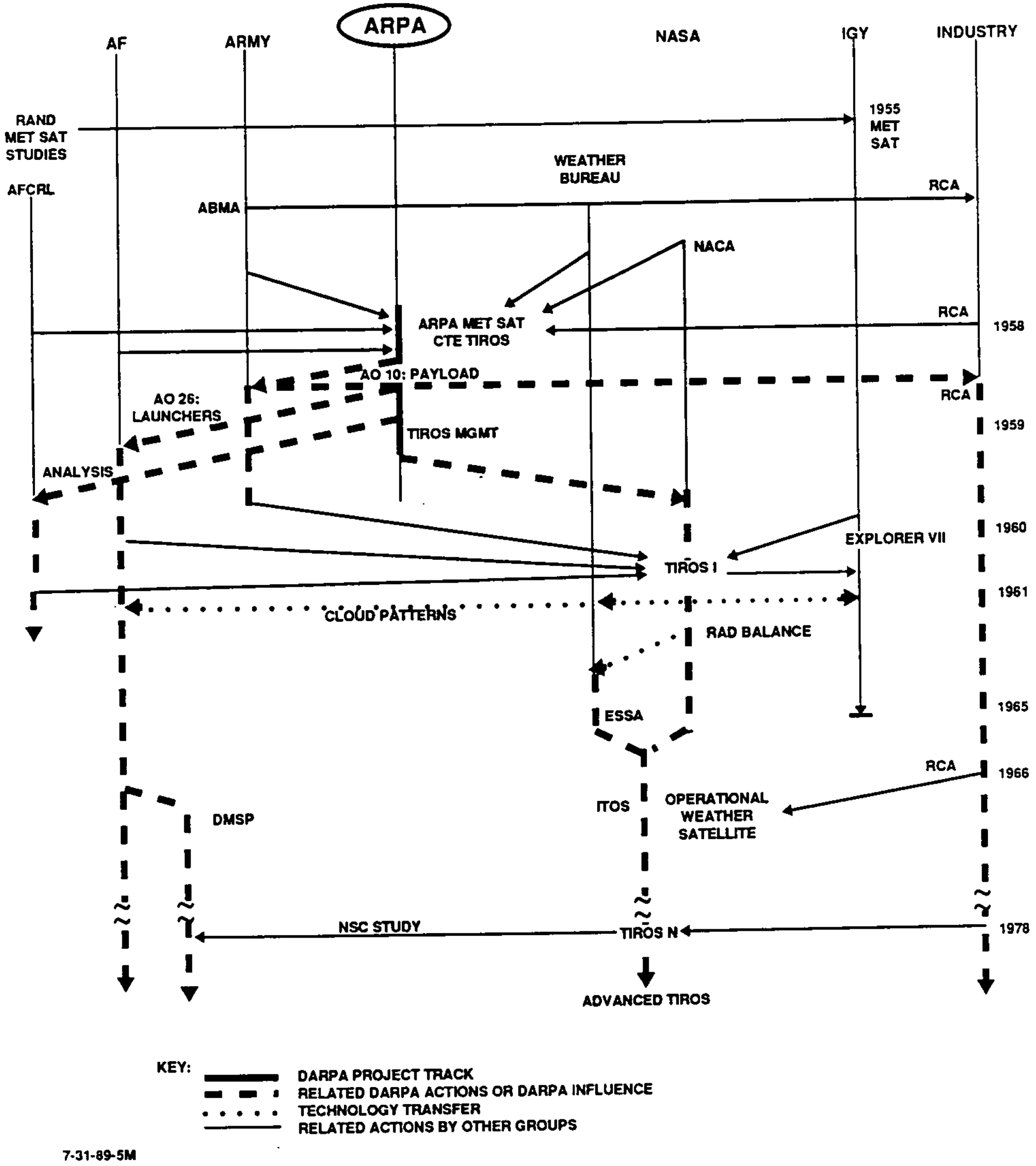
[21] C. Cook, ibid.

TIROS


ARPA
AF
ARMY
NASA
IGY
INDUSTRY
RAND MET SAT STUDIES
1955 MET SAT
WEATHER BUREAU
AFCRL
RCA
ABMA
NACA
ARPA MET SAT CTE TIROS
RCA
1958
AO 10: PAYLOAD
AO 26: LAUNCHERS
RCA
TIROS MGMT
1959
ANALYSIS
1960
EXPLORER VII
TIROS I
1961
CLOUD PATTERNS
RAD BALANCE
ESSA
1965
RCA
1966
DMSP
ITOS
OPERATIONAL WEATHER SATELLITE
NSC STUDY
TIROS N
1978
ADVANCED TIROS
KEY:
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS
7-31-89-5M

III. TRANSIT NAVIGATION SATELLITE

A. BRIEF OVERVIEW

ARPA was responsible for getting the world's first global satellite navigation system (later called TRANSIT) started, with a timely, substantial push of the original work at the Applied Physics Laboratory in the fall of 1958.[1] The TRANSIT navigation system has provided reliable accurate positioning for the Navy's Polaris strategic submarines and other ships since the mid 1960's (fully operational in 1968). A commercial version served more than 8000 users in 1986 including more than 20,000 ships and a large number of oil drilling rigs at sea. The system's surveying capabilities (the reason for the name TRANSIT), accurate to a few meters, have contributed to improvement of nearly two orders of magnitude in positioning accuracy on the earth's land maps including those generated by the Defense Mapping Agency. TRANSIT is scheduled to be replaced by the DoD Global Positioning System (GPS) which uses different technology, in 1996.

B. TECHNICAL HISTORY

In the section about ARPA in his recent autobiography, Herbert York, ARPA's first chief scientist, says TRANSIT was the only Navy Space proposal at the time.[2] York also says that most of the things ARPA touched in these early space days had, in fact, been around a while. TRANSIT, however, had only been invented in March 1958, about the same time that ARPA began. When the Sputniks were launched in late 1957, researchers at Johns Hopkins Applied Physics Laboratory (APL) found that by accurately measuring the time-varying doppler shift of the radio signal from Sputnik as it went by, they could determine its orbit, and McClure of the same laboratory suggested that this procedure could be inverted: from a knowledge of the satellite orbit and the doppler measurements, it was

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[1] ARPA Order #25 of 9/25/58 to BuWeps, Dept. of the Navy, for $8.9 million for a "doppler navigation system."

[2] H. York, *Making Weapons, Talking Peace*, Basic Books, 1987, p. 146. York points out that the idea of using a cooperative satellite for position location was old. However, obtaining the information from doppler measurements and the equation of motion in a gravitational field was new.

possible to determine the location of the measurement.[3] The satellite orbit could be determined by ground stations and communicated to the satellite, which in turn could transmit updated orbit parameters to the "user," along with the cw signal for doppler determination. With a computer, the "user" could quickly determine his location.

There were some striking advantages over other forms of navigation:[4]

1. Since the measurement of angles or directions are not required, simple nondirectional receiving antennas suffice. Directional antennas aboard a rolling, pitching ship are complicated and create a serious maintenance problem.
2. Since optical measurements are not involved, the system would be immune to the vagaries of the weather. For months on end, the skies over the northern Pacific and Atlantic Oceans are cloud covered. During such periods, celestial navigation is useless.
3. All of the equipment sites that are required to operate the system could be within the U.S. This avoids the political and logistical problems associated with operating stations in foreign countries.
4. On land, repeated Doppler "navigation" at a fixed site becomes a new form of surveying. The earth could be surveyed globally in an internally consistent coordinate system.

These features were particularly attractive for use by a submarine, which could briefly expose a small antenna at suitable times, to quickly determine its position.

Within a month after the analysis of the first doppler measurements:[5]

> ... "the essential elements of the present day Transit System were described in a 50-page proposal to the Navy Bureau of Ordnance complete with block diagrams, power and weight estimates, and an accuracy analysis.."

Although the Navy was then engaged in developing the Polaris system, and gave informal support to the work at APL, apparently some in the Navy did not want to say an improved navigation capability was needed at that time. Because ARPA then had DoD

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[3] "The Gestation of Transit as Perceived by One Participant," by T. Wyatt, Johns Hopkins. H.D. Black, ibid. p. 3, *John Hopkins APL Technical Digest*, Jan. - March 1981, Vol 2, # 1, p. 32. This issue of the Technical Digest is dedicated to Transit. Cf. also "The Genesis of Transit," internal APL memo by G.C. Weiffenbach, Mar. 1986.

[4] "Satellite for Earth Surveying and Ocean Navigation," H.D. Black, ibid. p. 3. Cf. also "Terrestrial, Lunar and Planetary Applications of Navigation and Geodetic Satellites," by John D. Nicolaides, Mark M. Macomber and Wm. M. Kaula, *Advances in Space Science and Technology*, Vol. 6, 1964.

[5] T. Wyatt, ibid., p. 32.

responsibilities for satellites, APL brought their transit proposal to ARPA in early fall of 1958. ARPA responded positively in October with funding and authorization to build spacecraft and ground stations and soon afterwards for launch vehicles. The scope of work program included most of the elements eventually in the operational system (see Fig. 1):[6]

1. Spacecraft (always called "satellite" whether in the shop or in orbit) -- design, construction, and operation;
2. Tracking stations -- design, construction, and operation;
3. Injection station -- design, construction, and operation;
4. Navigation equipment -- design and construction;
5. Geodesy -- expansion of the then-current knowledge of the earth's gravity field:
6. Launching vehicles -- design, construction, and field operations after the first few launchings.

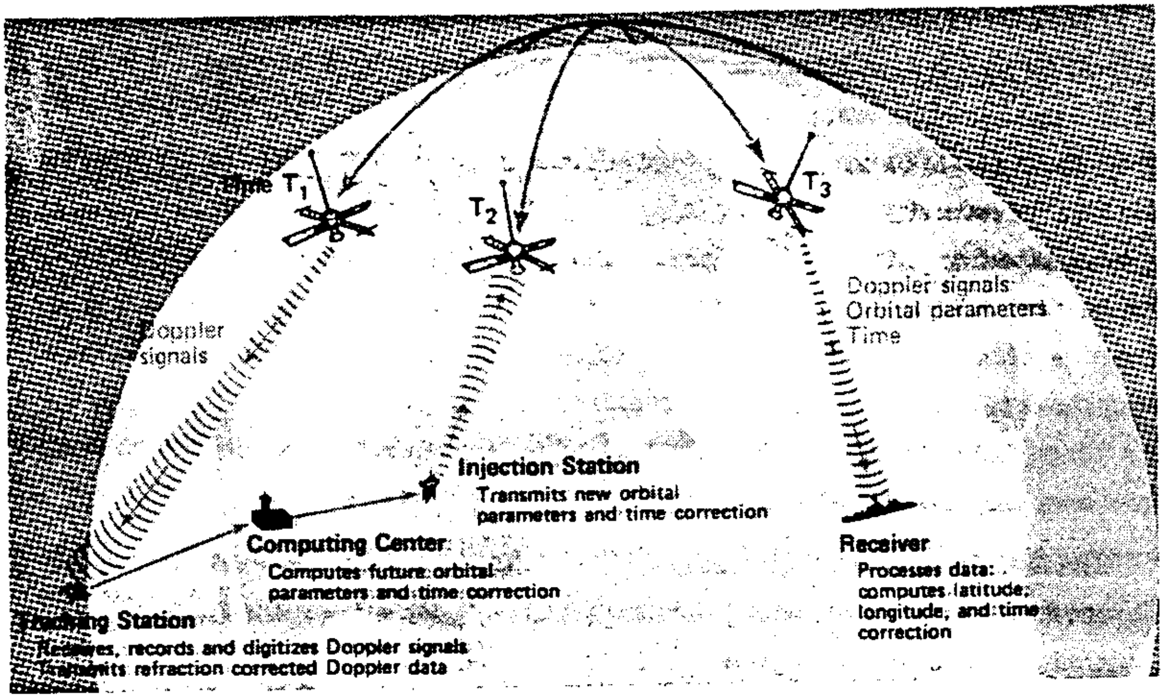

Figure 1. System Architecture of the Navy Navigation Satellite System (Transit).
From H.D. Black, Ibid., p. 4.

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[6] T. Wyatt, ibid., p. 32.

The APL project engineer states:[7]

> ...in May 1959, APL issued a program plan identifying an ARPA experimental phase and a Navy operational phase. The plan optimistically envisioned six launchings in the following fiscal year and eight more in the subsequent two years to achieve a full operational capability in 1962. The plan included design and manufacture by APL of launch vehicles (possibly based on an adaptation of the Polaris missile), a worldwide complex of 16 ground stations, and 18 shipboard navigating equipments.
>
> I accept full responsibility for the design of a plan so wildly ambitious. Only slightly less astonishing than the plan, however, was its ready acceptance (including its estimated cost) by the Department of Defense.

Soon afterwards, however, DoD assigned all military launch responsibility to the Air Force. Arrangements for the launch vehicles were then made by ARPA on the basis of the evolving TRANSIT payload characteristics, the developing launch vehicle capabilities and availabilities and, the needs of other "piggy back" payloads.[8] Some of these other payloads included an NRL radiation experiment (GREB), a Naval Ordnance Test Station (NOTS) package to measure infrared background, and the Army Map Service's SECOR radio location package, to permit determination of its comparative accuracy. The early TRANSIT satellites (one version shown in Fig. 2) were all built by APL. These eventually weighed about 110 lb of which most of the additional weight over 50 lb for the working system was for redundancy and other safeguards. Arrangements for the initial launchers were made expeditiously: Seven vehicles, at a cost of ~ $28 million were provided for by ARPA between 4/59 and 7/59.[9] The Air Force THOR-ABLE and THOR-ABLE STAR, each capable of launching several hundred pounds into the required ~ 1000 km orbits, were used for the first launches. This orbit was to be nearly circular and far enough above the earth's atmosphere to avoid appreciable drag. The IGY Baker-Nunn satellite tracking cameras were helpful in determining early orbits.

The first TRANSIT launch was in 1959. While this launch failed to achieve orbit, it still provided useful doppler data. The next TRANSIT, 1B, achieved orbit in 1960 and demonstrated feasibility of the system. Three more TRANSITS, of evolving design (see

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[7] T. Wyatt, ibid., p. 32. Transit launches supported by ARPA were: one in 1959 which failed to achieve orbit--but provided useful doppler from data; one in 1960 which achieved orbit and demonstrated feasibility; three in 1961; and two in 1962, of which one was for Geodesy.

[8] See IDA TE 205 of 12/4/59, "Revised Development and Funding Plan for TRANSIT," by Roger S. Warner of IDA/ARPA staff, which outlines the history and plans to that date.

Fig. 3),[10] were launched in 1961. The first TRANSITS were not oriented and had nearly omnidirectional antennas. Two frequencies were broadcast in one circularly polarized mode to allow compensation for ionospheric effects. Later TRANSITS were smaller, used unfolding solar cell frames, and eventually were gravity-stabilized toward the earth's center. This allowed directional antennas to be used, decreasing power demands. The move to smaller satellites was planned in order to make use of the less expensive SCOUT launchers.[11]

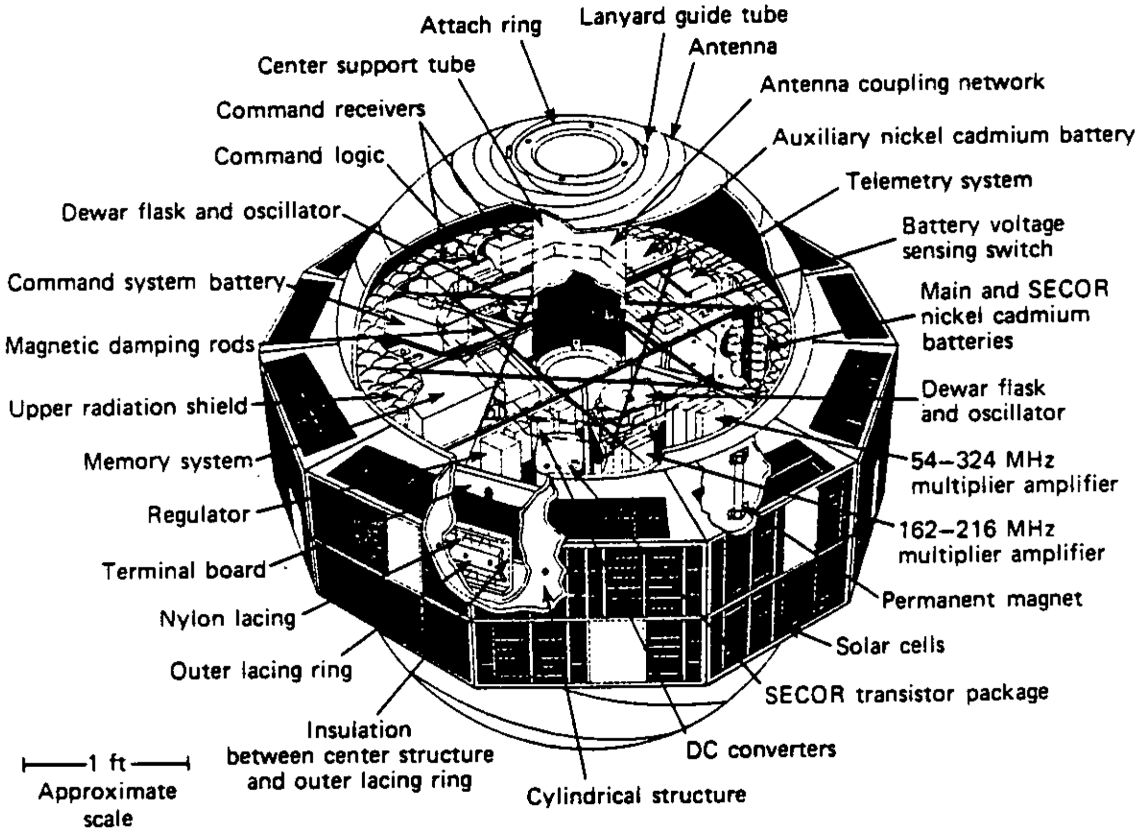

Figure 2. Cutaway View of TRANSIT 3-B Satellite Illustrating Key Components (U.S. Navy and APL/JHU)

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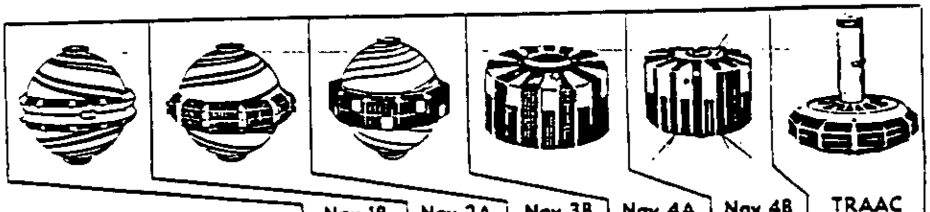
[9] Thus ARPA Order 17, Task 4 of 4/59 provided nearly $5.1M to the Air Force for a Thor Delta and Thor 104: Task 6, of 4/59 for two Thor Hustlers, for nearly 3.4M; and A.O. 97 of 7/59 for Thor Delta, Thor 104, and Thor Agena; all for launches of navigation satellites.

[10] John D. Nicolaides, ibid., p. 168.

[11] Roger S. Warner, ibid. The solid propellant SCOUT was a NASA development. The history of SCOUT is described in "A New Dimension," NASA Reference Publication 1028, Dec. 1978, p. 704 ff.

It soon became clear that geodetic knowledge would have to be improved in order to attain the desired accuracy for POLARIS, and that this knowledge would have to be developed largely by experiments with TRANSIT itself.



	Nav 1B	Nav 2A	Nav 3B	Nav 4A	Nav 4B	TRAAC
LAUNCH DATE	APRIL 13, 1960*	JUNE 21, 1960	FEB 21, 1961**	JUNE 29, 1961	NOV 15, 1961	NOV 15, 1961***
FREQUENCIES "B" SYSTEM "C" SYSTEM "Z" SYSTEM	162-216mc 54-324mc	162-216mc 54-324mc	162-216mc 54-324mc	54-324mc 150-400mc	54-324mc 150-400mc	54-324mc
RMS FREQUENCY NOISE AS MEASURED AT TRACKING STATIONS "B" SYS. 162-216mc "C" SYS. 54-324mc "Z" SYS. 150-400mc	5 Parts in 10^{9} 5 Parts in 10^{10}	1 Part in 10^{9} 7 Parts in 10^{10}	5 Parts in 10^{10} 5 Parts in 10^{10}	2 Parts in 10^{10} 2 Parts in 10^{10}		
MEMORY: TYPE : CAPACITY	None	None	Magnetic Shift Register 384 bits	Delay Line 2049 bits	Ferrite Core 1344 bits	None
WEIGHT	265 lbs.	223.3 lbs.	290.3 lbs.	175.1 lbs.	198 lbs.	233 lbs.
INITIAL PERIGEE ALTITUDE	378 km	621 km	178 km	883 km	950 km	
INITIAL APOGEE ALTITUDE	754 km	1070 km	978 km	994 km	1111 km	
INCLINATION	51.3 deg.	66.7 deg.	28.4 deg.	66.8 deg.	32.4 deg.	32.4 deg.

* Note: Nav 1B ceased radiating on July 11, 1960.
** Nav 3B entered the atmosphere on March 30, 1961.
*** Launched pickaback on Transit 4B.

Figure 3. TRANSIT Satellites Launched During 1960 (U.S. Navy and APL/JHU). From Nicolaides, ibid., p. 176.

According to an overview by the project engineer:[12]

> ...the number and the variety of satellites ultimately found necessary were not anticipated at the outset. It was assumed in the first program plan that 50% of the satellites would be launched and operated successfully and that successful satellites would have an average life of one year. No allowance was made for mistakes or for the extent of the design evolution. Unfortunately, these assumptions were overly optimistic. Early on, it became evident that the Transit program would require special-purpose satellites for geodesy, radiation measurements, radioactive isotope power supply trials, and attitude-control experiments. Some of these satellites, of course, had as their primary missions the support of national objectives other than Transit. Therefore, the number of APL-built satellites directly or partially related to the Transit program grew to a total of 36 by the time the system was declared fully operational in October 1968. Eight of the satellites were victims of launch-vehicle failures and two were damaged by a high-altitude nuclear test (Project STARFISH).

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[12] T. Wyatt, ibid., p. 33.

The STARFISH event took place in 1962, after ARPA involvement in TRANSIT. In fact, some of the early TRANSIT satellites have had useful lifetimes of over 10 years.[13] Geodesy, in particular the accuracy of models of the earth's gravitational field, was soon found to be a limiting factor to TRANSIT. It was not until about 1965 that a model became available allowing the desired < 1/4 nmi positional accuracy for POLARIS.

The first POLARIS submarine was declared operational by the Navy in late 1960. By 1963, some operational use was made of TRANSIT by POLARIS; in 1968 the TRANSIT system was declared fully operational by the Navy.[14] The system was not adopted by NASA, however, possibly because of its inability to track geostationary satellites.[15] Commercial use of TRANSIT also dates from 1968. The commercial Magnavox receivers use only one frequency, and also use a simplified cycle counting technique possible with reception of signals from an entire pass of the satellite. Receivers on Navy ships use two frequencies to allow ionospheric compensation and more sophisticated algorithms which use only a segment of a single satellite pass. DMA, for mapping purposes, has developed its own receivers.

The current TRANSIT system consists of a constellation of about seven satellites and a ground tracking network. The Navy plans a phaseout of TRANSIT in about 1996, when the GPS, which does not use the doppler principle, is scheduled to be available. GPS is to provide global, real time navigational fixes of higher accuracy than TRANSIT.

C. OBSERVATIONS ON SUCCESS

The TRANSIT proposal was brought to ARPA by APL, a major contractor-operated R&D laboratory of the Navy. While the original motif was scientific curiosity, the implications of the TRANSIT concept were quickly appreciated at APL, which also had responsibilities for the POLARIS project.[16]

Apparently the Navy would not support the proposal at the time. To demonstrate feasibility could be expensive and risky. Partly, the risks were those of a new space

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[13] An account of TRANSIT's successes and problems are given by Thomas A. Stansell, Jr. of Magnavox, in "The Many Faces of TRANSIT," paper presented at the 38th meeting of the Institute of Navigation, 1977.

[14] Joint paper on the Navy Navigation Satellite System (TRANSIT) Status and Plans," by O.L. Sentman, Robert J. Danchick, and Lawrence J. Ranger, APL 1987.

[15] "Technical Innovations in The APL Space Department," by R.B. Kershner, APL Technical Digest, Vol #4, Oct. 1980, p. 264.

[16] Kershner, ibid., p. 265.

system with a very high premium on reliable, accurate performance at a time when launch reliability was not high and there was little experience with reliability of space systems. While the key principle involved seemed straightforward and had already been checked, roughly, using the Sputniks, and no major new technology development appeared to be necessary, it was not clear at the outset that the accuracy of better than 1/4 nautical mile needed for POLARIS, could be attained. A number of experiments with the system were needed to develop a much improved model of the earth's gravity field before this accuracy was demonstrated.

ARPA responded very quickly with funding in sufficient quantity to cover construction of the satellites and related ground stations, plus several launches and support systems, for an outlay of about $28M at this stage. This was enough to give TRANSIT a very good chance of getting through a feasibility demonstration. ARPA bought the APL development plan and gave them a free hand, except for arrangements for the launch vehicles and added payloads--which ARPA did itself. This enabled APL to concentrate on the satellite and ground system. Regarding the ARPA management the APL project engineer states:[17]

> The work at APL was also facilitated by the rapidity with which decisions could be obtained from a streamlined DoD organization. During the first year, Roger S. Warner, Jr. (of ARPA) was both the point of contact and the decision maker. In the following year or two, the entire DoD management team comprised only two or three individuals. The government's program managers were both highly competent and highly motivated.

While there was some POLARIS support from 1959, there was some difficulty in obtaining adequate Navy funding through 1961. ARPA funding in 1960 and 1961 for TRANSIT appears to have been about $24M, for a total outlay of about $42M. The strength of ARPA support, rapidity of progress, demonstration of feasibility, and diminishing expected costs ensured Navy support from 1962 onwards. It took until about 1965, and an expenditure by the Navy in the hundred million range, to achieve the accuracy desired for POLARIS. By this time the POLARIS budget was high, so that this was a small fraction.

ARPA also made TRANSIT known to other potential military users, such as DMA, and also in the civilian maritime area. The impact of TRANSIT on mapping, geodesy, and land surveying were somewhat anticipated and have been very great. An unanticipated,

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[17] T. Wyatt, ibid., p. 32.

major impact occurred in oil rig placement in ocean shelf regions.[18] The impact on oceanography has been very great.[19]

About 36 operational TRANSIT satellites have been launched, at a systems cost to the Navy approaching $1/2 billion. The commercial investment for TRANSIT navigation equipment has been estimated as about $1/2 billion.[20] While the GPS system, now scheduled to replace TRANSIT (and other DoD navigation systems) by 1996, uses different technology, the success and reliability of TRANSIT may be credited with establishing the basis for wide acceptance of a satellite navigation system.[21]

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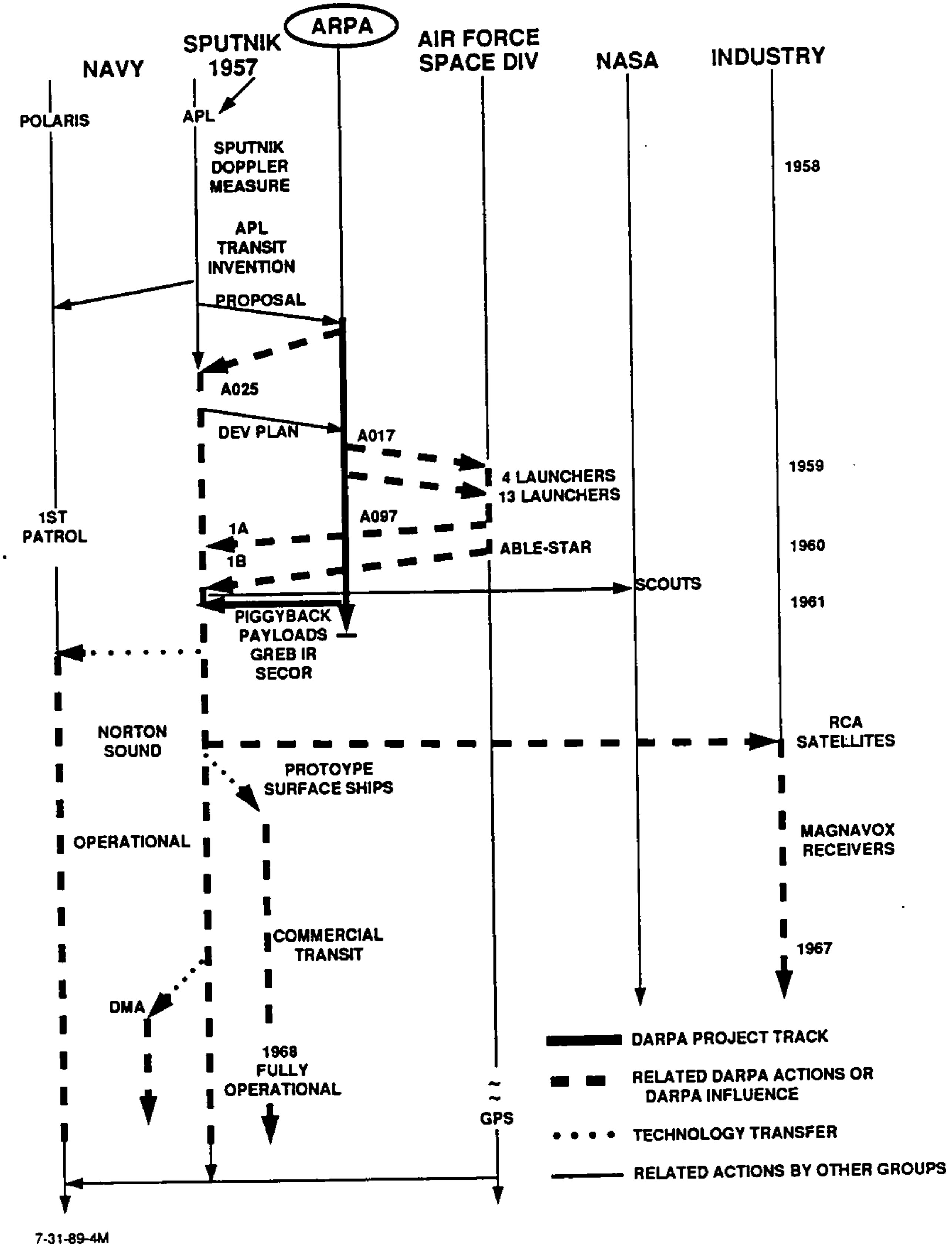
[18] Satellite Doppler Tracking and its Geodetic Applications," Phil. Trans. Royal Society of London A-294, 1980, pp. 209-406. An account of a discussion on this topic held at the Royal Society 10-11 October 1978.

[19] Thomas A. Stansell, ibid., p. 93, quotes Dr. Ewing, head of Columbia University's Lamont Laboratory, to this effect, regarding the development of oceanography.

[20] Discussion with T.A. Stansell, 1/90.

[21] Discussion with Dr. C. Cook, 12/89.

TRANSIT


ARPA
NAVY
SPUTNIK 1957
AIR FORCE SPACE DIV
NASA
INDUSTRY
POLARIS
APL
SPUTNIK DOPPLER MEASURE
1958
APL TRANSIT INVENTION
PROPOSAL
A025
DEV PLAN
A017
4 LAUNCHERS
13 LAUNCHERS
1959
1ST PATROL
A097
1A
1B
ABLE-STAR
1960
SCOUTS
1961
PIGGYBACK PAYLOADS GREB IR SECOR
NORTON SOUND
RCA SATELLITES
PROTOYPE SURFACE SHIPS
OPERATIONAL
MAGNAVOX RECEIVERS
COMMERCIAL TRANSIT
1967
DMA
1968 FULLY OPERATIONAL
GPS
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS
7-31-89-4M

IV. CENTAUR

A. OVERVIEW

CENTAUR, the first liquid hydrogen-liquid oxygen burning upper stage for efficiently placing sizeable payloads into geosynchronous orbit, or into lunar and deep space missions, was first funded by ARPA in 1958. Transferred to NASA in late 1959, CENTAUR, after a number of problems and failures, had its first successful orbital flight in 1963, and its first successful mission in 1966. Since then it has been a very reliable "workhorse" for placing payloads, including DoD's FLTSATCOM, into geosynchronous orbit. A version of CENTAUR is planned to go on the Air Force's TITAN IV. CENTAUR engine technology has also been used in the upper stages of the large SATURN rockets used in the APOLLO manned flight series to the moon (see Chapter V), and in the liquid hydrogen-oxygen engines also used by the SHUTTLE.

B. TECHNICAL HISTORY

The advantages of a hydrogen-oxygen fuel combination to achieve high exhaust velocities were recognized by early rocket pioneers. U.S. efforts on liquid hydrogen propulsion systems date back to before WWII, at NACA's Lewis Flight Propulsion Laboratory. The engineering difficulties of the necessary cryogenic systems were recognized during WWII in the U.S. and Germany. After WWII the Air Force funded work on liquid hydrogen-liquid oxygen (LH_2/LOX) fueled rockets at Ohio State University, and some fundamental work in the same direction was conducted at the NACA Lewis Laboratory. Those early experiments showed that exhaust velocities in the range of 3500 m/sec could be attained with LH_2/LOX. Early studies of satellites, including some directed to achieving orbit with a single stage, recognized the potential advantages of an LH_2/LOX combination, particularly if housed in light, internally pressurized structures.[1] In this 1945-1950 period some significant earlier studies of figures of merit of different

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[1] Notably the Martin HATV vehicle design, studied for the Navy's Bureau of Aeronautics. John L. Sloop, "Liquid Hydrogen as a Propulsion Fuel," 1945-59, NASA SP 4404, 1978, p. 44.

vehicle weight and propellant combinations in the U.S. and Germany, were further extended.[2] However, these early initiatives were not followed up immediately.

A number of major advances in engineering large-scale liquid hydrogen generators and storage systems were made by the Atomic Energy Commisson (AEC) in the early 1950s for their early work on thermonuclear devices. In the mid-1950s also, following recommendations of their Science Advisory Board and of NACA's Lewis Laboratory, the Air Force commenced efforts to use liquid hydrogen for aircraft propulsion at high altitudes. This work led, in 1955, to flight tests of a Lewis-designed jet engine in a modified B-57 aircraft. Soon thereafter the AF commenced the (then) classified project SUNTAN, in which Pratt and Whitney (P&W) was funded in the 1956-1958 time period to develop an LH_2-burning engine for a high-altitude surveillance aircraft envisaged as a successor to the U2.[3] SUNTAN took advantage of much of the AEC-developed LH_2 technology and made a number of further advances, notably in pumping LH_2. Eventually, (in 1958) P&W successfully ran an LH_2 turbojet engine with ratings approaching the desired surveillance aircraft's characteristics. SUNTAN was dropped in 1957, however, partly because of controversies over the surveillance range capability the LH_2 technology would allow, but mostly because, after Sputnik, attentions turned to satellites for the surveillance mission.

About the same time, K. Ehricke of Convair made proposals to the Air Force for an LH_2-fueled upper-stage system based partly on Convair's thin-skinned, pressurized structure technology used successfully in the Atlas missile. Pratt and Whitney was also proposing, together with Lockheed, the application of the LH_2 technology lessons learned in SUNTAN to upper stages to boost large surveillance satellites into geosynchronous (GEO) orbit. In July 1958, the Air Force SUNTAN management team suggested to ARPA (which had overall responsibility for DoD Space Systems) a joint Convair-P&W effort which would build on the strong points of both organizations. At the time, the IDA staff supporting ARPA (ARPA/IDA) included several individuals who had strong backgrounds in related propulsion technology.[4] R. Canright, one of these experts, was involved in developing an early ARPA plan for launch vehicles matched to payloads including provision for use of LH_2/LOX upper stages.[5] NASA, which was just established, as one

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[2] Notably by W. von Braun in Germany and R. Canright of JPL.

[3] "Liquid Hydrogen as a Propulsion Fuel," ibid., p. 141.

[4] Ibid., p. 180.

[5] "Proposed Vehicle Program," IDA TE 110, 16 Feb. 1959, G.P. Sutton and R.B. Canright.

of its first actions, formed the Silverstein Committee to coordinate national plans for large space vehicles. Early considerations of the Silverstein Committee brought out advantages of LH_2/LOX upper stages, and ARPA acted quickly, before the end of August 1958, to fund, through the Air Force, a new Convair-P&W proposal for CENTAUR with LH_2/LOX engines to be used as an ATLAS upper stage.[6]

Soon thereafter, in October 1958, NASA requested transfer of CENTAUR, which was worked out the following year with Air Force continuing as manager and NASA promising to develop a number of CENTAUR upper stages, for which the "user" agencies would supply payloads, and an overall NASA-DoD Steering Committee which included a DoD representative with responsibility for future DoD communication satellites.[7] Large communication satellites, in geosynchronous orbit, were envisaged as high priority military payloads. A little later, still another DoD-NASA committee made an intensive study of the characteristics of the large launch vehicle SATURN, recommending adoption of the proposal that SATURN upper stages use LH_2/LOX. The Army Ballistic Missile Agency's (ABMA) von Braun group, which was building the SATURN, initially opposed LH_2/LOX because of its dangers and the light structure involved, but eventually agreed to it.[8]

Reflecting early optimism as well as the strongly felt need for its capability, the first CENTAUR flight test was scheduled for January 1961.

> CENTAUR was "the" rocket by which NASA would conduct extensive earth orbit missions, lunar investigations, and planetary studies. Aside from military missions assigned to CENTAUR, which were to be considerable, NASA planned to launch one operational CENTAUR every month for a period extending well into the 1970s and beyond.[9]

NASA had initially assigned CENTAUR management to its Marshall Space Flight Center, apparently because of that Center's responsibility for SATURN, a much larger project, including the planned use of CENTAUR-related engine technology for SATURN's upper stages.

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[6] AO 19 of 8/58, CENTAUR, for $21.5 million.

[7] Ibid., p. 201.

[8] Ibid., p. 238.

[9] "History of CENTAUR," NASA Lewis Research Center, undated, p. 2. For comparison, in 1988 ATLAS-CENTAUR launch capabilities were 4-6/year.

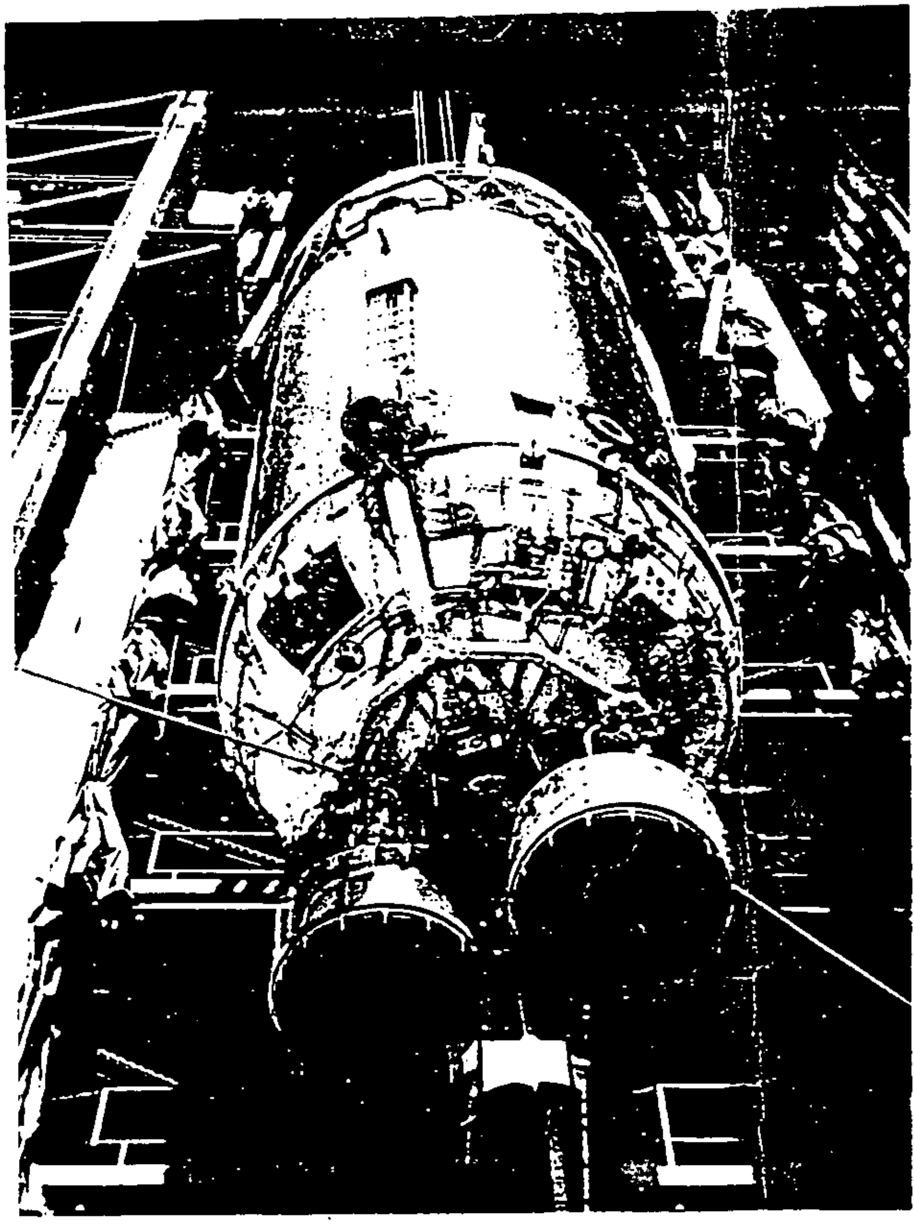

Figure 1. CENTAUR. This Version, Made for an ATLAS Second Stage, Is About 9 m in Length and 3 m in Diameter.[10]

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[10] D. Baker, "The Rocket, The History and Development of Rocket and Missile Technology," Crown, NY, 1978, p. 147.

The CENTAUR configuration then envisaged, shown in Fig. 1, involved two P&W RL-10 engines with about 15,000 lb of thrust each.[11] The nozzles, subject to the high temperature hydrogen flame, were also cooled by the liquid H_2. The practicability of doing this had been proved in previous work at several laboratories. CENTAUR was eventually to place more than four tons into low orbits, nearly two tons into geosynchronous orbit (GEO) and nearly one ton into an earth escape trajectory in combination with ATLAS and TITAN first stages. Figure 2 shows a typical trajectory to GEO.[12] There were considerable technical issues involved: besides those of the cryogenic systems for the LH_2/LOX fuel, there were the pumping and control of these liquids in a zero-gravity environment, the embrittlement of the thin-skinned structural sections subjected to low temperature, the complex nozzle cooling system, precision control of starting and restarting two engines, and the navigation and propulsion control systems for achieving precise orbits.

These issues proved to be too much for such an optimistic schedule, and there ensued a stream of test stand explosions and failures. In March 1962 the first CENTAUR flight test exploded shortly after liftoff. These events dampened DoD plans for use of CENTAUR, in particular for project ADVENT, which had the objective to place a (then) large communications satellite in geosynchronous orbit.[13] NASA then reassigned CENTAUR responsibility to their Lewis Laboratory, and in November 1963 the first successful (single stage) flight took place. Shortly thereafter the SATURN upper stage Centaur-type LH_2/LOX engines were also successfully operated.

In 1966 a successful series of CENTAUR-lifted missions began. During this 1961-66 period there were also improvements in the size and accuracy of computer-

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[11] Baker, op. cit., p. 147, Table 1, p. 167.

[12] From H.M. Bonesteel, "ATLAS and CENTAUR Evaluation and Evolution," Convair-General Dynamics Co., 1982.

[13] A.D. Wheelon, "The Rocky Road to Communications Satellite," AIAA 24th Aerospace Sciences Meeting, January 6-9, 1986, AIAA Document 86-0293, p. 5. There were plans, in 1958-59, for several DoD communication satellites, to be placed in GEO orbits by Centaur in 1962. IDA TE-29, Mar. 27, 1959, "Instantaneous Global Satellite Communications Systems," by S.B. Batdorf. These were eventually passed by ARPA and DoD to the Army's project ADVENT. See SAMSO chronology, 1954-59, Air Force Systems Command, Space Division History Office, p. 117. The ADVENT experience had many repercussions in DoD, one of which was the formation of the Defense Communications Agency, I. Getting, "All in a Lifetime," Vantage 1989, p. 534.

controlled inertial navigation and guidance systems. According to a Lewis Laboratory statement:[14]

> Coupled with already proven Atlas first stages, Centaur vehicles sent seven Surveyor spacecraft to probe the surface of the Moon between May 30, 1966 and January 7, 1968, furnishing valuable data for the first manned landing on the Moon in July, 1969.
>
> Other important Atlas/Centaur missions followed, including boosting the Orbiting Astronomical Observatory to scan the stars from above the Earth's atmosphere ... sending two Mariner spacecraft to chart the planet Mars ...

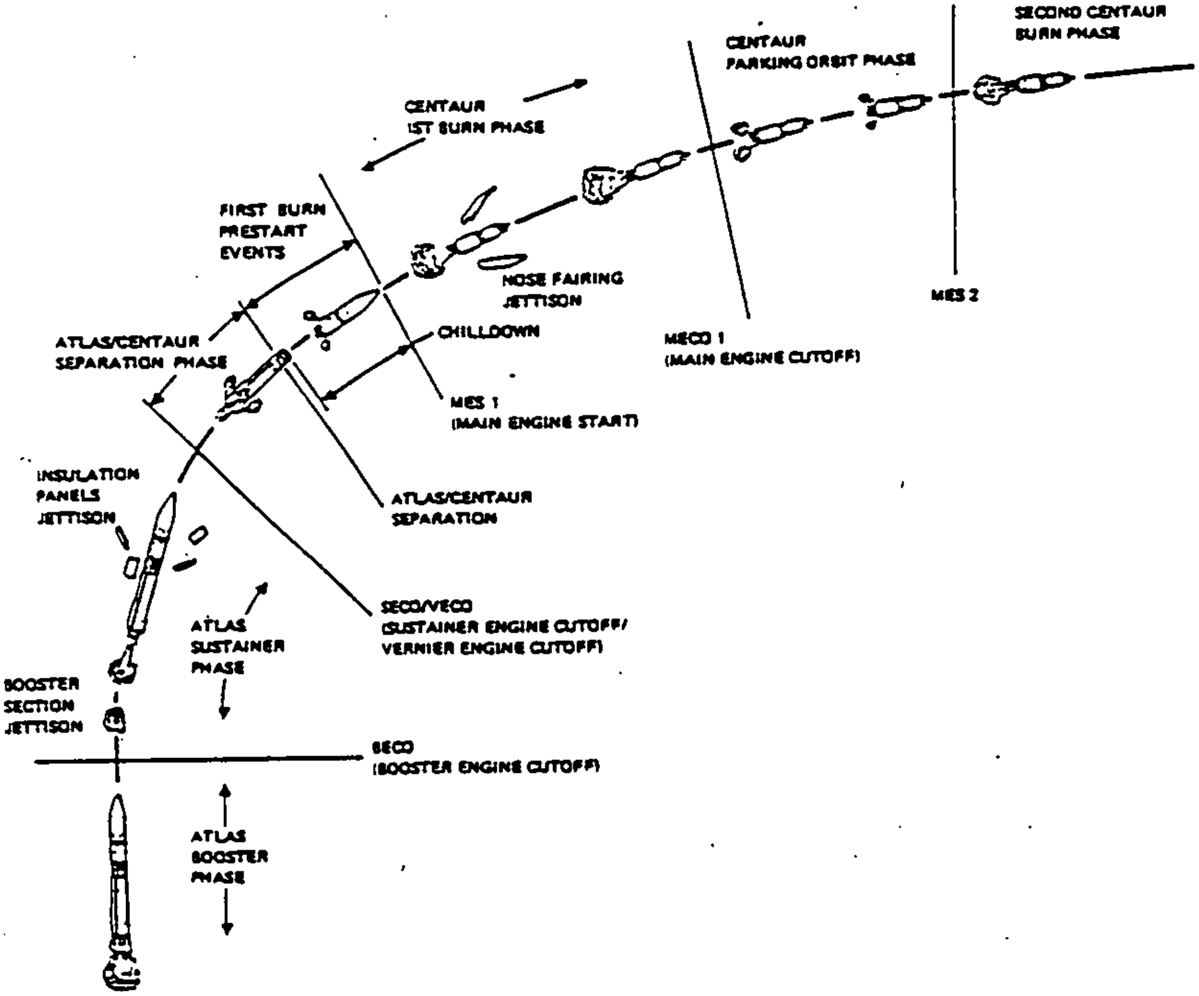

Figure 2. Atlas/Centaur Parking Orbit Mission Delivering a Spacecraft to Synchronous-apogee Transfer.

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[14] "History of CENTAUR," ibid., footnote 7, p. 3.

> launching two Pioneers to Jupiter on a solar system escape trajectory and a Mariner to Venus and Mercury.
>
> The Centaur stage combined with the Air Force Titan III booster provided a capability to launch larger spacecraft like Helios A and B around the Sun, two Vikings to Mars, and two Voyagers to Jupiter, Saturn and beyond.
>
> Centaur has flown not only exploratory scientific missions but also those with terrestrial benefits such as Applications Technology Satellites and the Intelsat, Comstar and Fltsatcom communication satellites. Centaur has delivered these domestic and military communication satellites into geosynchronous orbit.
>
> Centaur today is a mature, high-energy, still-viable upper stage with an overall operational reliability record of 96% ... 100% since 1971.
>
> As Centaur begins its third decade, it is being modified to fit into the Space Shuttle as a high-energy upper stage and will launch the Galileo spacecraft for further study of Jupiter and its moons as well as send the Ulysses spacecraft over the poles of the Sun.

However, after the Challenger disaster, NASA cancelled its plans for use of CENTAUR with the Shuttle, after four years and $0.7B of effort, citing safety issues.

The major DoD use of CENTAUR to date has been to launch FLTSATCOMS. Since the mid 1970s a more recent (1988) assessment credits ATLAS/CENTAUR with 6.75 tons to low earth orbit (LEO), and cites a new LH_2/LOX engine at the top of the priority list of the focussed-technology projects now funded by the Air Force under the DoD/NASA Advanced Launch System projects.[15] CENTAUR is also paired with TITAN IV in future Air Force plans.[16]

Table 1 shows CENTAUR missions until 1982. Figure 3 illustrates the construction of the SLVD-3D, the most recent ATLAS-CENTAUR combination.

C. OBSERVATIONS ON SUCCESS

Much of the CENTAUR technology was available in 1958 when the Air Force brought the Convair proposal to ARPA. The ARPA staff for CENTAUR was headed by R. Canright, who was thoroughly familiar with LH_2/LOX technology. The key cryogenics

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[15] Launch Options for the Future," Congressional Office of Technology Assessment, 1988, p. 57.15.

[16] Discussion with Dr. C. Cook, 12/89.

Table 1. CENTAUR Missions[17]

ATLAS/CENTAUR (59 Missions)		TITAN/CENTAUR (7 Missions)	
Mission Type	Number	Mission Type	Number
Test Flight	8	Test Flight	1
Surveyor	7	Helios A	1
Applications Technology Satellites (ATS)	2	Helios B	1
Orbiting Astronomical Observatory (OAO)	3	Viking A	1
Mariner Mars	4	Viking B	1
Intelsat IV	8	Voyager 1	1
Intelsat IV A	6	Voyager 2	1
Pioneer F	1		
Pioneer G	1		
MVM	1		
Comstar	4		
High Energy Astronomical Observatory A	1		
High Energy Astronomical Observatory B	1		
High Energy Astronomical Observatory C	1		
Fltsatcom	5		
Pioneer Venus	2		
Intelsat V	4		

OPERATIONAL RELIABILITY	
Atlas/Centaur (last 36 Flights)	94%
Titan/Centaur (six Flights)	100%
Centaur Stage (last 40 Flights)	100%

and engine technologies had been investigated extensively by NASA and the Air Force, and the light structural technology was an adaption of that used in the ATLAS missile. Several leaders in early space technology felt that LH_2/LOX was needed for a variety of missions, especially for powering second stages to geosynchronous orbit. Apparently the only technical group that did not favor CENTAUR at the time was von Braun's team, which while forward in concept was conservative in its engineering. ARPA's timely action gave

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[17] From H.M. Bonesteel, "ATLAS and CENTAUR Evaluation and Evolution," Convair-General Dynamics Company, 1982.

CENTAUR an early, substantial boost, and probably moved its schedule ahead some months. The effort thus started may have helped to get the CENTAUR LH_2/LOX technology past the von Braun group's objections, since they eventually agreed to it for SATURN upper stages, for which they were responsible. NASA leadership was convinced of the merit of LH_2/LOX and undoubtedly would have pushed it anyway. There were ambitious early plans for CENTAUR's use, and assignment of CENTAUR responsibility was made to Huntsville, evidently in the belief that engineering difficulties had been overcome. After several failures, however, CENTAUR responsibility was reassigned to the group more familiar with cryogenic engineering, the Lewis Laboratory. These early failures forced cancellation of ADVENT, a major joint-Service program, and somewhat negatively influenced the subsequent military usage of CENTAUR, its main utility overall having been for NASA flights. However, CENTAUR has put the FLTSATCOM satellites in orbit from the mid 1970s. The degree of acceptance of LH_2/LOX technology as efficient, economical, and practical, evidenced by the CENTAUR launch record indicates the correctness of the ARPA and NASA judgements. CENTAUR technology was essential for the APOLLO missions, and is used today in one of the TITAN IV configurations, and, with new hardware, in the LH_2/LOX SPACE SHUTTLE engines. CENTAUR, in a variety of versions is still a "workhorse" today, and of value to U.S. space capability that is hard to overestimate.[18]

The total, one-time recorded ARPA outlay for CENTAUR was $22M. The total cost of CENTAURS launched to date appears to exceed $2 billion.[19]

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[18] C. Cook, ibid.

[19] C. Cook, ibid.

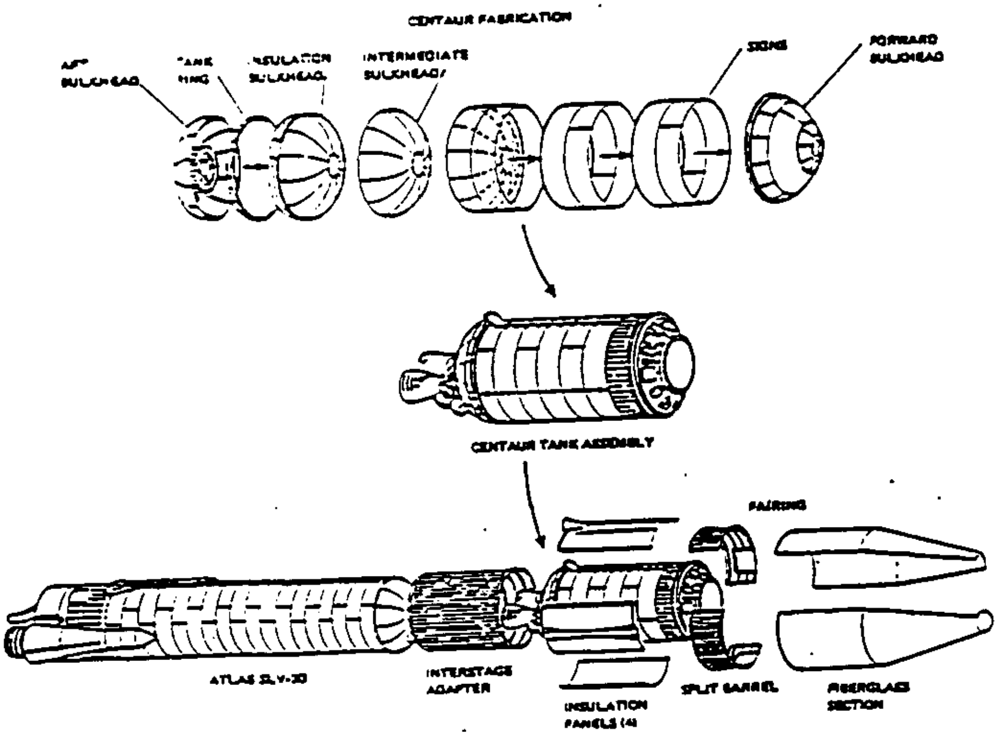
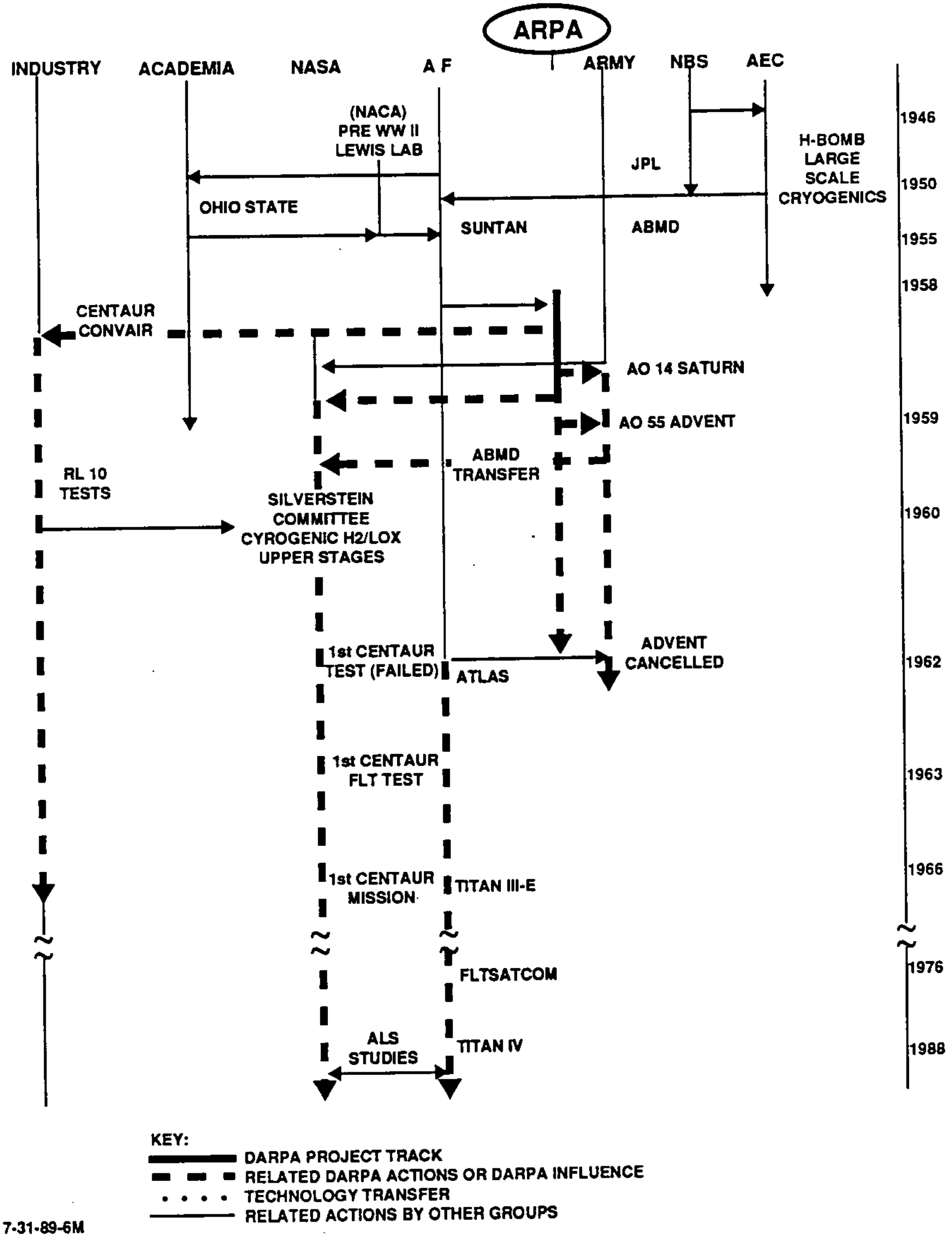


Figure 3. SLV/3D Fabrication Sequence

CENTAUR



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V. SATURN

A. BRIEF OVERVIEW

"The authorization of a large rocket vehicle by the Advanced Research Projects Agency in August 1958 and assignment of its development to the Army Ballistic Missile Agency (ABMA) marked the beginning of a series of successful large launch vehicles."[1] Besides support of the original proposal of the Von Braun AMBA group, the ARPA suggestion of using a cluster of available rocket engines to achieve large first stage thrust at an early date and at low cost proved highly successful. Together with use of the liquid hydrogen technology developed earlier for the CENTAUR vehicle for the upper stages, the ARPA-initiated SATURN I series was used in tests for the NASA's APOLLO program and later for the SPACELAB program, for a total of 19 successful flights.

B. TECHNICAL HISTORY

There were a number of initiatives in the mid-1950's for large boosters in the millions of pounds thrust range. In 1956, for example, the Air Force Science Advisory Board (SAB) made a recommendation for such a development. This led, a little later, to an Air Force effort to construct a single-barrel liquid propellant rocket engine approaching 5 million pounds thrust, eventually called NOVA.[2] In early 1957 the Army's Ballistic Missile Agency (ABMA) rocket group under Wernher Von Braun began studies of an approach to a large booster involving a cluster of rocket motors.[3] In late 1957, after Sputnik, a more specific design for such a vehicle, using a cluster of four Rocketdyne E-1 engines to achieve about 1.2 million pounds of thrust, was included by this ABMA group, under the name JUNO V, as a major feature of a proposal for a "National Integrated Missile and Space Development Program." This was only one of several proposals for large rocket

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[1] "Liquid Hydrogen as a Propulsion Fuel," by John L. Sloop, NASA SP 4404, NASA history series, 1978, p. 223, and "Stages to Saturn" by Roger E. Bilstein, NASA SP4206, p. 23, 1980, Bilstein gives a detailed technological history of the Apollo/Saturn launch vehicles.

[2] A brief history of early U.S. rocket developments is given by a key participant, the second of the presidential Science Advisors, George Kistiakowsky, in *A Scientist at the White House* Harvard 1976, pp. 95-99. The name NOVA, confusingly, was used for several different booster approaches.

[3] "A History of the Saturn 1/1B Launchers," by David Baker, Spaceflight 1978, p. 146.

programs at the time, made in the strong national desire to "catch up and move ahead" in space. The ABMA proposal aimed to make available quickly and cheaply, for whatever national programs might be undertaken, a large booster capable of putting payloads of many tons into orbit. It was fairly clear that a manned space program would have such a requirement and at the time it was believed also that large military communications and surveillance satellites might be needed. One of ARPA's main tasks after its formation, largely in response to this national push, was to make rational choices among these options and to move things ahead rapidly.[4]

Soon after its inception, ARPA was invited to present its plans for launch vehicles to the National Security Council. ARPA's representatives recommended the use of clusters of available rockets and the use of liquid hydrogen and liquid oxygen (LH_2/LOX) to make efficient upper stages.[5] Remarkably prescient regarding subsequent events, these recommendations reflected the backgrounds and expertise of the then ARPA/IDA staff.[6] While the idea of using clusters of engines offered the advantages of redundancy, to some it appeared complex, with the possibility of difficult control problems.[7]

After consideration of the Von Braun group's proposal, Canright and Young of ARPA/IDA suggested the use of a cluster of 8 MB-3 (again Rocketdyne) engines, which had been proven in the JUPITER and THOR programs, rather than the four still developmental E-1 engines proposed by ABMA. This change was agreed to by Von Braun and the JUNO V clustered booster project got under way in August 1958.[8] The engines, however, required considerable modification to be used in a cluster configuration.[9]

The first goal of the program was to demonstrate the feasibility of the engine cluster concept by a full-scale, captive firing. In September the project's scope was extended to include at least four flight tests. ARPA Order 47 provided for tests for the captive firings,[10] and for design studies of future launch facilities. Figure 1 shows one of the early

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[4] "Making Weapons, Talking Peace," by H. York, Basic Books, 1987, p. 142, ff.

[5] "Liquid Hydrogen as a Propulsion Fuel," ibid., p. 224.

[6] The National Security Council presentations were made by R. Canright of ARPA/IDA who had been active in hydrogen-oxygen rocket research at JPL and assistant director for missiles at McDonnell-Douglas.

[7] Kistiakowsky, ibid., footnote 2.

[8] AO 14, 8/15/88, for $92.5 million.

[9] "Stages to Saturn," ibid., p. 79, details this history and emphasizes the low cost aspect of this early work.

[10] AO 47 of 12/58 $8.4 million.

vehicles returning from a static test. In November a new, more ambitious objective was approved: "to develop a reliable, high performance booster to serve as the first step of a multistage carrier vehicle capable of performing advanced space missions."[11]

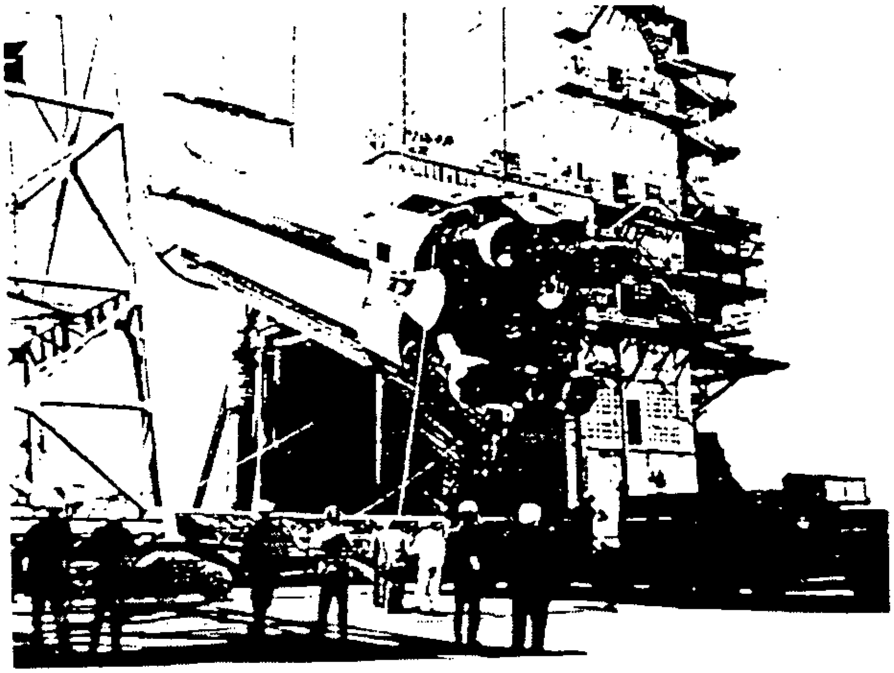

Figure 1. Removal of the Booster From the Static Test Stand

In February 1959, at ABMA request, ARPA approved a change of the clustered booster project's name from JUNO V to SATURN. The first SATURN flight was planned for October 1960. The upper stages had to be chosen well before then, and an ARPA study of this issue in May 1959 recommended using a two-engine TITAN configuration as second stage, with several CENTAUR engines in the third stage. Again the motif for this choice was to move ahead with available and near-future technology as far as possible.[12] However, soon thereafter, H. York, the first DDR&E, proposed to cancel SATURN, on several grounds:[13] (1) the only justifiable national mission for a very large booster was manned space flights; (2) there were no military missions that required manned space flight and all justifiable military missions then envisaged could be lifted by the TITAN and its

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[11] Second Semi-annual Technical Summary Report on ARPA Orders 14-59 and 4-7-59, by ABMA, U.S. Army Ordnance Missile Command, 15 Feb. 1960.

[12] Discussion with J.C. Goodwyn, 10/88.

[13] Quoted in "Liquid Hydrogen as a Propulsion Fuel," ibid., pp. 227-228.

planned future extensions (in particular, several small communications satellites, which could be handled by TITAN, were better than a few larger ones); (3) SATURN as then being constructed was not large enough for extended manned space flights, which should all be undertaken by NASA. Similar viewpoints were apparently held by Kistiakowsky, the President's Science Advisor, and his PSAC advisors.[14] However, R. Johnson, head of ARPA at the time, strongly maintained that there were military needs for large payloads, especially for manned vehicles capable of maneuvering and returning to earth.[15] As a result of York's proposal a joint DoD-NASA committee was convened to consider the by now multifaceted problem,[16] which included: (1) Defense payloads and boosters to lift them; (2) NASA's future need for large boosters; (3) ABMA's future, largely tied to SATURN, (4) transfer of ABMA to NASA.[17] This committee considered SATURN, TITAN and NOVA, concluding that SATURN (in retrospect SATURN I) was the best bet for the near future, citing also its greater payload capability and operational flexibility. The committee also recommended further study of upper stages. York reversed his views, apparently partly as a result of the recommendation of this committee, and partly because to keep ABMA alive, SATURN, its major occupation, would have to be funded initially by DoD. Shortly aferward, ABMA was transferred to NASA.

As the joint DoD-NASA committee had recommended, the issue of second stages for SATURN was studied by NASA and ABMA. Eventually the viewpoint of NASA's Lewis laboratory prevailed and LH_2/LOX was recommended for the second and third stages.[18] The third stage was to use a cluster of CENTAUR RL-10 engines, and for the second stage a larger, 200,000-lb thrust LH_2/LOX engine was to be developed. Shortly afterward the "SATURN vehicle team" was formed with NASA and DoD participation,

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[14] Kistiakowsky, ibid., p. 80: "it was our conclusion that aside from political considerations the most sensible thing to do is to abandon the Saturn and to concentrate on the NOVA, starting with a high engine NOVA vehicle and gradually progressing to multi-stage vehicles. This admittedly leaves the Soviets superior to us until the late 1960's, but ensures a reasonable overall level of effort and ensures the space program as a truly civilian effort."

[15] Johnson especially had in mind "MRS V", a maneuverable returnable space vehicle, a concept in many ways similar to the current project NASP. The AF was studying, at the time, DYNASOAR, a manned hypersonic space vehicle. Not long after SATURN's transfer to NASA, Johnson left ARPA. The extent of his considerable activity in this connection is described in Richard J. Barber, *History of ARPA, 1958-75*, Sec. III to III-41.

[16] Kistiakowsky, ibid., p. 75, describes SATURN as an inseparable mix of technical and administrative-political problems.

[17] Bilstein, ibid., p. 38.

[18] Report to the Administrator, NASA on SATURN development plan, by SATURN vehicle team, 15 December 1959.

under the chairmanship of A. Silverstein of NASA, to review more closely and recommend definite SATURN configurations to meet anticipated NASA and DoD needs, including DYNASOAR.[19]

The Silverstein group recommended sequential development of a SATURN "C" family of vehicles, beginning with the SATURN CI, later called simply SATURN, with the ARPA/ABMA developed first stage, and upper stages at first based on the CENTAUR RL-10 engine, and later, for the second stage, the new 200,000-lb thrust L-2 LH_2/LOX engines. Still later SATURN, according to this plan, was to use a cluster of million-pound-thrust NOVA-type engines as a new first stage, together with the L-2's for the second stage and RL-10's for the third.[20] This "map" of the Silverstein committee was largely followed in subsequent events, through SATURN V, the vehicle for the manned lunar expeditions.

On the basis of the Silverstein recommendation NASA now planned a 10-vehicle SATURN C-1 flight series, using the ARPA/ABMA first stage, to be followed in 1967 by the larger SATURN C3 (or SATURN V) type. With highest national priority assigned in 1960, two SATURN C1's were planned for launch in 1962. A thrust of 1.3 million pounds was achieved in April 1961, in a captive, flight-rated test of eight clustered H-1 engines at Marshall Space Flight Center.[21] Plans for successive configurations of SATURN had by then progressed rapidly, including provision for recoverability of the first stage. The manned lunar expedition in 1967 was announced in May 1961.

The C-1 ARPA/ABMA first stage was successfully launched in October 1961 and in November 1961 the first industrial contract for 20 C-1 first stages was let to Chrysler for $200M.

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[19] The Silverstein Committee had one month to come up with its recommendation.

[20] Interestingly, the ARPA representative on the Silverstein Committee, G.P. Sutton, apparently was still recommending further studies of ATLAS type engines. This was due apparently to the desire to use existing systems and reduce costs; LH_2/LOX in this conservative ARPA approach, would come later. LH_2/LOX had been previously recommended by Canright, and was pushed successfully by Silverstein. An additional reason for ABMA's deciding to choose the wider and lighter cryogenic engine configuration was the bending moments for then prospective heavy payloads, such as DYNASOAR. Discussion with J.C. Goodwyn October 1988.

[21] A chronology of the SATURN tests is given in D. Baker, *The Rocket, The History and Development of Rocket and Missiles Technology*, Crown, NY 1979, p. 243ff.

The 10 NASA SATURN C-1 flights included several which used clusters of the CENTAUR type engine for second stages and a smaller cluster for third stages and tested APOLLO procedures and components. Except for the failure of one H-1 engine in one of the flights, which was nearly completely compensated for by the control system and the remaining engines, all the C-1 flights were completely successful.[22] The follow-on SATURN 1B, with the clusters of 200,000-pound thrust L-2's LH_2/LOX, for the second stage, and CENTAUR engines for the third stage, was used to test the APOLLO system and its engines, including docking maneuvers in earth orbit, through 1966. In late 1966 the test flights of the SATURN V configuration began.

The remaining SATURN 1B vehicles were brought out of storage in 1973 to support the SKYLAB Space Station program and the APOLLO-Soyuz project. In all, between 1961 and 1975, 19 launch vehicles of the SATURN I family had served to rehearse moon landing flights and to support manned space flight programs.[23] In addition, 22 unused H-1 engines eventually were employed as first stages of NASA's DELTA rockets.

Since the Challenger disaster there has been renewed interest in the capabilities and cost of large-payload options for the future. A recent study indicates that large military payloads into GEO are likely whether or not the SDI continues[24]. One option being followed up in a joint AF/NASA program is the ALS (Advanced Launch System), with capability somewhat greater than SATURN I.

C. OBSERVATIONS ON SUCCESS

While there were similar ideas in the ARPA/IDA staff the JUNO V (predecessor to SATURN) proposal was made to ARPA by the Von Braun ABMA team. Initiation of the JUNO V-SATURN program occurred in a time of major, national concerns regarding U.S. posture and capabilities in space, and about responsibilities for space-related activities. It involved an inextricable mixture of technical, administrative and political factors. ARPA's

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[22] The inertial guidance system used in the C-1's were planned by ABMA to involve components used previously by ABMA in JUPITER and REDSTONE, which in turn stems from the system used in the German V2 in WW II. ARPA insisted that ABMA also use new systems like those developed for ATLAS and TITAN. The eventual inertial package used a stable platform evolved from earlier ABMA work with inertial components stemming from the TITAN. Bilstein, ibid., p. 243. Discussion with J.C. Goodwyn, October 1988.

[23] Baker, ibid., p. 245.

[24] "Launch Options for the Future," Office of Technology Assessment, U.S. Congress, 1988.

objectives were to be able to get large payloads into orbit consistently, for whatever use, as quickly as possible without excessive cost. Later, when national concerns lessened, opposition to this route was led by York (DDR&E) and Kistiakowsky (President's Science Advisor). This opposition preferred a more leisurely, but direct route to a SATURN V-type system, all under NASA. Thirty years later, there are again studies of how to get large military payloads into orbit at low cost, re-examining the old approaches, among others.

While it was an adhoc system involving much available technology, SATURN I still required engineering the engines and tanks, and the solution of a new complex multiple rocket system control problem. The ABMA group was probably the most experienced and capable in the U.S. at the time, and best able to build and test SATURN at low cost and in a short time. At the same time, the ARPA support enabled this group to keep going over the period of transfer of space responsibilities to NASA. The decision to use this capability for SATURN, and keep ABMA going as a national asset seem to have been made by H. York, then DDR&E, in spite of his earlier views. ARPA had backed the ABMA group and had York's earlier opposition to SATURN prevailed there might have been a significant delay in the NASA program.

Besides the timely ARPA initial funding action, the ARPA technical interventions regarding using available engines and more modern inertial control technology had a significant impact on the successful C-1 series. The ARPA early action in funding CENTAUR's ongoing LH_2/LOX technology probably helped considerably to overcome Von Braun's initial opposition to this and the associated light structures for second stages. The ARPA plan was to use this technology gradually, using initially more conservative and less costly second stages, but NASA's (Silverstein's) interest in LH_2/LOX pushed this higher risk technology further for use in all upper stages of SATURN. No doubt CENTAUR or something similar would have been soon funded by NASA in any case. However, in these early days time was very important. It appears also that without the LH_2/LOX technology the NASA moon project could not have occurred when it did.[25]

While the SATURN 1 launch series was remarkably successful, doubts remain about the necessity for the number of flights that actually took place. The risk of failures, undoubtedly very important, was lessened by the approach of the conservative Von Braun team.[26]

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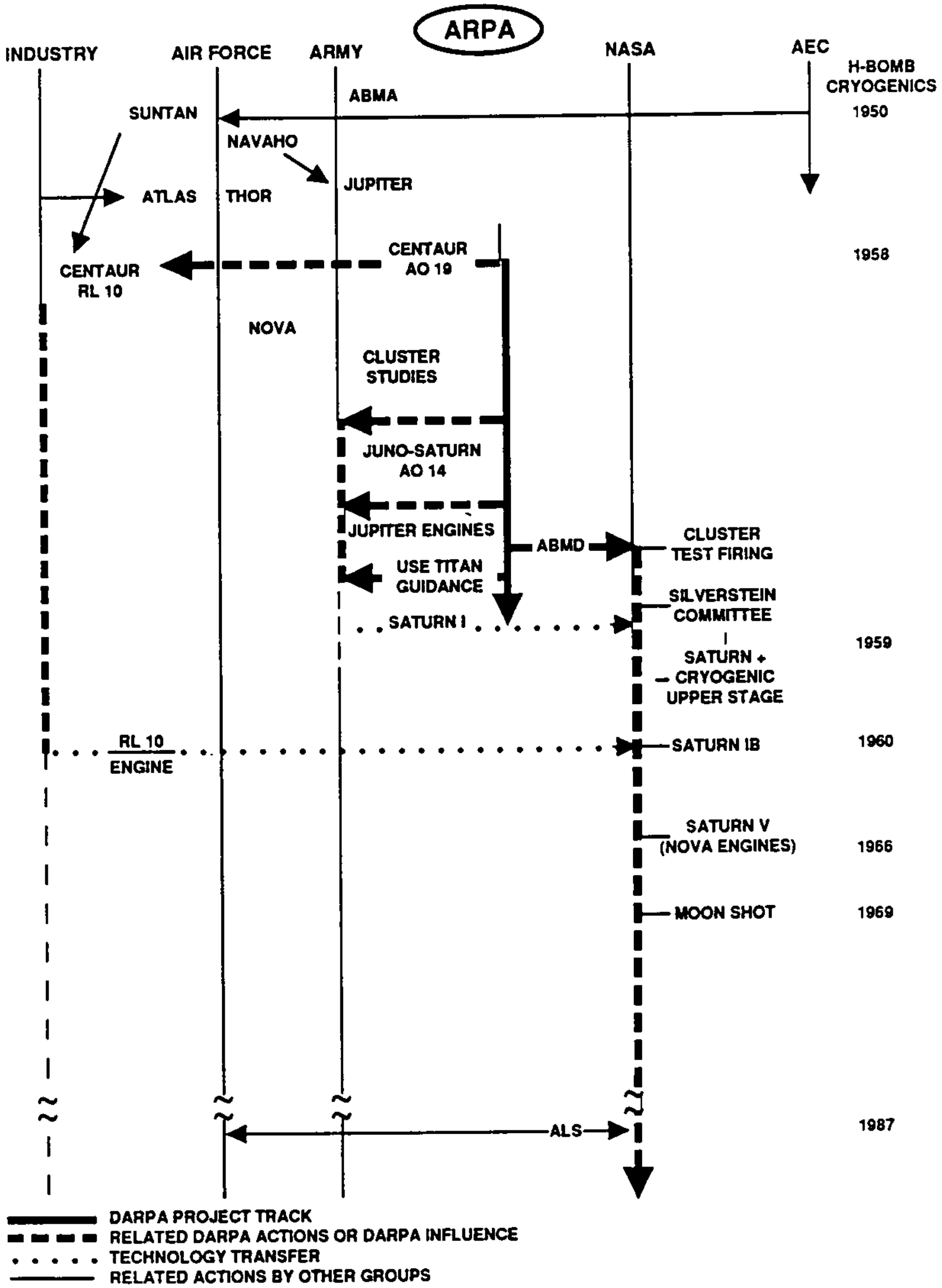
[25] Bilstein, ibid., p. 189.

[26] ibid., p. 336.

ARPA's recorded outlay for SATURN was about $93M for the rocket and $8.5M for a test stand, totalling nearly $102M. NASA's outlays for Saturn were about $4 billion dollars.

SATURN



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B. DEFENDER: ANTI-BALLISTIC MISSILE

VI. ESAR PHASED ARRAY RADAR

A. BRIEF OVERVIEW

ARPA pioneered the construction of large ground-based phased array radars with ESAR (Electronically Steered Array Radar). Constructed in less than two years, and completed in the fall of 1960, the low-powered L-band ESAR immediately demonstrated computer control of beam steering in two dimensions, with a capability of detecting and tracking space objects on a par with other space surveillance systems. ESAR led directly to the Air Force Space Tracking Radar, FPS-85, which is still operational today. ESAR's successful performance accelerated an ARPA program of phased array components which has impacted all subsequent U.S. large phased array systems. ESAR's performance, better than predicted, at a high but not unreasonable cost, also encouraged Bell Telephone Laboratories to move rapidly toward construction of phased array radars for the Army's ballistic missile defense projects.

B. TECHNICAL HISTORY

In 1957 a President's Science Advisory Committee panel and many other experts had pointed out the need in ballistic missile defense (BMD) and space surveillance to detect, track and identify a large number of objects incoming or moving at very high speeds. Electronic steering of radar beams in two angular dimensions, more agile than mechanically steered antennas, offered significant advantages for this purpose. While several electronically steered arrays had been built before 1958, such as the Navy's TPS 48 and TPS 33, these did not have the large aperture and high power required for BMD and space applications and used a combination of phase and frequency scanning.[1] A number of experts were skeptical of the practicality of constructing a reliable large phased array system, with the technology available, at reasonable cost. An attempt to do so by Bendix

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[1] "Survey of Phased Array Accomplishments and Requirements for Navy Ships," Merrill I. Skolnik, in *Phased Array Antennas*, Eds. Oliver and Kniiuel, Artech House, 1972, pp. 17-18.

began in 1958 under Air Force sponsorship and was turned over to ARPA in accordance with DoD assignment to ARPA of responsibility for advanced technologies for BMD.[2]

ARPA decided to open a competition for design and construction of a large experimental two-dimensional phased array, with beam steering under computer control. This was to be the first array steered altogether by phase control. ARPA solicited proposals and selected Bendix largely because of the work they had done for the Air Force and the prospects they offered of using reliable low-cost, production-type technology for the many components involved in a phased array.[3] AO 29 of 9/58 provided $15 million for a wideband phased array radar (EPS 46-XW 1). Work began in Spring of 1959 and the array was completed in November of 1960. A 90-element linear phased array was constructed first to check out the Huggins wave-mixing approach to steering phase control, and other techniques, such as ceramic tetrodes for transmitter power amplifiers, one for each broadband antenna element.[4] After successful demonstration of a one-dimensional array ESAR was extended to fill out a two-dimensional array. Figure 1 shows the completed ESAR array. There were spaces for 8000 elements, but only 760 were actually connected to transmit-receive modules for the experiments involving ESAR. This, together with the power limitation of the available tetrodes, made ESAR a low power system, which was considered acceptable for an experimental program. Computer control and processing, key features of ESAR, were designed-in and built with IBM participation, with solid state components used wherever possible. An account by one of the Bendix engineers states that ESAR was also used to develop the techniques of "Space Tapering," using fewer active elements with spacing arranged to give nearly the same sidelobes, which has since been used in most phased arrays.[5]

A radar textbook gives a description of the system:[6]

> ESAR....is an example of an electronically steerable array using a frequency conversion phasing scheme. The antenna is 50 feet in diameter. The beam can be scanned in less than 20 microseconds. A cluster of 25 scanning

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[2] IDA TE-54, Mar 20, 1959, "Technical Evaluation of Air Force Development Plan for ESAR."

[3] Discussion with A. Rubenstein, IDA, ex-ARPA DEFENDER Program Manager, 11/87. Bendix's performance in automobile radio manufacturing was a factor in its selection.

[4] A description of several of these features of ESAR is given in "Electronically Scanned Air Force Systems I," by Moses A. Dicks, et al. *Radar Techniques for Detection, Tracking and Navigation*, Gordon and Breach 1964, p. 397ff.

[5] "The AN/FPS 85 Radar Systems," J. Emory Reed, *Proc. IEEE*, Vol. 57, 1969, p. 334.

[6] *Introduction to Radar Systems*, M.I. Skolnik, McGraw Hill, 1962, p. 318.

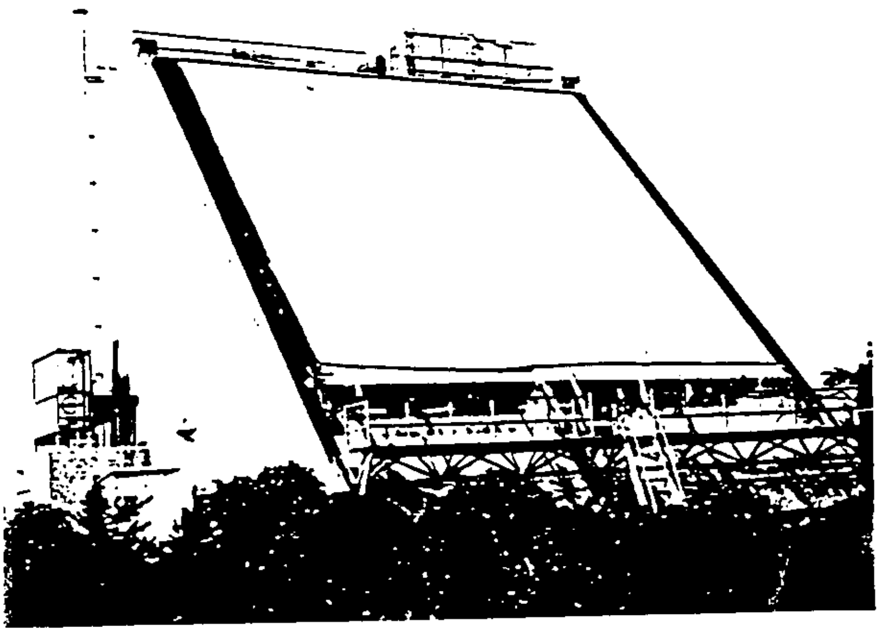

Figure 1. ESAR

beams, 5 rows in elevation and 5 columns in azimuth, can be generated by the ESAR system. A separate transmitter feeds each of the L-band periodic antenna elements.

Important capabilities proven by the experimental ESAR included multiple target tracking, beam formation and accuracy determination, sidelobe measurements, and constructional maintenance procedures.[7]

Operating ESAR for tests as its construction went along was immediately successful: even with its low power it proved possible to detect and track space objects at least as well as the other existing space surveillance systems could at the time. The ARPA-assigned Air Force project managers for ESAR at RADC, enthused by this success, proposed that the Air Force construct a follow-on, larger high power phased array radar for space tracking based largely on ESAR technology. Experts from Lincoln Laboratories, who had a large phased array study project since early 1959, were skeptical, pointing out that the failure rate of the numerous conventional high power electronic tube components

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[7] J. Emory Reed, ibid.

used might be high and lead to overwhelming reliability problems. But with DoD backing the Air Force proceeded with the FPS-85 phased array radar, different from ESAR in having separate (but adjacent) transmit and receive antennas, and in a larger number of elements and a much higher power level, providing for the possibilities of numerous tube failures by arranging for a large number of people to do replacements, and pointing out the graceful degradation characteristics of phased arrays, demonstrated by the success of "space tapering" in ESAR. The contractor, again Bendix, completed FPS-85 in 1963, and the expected large numbers of replacement tubes were found not to be necessary in its operation. After a fire destroyed the first FPS-85 in 1964, it was rebuilt in 1968 with updated technology and components.

Table 1 shows the evolution of large phased array technology in the U.S. beginning with ESAR and briefly describes the common features, and differences, of ESAR and the new FPS-85 together with features of other major phased arrays.[8] In 1968 it could be said that:

> The AN/FPS-85 is the most advanced operational large computer-controlled multifunction phased array radar. It has a range of several thousand miles and can detect, track, identify, and catalog earth-orbiting objects and ballistic missiles. This system is important to the North American Air Defense Command's space detection and tracking system because it can detect, identify, and track hundreds of objects concurrently in a constantly increasing population of earth-orbiting objects.[9]

The FPS-85 quickly became part of the AF SPACETRACK System, and is still operational today. Because of its flexibility, a scanning program to detect possible submarine launched ballistic missiles was added, making the FPS-85 also part of the current ground-based SLBM warning system.[10]

ESAR was operated as an experimental system for several years. However, FPS-85, which had more advanced technology, began to provide better opportunity to test techniques for desirable improvements such as techniques for wider bandwidth operation.[11]

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[8] *Radar Technology*, E. Brookner, Artech House, 1984, p. 331.

[9] J. Emory Reed, ibid., p. 324..

[10] "Warning and Assessment Sensors," by J. Toomay, Chapter 8 of *Managing Nuclear Operations*, Ed., A. Zraket, Broomings 1984, p. 297.

[11] Discussion with Major General Toomay (USAF, Ret.), December 1987.

Table 1. Chronology of Large Phased Array Technology in the U.S. After Kahrilas, see footnote 8.

Radar	Design	Date Completed
ESAR (Bendix)	One tetrode per radiating element 746 radiating elements IF phase shifting	1960
AN/FPS-85 (Bendix)	High power-multiple transmitters Separate transmit and receive arrays Confined feed Thinned receive array Diode phase shifters	1968
HAPDAR (Sperry)	Monopulse space feed Thinned Diode phase shifters	1965
PAR (GE)	High power-multiple transmitters Monopulse confined feed Subarrays Diode phase shifters	1974
MSR (Raytheon)	High power Monopulse space feed Fully filled Diode phase shifters	1969
AN/TPN-19 PAR (Raytheon)	Offset monopulse space feed Optical magnification reflect array Limited scan Ferrite phase shifters	1971
PATRIOT (Raytheon)	Monopulse space feed Fully filled Ferrite phase shifters	1975
AEGIS (RCA)	Multiple transmitters Monopulse confined feed Varying size subarrays Ferrite phase shifters	1974
Sperry Dome (Feasibility) Radar (Sperry)	360 deg in azimuth; zenith to 30 deg below horizon C-band. 1MW peak, 5 kW average, 50 ft range resolution 2 s volume search frame time, 427 pps Dome-cylinder items, 6 ft diameter; confined feed	
COBRA DANE (Raytheon)	High power-multiple transmitters Very wide bandwidth Monopulse confined feed Thinned Subarrays	1976
PAVE PAWS (Raytheon)	Solid state Thinned	*Under construction

*Since this list was published, PAVE PAWS is now regarded as operational

The important success, and the limitations of ESAR, lent emphasis to a broad-based phased-array component and techniques program at ARPA. Substantial efforts were made to develop low-cost high power tubes and phase shifters, extend component frequency ranges, and to find ways to increase bandwidth, to apply digital techniques, and in the study of antenna coupling.[12] This technology has improved all U.S. phased array projects. The ARPA cross-field high power amplifier developments, in particular, later proved important in the development of the Navy's AEGIS phased array.[13]

The impact of ESAR on later large phased array efforts associated with ballistic missile defense efforts was less direct, but real. According to Mr. Albert Rubenstein, ARPA program manager at the time, Bell Telephone Laboratories (BTL), then constructing the Army's Nike-Zeus Ballistic Missile Defense System, were kept closely informed about ESAR, and a special effort was made to completely document ESAR.[14] The BTL program manager, however, does not recall any specific technical impact of ESAR.[15] The major influence of ESAR on BTL seems to have been by way of encouragement or provocation: the fact that ESAR worked well, did not have major reliability problems, was constructed rapidly and well documented technically, and had a known cost which was not unreasonably high. Also, OSD confidence in phase arrays was strongly influenced by ESAR's success, and strengthened the basis for OSD's insistence that the Army incorporate phased arrays in their BMD program.

The Bell "History of Engineering and Science in the Bell System" gives their history at the time:[16]

> In 1960 Bell Labs conducted fundamental investigations of phase controlled scanning antenna arrays for possible application to the Ballistic Missile Defense System. Arrays with their inertialess beams would provide greater capabilities against the high traffic level threat. This consideration became

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[12] For example, AO 136 of 2/60 for phased array tube development; AO 337 for diode and ferrite phase shifters, AO 345, of 4/62, multiple beams Klystron for phased arrays; AO 436 for High Power, Electrostatically focussed Klystron, of 7/63, Codiphase digital radar, AO 74, of 4/59, and also IDA 7E 196, June 1959, by T.C. Bazemore.

[13] "System Design Considerations of the AN/SPY-1 Transmitter," by G.R. Lorant, et al., 18th Tri-Service Radar Symposium, 1972, Vol. II, p. 21.

[14] Discussion with Mr. Albert Rubenstein, IDA, ARPA Defender Program Manager in 1958-59, December 1987.

[15] Discussion with C. Warren, 12/87. BTL, very strong technically, was used to going its own way. Discussions with Dr. C.W. Cook, and C.M. Johnson, December 1988.

[16] "A History of Engineering and Science in the Bell System," M.O. Fagen, ed., BTL, Inc., 1978, p. 431.

> one of the principal technical reasons advanced in 1963 for not proceeding with the tactical deployment of the original Nike-Zeus System. In Nov. 1960 at Redstone Arsenal, Bell Laboratories representatives gave a presentation to ARGMA on the subject of phased arrays in a terminal defense... to report on the study to date and to provide a basis for a proposal to do exploratory phased array work ... authorization was granted in June 1961 ... ground breaking (was) in March 1963.

It should be recalled that by November 1960 ESAR had been constructed and successfully operated.

In 1963, at White Sands Missile Range, BTL constructed MAR 1, the first large hardened phased array dedicated to BMD, under the NIKE X program. MAR used different phase-shifting technology than ESAR, and had considerable difficulty with component reliability.[17] However, BTL later successfully managed construction of several other large phased arrays in later phases of the Army BMD program, which ended in 1975. The last of the BMD phased arrays of this period, the high power PAR, constructed by GE at Grand Forks, South Dakota, is still operational as part of the Air Force Space Tracking System and as a threat discrimination element in the AF ballistic missile warning system.[18] According to C.M. Johnson, Army SAFEGUARD Project Manager in 1970, one of the approaches considered in design competition for the PAR was that of FPS-85, with a separate transmitter and receiver array. A different set of technologies, however, was chosen for PAR, to meet the requirements for a hardened system. Including a common transmitter and receiver array, and the use of a "space feed" with fewer transmitting tubes, gave PAR a somewhat higher power and bandwidth than the FPS-85.[19]

In the mid-1960's ARPA funded construction of HAPDAR, an S-band demonstration low cost "hard point defense" phased array design by Sperry, which was located at White Sands, and has been used for a number of years in radar beam management experiments.[20] In this same period ARPA also conducted a broad technology

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[17] Ibid., p. 432.

[18] "Warning and Assessment Sensors," by John C. Toomay, Chapter 8 of "Managing Nuclear Operations, Ashton Carter et al., Eds., Brookings 1984, p. 296-7.

[19] "Ballistic Missile Defense Radars," Charles M. Johnson (U.S. Army Safeguard System Office), IEEE Spectrum 7, 3, March 1970, pp 32-41.

[20] AO 516 "HAPDAR," 10/63. Cf. also "HAPDAR-An Operational Phased Array Radar," by Peter J. Kahrilas, *Proc. IEEE*, Vol. 56, No. 11, Nov. 1968, p. 967.

program to address the problems of hardened, low-cost phased array radars.[21] ADAR: an Advanced Design Array Radar Study, synthesized much of this technology, and defined an up-to-date phased array radar system for operation in a nuclear attack environment.[22] The crossed-field, high power amplification technology initiated by ARPA had an important later impact on the AEGIS system.

C. OBSERVATIONS ON SUCCESS

ESAR was an extension and acceleration, by ARPA, of previous Air Force-funded effort, toward a "space track" radar inherited with ARPA's space responsibilities. There were a number of high level recommendations that phased arrays would be necessary for the BMD mission. It was considered a risky venture at the time, pushing the state of the art of phased arrays, scaling up to large size, using computers to control the system and process its data. Dr. J. Ruina, then reponsible for missile defense R&D under DDR&E, was told by Bell and Lincoln Laboratories that large 2-dimensional phased arrays would be beyond the state of the art. ESAR's history seems very contemporary: in spite of the experts' negative views, ARPA decided to issue an RFP emphasizing cost-cutting to fend off strong fears about the cost of such systems, and contracted a fast paced effort to a firm relatively new in the game.

ESAR was very successful, at every stage of construction and testing, causing considerable excitement in the RADC managers. ESAR pioneered "space tapering" and "array thinning" and demonstrated the important graceful degradation characteristic of phased arrays. Because of the degree of high-level interest, timing of these achievements was critical. The same office at RADC which managed ESAR for ARPA took over direction of the FPS-85 with Gen. J. Toomay as program manager. Indirectly, ESAR's success encouraged a major phased array effort to get going, for BMD, by Bell Labs. Bell, however, used different technologies in a painful learning experience.

The ARPA phased array components and techniques program, which intensified after the success of ESAR, had a very broad impact on subsequent military phased array efforts, and more directly its results were used in the construction of the HAPDAR low cost demonstration array at White Sands, and the ADAR phased array study and

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[21] For example, AO 136 of 2/60 for phased array tube development; AO 337 for diode and ferrite for phase shifters, AO 345, of 4/62, multiple beams Klystron for phased arrays; AO 436 for High Power, electrostatically focussed Klystron, of 7/63.

[22] AO 498, 513, of 10/63, and 663 of 10/65.

development. In the opinion of several experts, this broad phased array technology effort was the only one of its kind, and the results have influenced all other major phased array efforts since that time.[23]

The recorded outlay for construction of ESAR and its testing, and also including the early experimental work extending bandwidth using the FPS-85, was about $20M. ARPA outlay for the phased array technology program appears to have been about $25M. The original FPS-85 cost about $30M, and its replacement after the fire, about $60M.[24] The BTL phased arrays built for the Army's BMD project cost nearly $1B.

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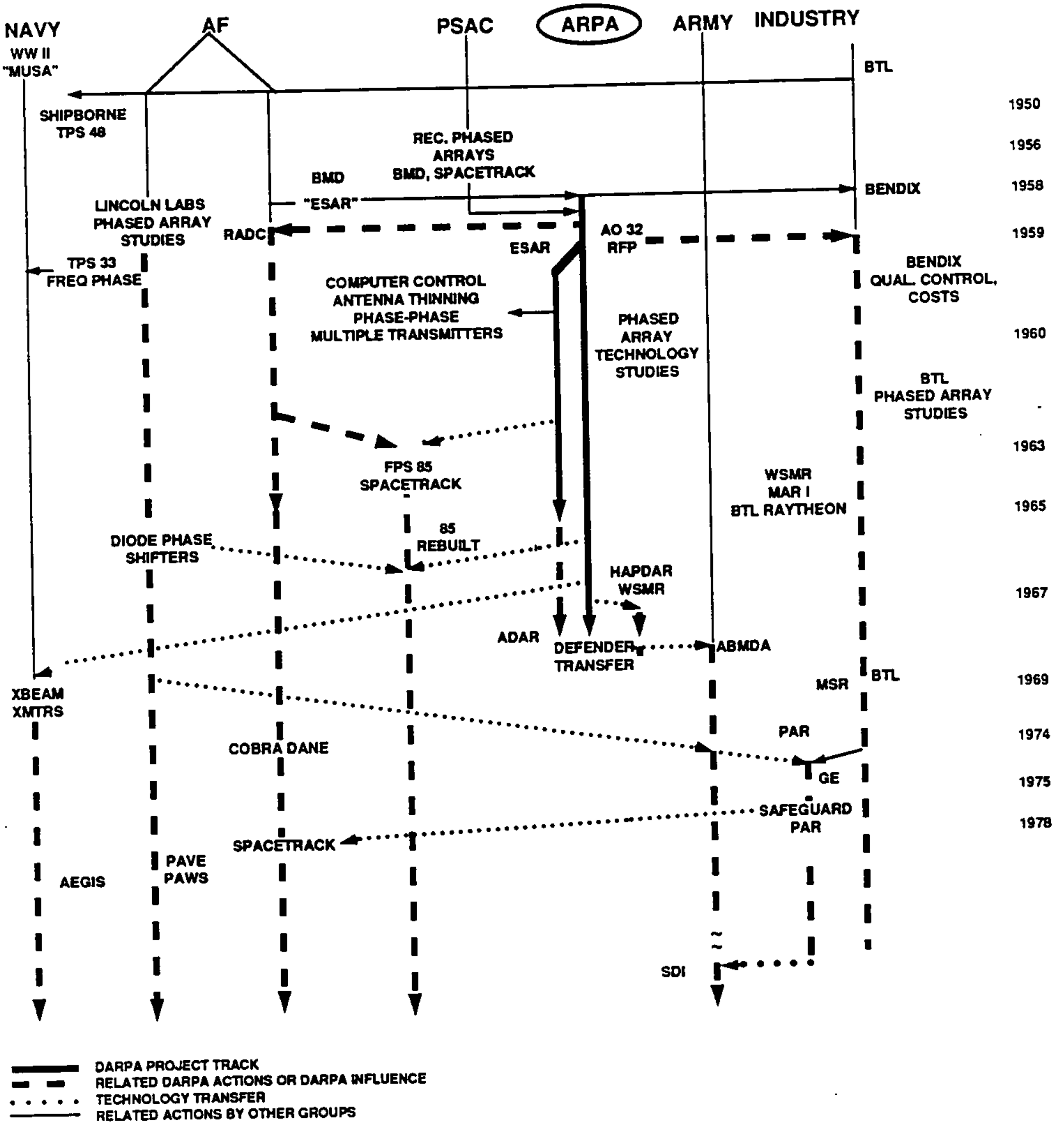
[23] Discussions with Dr. M.I. Skolnik and Major General Toomay.

[24] Discussion with MG Toomay, 1/90.

ESAR



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SDI
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS

VII. TABSTONE INFRARED MEASUREMENTS

A. BRIEF OVERVIEW

In response to an 18-month assignment from DoD in late 1960 to answer the critical question of the utility of infrared (IR) satellite early warning systems against ICBM's, ARPA initiated and directed project TABSTONE (target and background signal to noise experiments). TABSTONE was the most comprehensive and well-coordinated program of IR field and laboratory measurements, analysis, and technology development up to that time. At the end of 18 months TABSTONE had progressed far enough for ARPA to give a positive answer which raised the level of confidence in DoD and enabled development of the technology of the current U.S. IR satellite early warning systems (SEWS). The TABSTONE scientific results also had a major impact on design considerations for subsequent developmental programs leading to current U.S. systems, to improvements (such as the Advanced Warning Systems), and to SDI programs.

B. TECHNICAL HISTORY

When U.S. ballistic missile programs began to get under way in the mid to late 1950's, ground-based observational systems for tracking took advantage of the intense light emitted in the early launch phase, and such phenomena as reflection of solar radiation from the plume and missile body at higher altitudes. Soon, efforts began to measure quantitatively the intensity and spectral content of this radiation, some using high altitude aircraft. The Inter-Service Radiation Measurements Program, coordinated by the Air Force's Cambridge Research Laboratory, was one of the major efforts of this type. In the late 1950's the AF had also formed plans for infrared sensors for missile launch detection in its early 117L satellite program.[1]

In the late 1950's also a PSAC panel under William E. Bradley conducted a broad review of the problem of ballistic missile defense. The panel recommended further investigation of the utility of infrared and optical sensors for the detection and tracking of

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[1] *Deep Black* by William E. Burrows, Random House, New York, 1986, p. 84.

ballistic missiles in the various phases of flight, including reentry. In this same time frame the Air Force had started studies of project BAMBI (Ballistic Missile Boost Intercept), which included IR sensors in space to detect and track ballistic missiles and warheads.

At its beginning ARPA was given, by the President and DoD, broad responsibility for space systems. After sorting out the various military satellite proposals, ARPA recommended that the multifunction, complex and expensive Air Force 117L satellite program be divided into several simpler systems. One of these new systems was an infrared satellite to detect missile launches, named MIDAS (Missile Detection Alarm System.[2] The other systems were the SENTRY, later the SAMOS satellites, dedicated to surveillance, and DISCOVERERS, for satellite technology development. Responsibility for all these 117L programs, which were in advanced stages of development, was returned to the Air Force by H. York after he became DDR&E in 1959.

MIDAS was reviewed by ARPA in 1959 and 1960 and a number of recommendations for changes were made, mainly toward more background measurements.[3] While there were some background measurements made for MIDAS the program seemed predominantly target-detection oriented. These recommendations seem to have had little initial impact, however, and the first MIDAS tests began, in near-earth polar orbit, in 1960.[4]

In 1958, in response to the Bradley Committee recommendations, ARPA's project DEFENDER began studies of sensors and measurement systems in the radar, IR and visible spectral ranges needed to improve understanding of the phenomenology of ballistic missiles from launch to reentry.[5] Under DEFENDER studies also were conducted of sensors for BAMBI, some of which were infrared systems.[6] BAMBI's emphasis was on midcourse intercept, but it also required launch-phase information. The DEFENDER IR effort also included fundamental work such as IR emissions from flames and the properties

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[2] ARPA BMD Technology Program Review, 3-14 August 1959, Vol. III (declassified) p. 1019 Air Force IR reconnaissance satellite studies apparently began in 1956.

[3] An IDA/ARPA team review made the review. Discussion with L. Biberman, IDA, 11/87 and IDA-T-E-157, by R.S. Warner, 19 August 1959. See also ARPA 1959 review, p. 1052.

[4] *History of Strategic Defense*, by R.L. Maust et al. SPC report SPC 742, Sept. 1981 and "Aeronautics and *Astronautics, An American Chronology of Science and Technology in the Exploration of Space*, 1955-60, by Eugene M. Emme, NASA 1961, p. 147.

[5] Lincoln Laboratory took on a major responsibility for carrying out reentry measurements studies in 1960 but was not strong, at the time, in the infrared area. ARPA helped lay out the early reentry IR measurements program. Discussion with R. Zirkind, 11/88.

[6] AO 6 AFSC, Task #7, 1/59. This task also included launch phase investigations.

of molecules.[7] Airborne IR measurement capabilities were considerably augmented.[8] Infrared phenomenology associated with nuclear explosions was also given attention.[9]

In the late 1950's also, significant efforts had been made by the U.S. infrared community which had, earlier, begun the important series of Infrared Information Symposia, and to make IR "state of the art" reviews. ARPA helped focus this effort by funding the publication of the first Handbook of Military Infrared Technology.[10]

In 1960 there was a review of missile launch detection programs by PSAC and other high level DoD committees. The main focus was the question of whether a MIDAS-type satellite IR system was workable. Available data seemed insufficient and unreliable. Recommendations were made by these groups that a new, coordinated national program be established to provide a better scientific basis to answer this important question.[11] Additional concern regarding this question came from early reports that MIDAS satellites and some other satellites carrying related infrared sensors all had a large number of false alarms.[12] An early theoretical analysis of the false alarm problem (later shown to be incorrect) indicated that it might be insoluble.[13] An editor of Aviation Week described the status of concern:[14]

> In the spring of 1961 the new administration's Defense Secretary, Robert S. McNamara, publicly expressed doubts over the feasibility of the MIDAS concept during Congressional hearings. "There are a number of highly technical, highly complex problems associated with this system," McNamara said. "The problems have not been solved, and we are not prepared to state when, if ever, it will be operational."

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[7] AO 6, Task 13, 4/59. At about the same time there was increased NASA research on radiation heating by rocket exhausts, cf. *Handbook of Infrared Radiation From Combustion Gases*, NASA SP 3080, 1973, p. iii.

[8] AO 6, Tasks 15, 4/59, 20, 5/59, and 31 of 4/89: the last for a "Global Systems to be Operational by 1962." AO 30 of 10/58 enabled AFCRL to undertake a large program ($12M) of IR measurements of rocket plumes and transmission from aircraft, and "piggyback" on missiles with different types of propellants and aircraft measurements of backgrounds. An amendment to the ARPA order for the TRANSIT satellite provided for a small NOTS sensor for background measurements especially of reflected sunlight for high clouds to supplement MIDAS. IDA TE 157, ibid.

[9] AO 111 of 11/59. MIDAS was to have some capability of nuclear explosion detection, cf., ARPA 1959 review, p. 1024.

[10] AO 161 of 6/60. The IEEE proceedings of Sept. 1959 was also dedicated to a state of the art review of IR.

[11] Discussion with R. Zirkind, 11/88.

[12] Discussion with R. Legault, IDA, 10/88.

[13] This analysis was made by P. Cutchis of IDA. Discussion with J. Jamieson, 12/88.

[14] *Secret Sentries in Space*, by Philip J. Klass, Random House, New York, 1971, p. 175.

> The basic problem, beyond unreliability troubles that then plagued all satellites, was that the infrared sensors could mistake the infrared radiation from sunlight reflecting off high-altitude clouds for rocket-engine plumes. This meant that a MIDAS satellite passing over the USSR might mistake a cluster of high-altitude clouds basking in the sunlight for a mass ICBM attack and flash a false alarm back to the U.S.

Meanwhile, the Air Force was proceeding with the next phase of MIDAS, involving somewhat higher orbits.[15]

> Even as McNamara was testifying, the USAF was readying two full-fledged MIDAS satellites for launch and much would be riding on their success or failure. The MIDAS payload weighed roughly 2,000 pounds, including delicate infrared sensors and complex electronics, and was mounted in the long nose section attached to the Agena. A powerful Atlas first stage was required to launch the MIDAS into the 2,000-mile near polar orbit that would be needed for operational use over the USSR to give the spacecraft sensors a wide-spanning view. On July 12, 1961, MIDAS-3 was successfully launched into orbit, with an apogee/perigee altitude of roughly 2,100 miles and an inclination of 91 degrees, from Vandenberg AFB, Calif.
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> The USAF disclosed that MIDAS-3, as well as MIDAS 4 which went into a similar orbit on October 21, would be tested against missiles fired from Cape Canaveral and Vandenberg, as well as against special flares designed to mimic the infrared characteristics ("signature") of rocket engines. It was shortly after the MIDAS-4 launch that the Kennedy administration dropped the heavy security cloak over the reconnaissance satellites, and it enveloped the MIDAS program as well. But from informed observers it was learned that the MIDAS was still encountering the same problem of positive identification of missiles and false alarms. It was clear that much more experimental data, and testing, were needed to devise sensors which could discriminate rocket-engine plumes from sunlight bouncing off clouds.

DDR&E Harold Brown assigned ARPA the task of answering the question whether a MIDAS-type system could work in late 1960, requiring an answer in 18 months.[16] The TABSTONE program was set up by ARPA in response to the DoD assignment, with R. Zirkind as director. TABSTONE was to go back to fundamentals, and would include a very broad range of field measurements, many of unprecedented quality, together with analysis of the results, and involved a substantial fraction of the expertise of the IR community. As a national program, TABSTONE was able to obtain ready cooperation and top priority on Service assets. After a preliminary internal assessment of the problem a meeting of experts was called in late 1960 to help define the program.

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[15] Ibid., p. 176.

[16] Discussion with R. Zirkind, 11/88.

In early 1961 TABSTONE programs got under way.[17] The work was carried out by industry, academic groups, the Air Force Cambridge Research Laboratory, Navy Laboratories, and IDA, and also included participation by Canadian and U.K. groups, all under TABSTONE direction. Many of the available capabilities and ongoing programs, including the IRMP, were extended, and some were modified. The capabilities of a number of IR measuring instruments were extended and improved, and a new IR imaging vidicon constructed. Chemical, physical, and aerodynamic problems connected with the phenomenology of IR emissions from rocket plumes at different altitudes were also addressed. Field measurements of missile plumes were made, some at ground level, but mainly from high altitude aircraft, and also from other rockets and "piggy-back" systems onboard the same missiles being measured, and from satellites. Measurements were made at wavelengths from the infrared through the ultraviolet, with as high spectral resolution as possible and with careful attention to calibration. Theoretical calculations were made of the emissions and absorption of molecules and of rocket exhaust phenomena. Properties of a wide variety of propellant compositions were measured, on a laboratory scale and in the field, mainly in static ground level experiments. The possibilities of countermeasures were also explored.

Background measurements were made from aircraft and balloons. Some statistical information on background was also obtained from instruments on satellites and high altitude probes. Transmission measurements were made from aircraft, some using solar emissions, and also using long tubes containing controlled gas mixtures.

Transmission data were analyzed in detail by a group at the National Bureau of Standards Boulder laboratory. These data formed part of the basis of later computer models of atmospheric transmission. Results on target emissions and background were summarized in a series of BAMIRAC (Ballistic Missile Infrared Analysis Center, set up under DEFENDER) reports for TABSTONE.

Some of the TABSTONE measurements in the early launch phase contributed also to the BAMBI studies. TABSTONE also made some measurements in midcourse, useful

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[17] AO 237 of 5/61 to ONR; AO 238 to AFSC, and AO 243 to Navy's BuWeps, all of 5/61. AO 236 of 6/61 provided for the University of Michigan's Ballistic Missile Radiation Information Center (BAMIRAC) and AO 250 of 6/61 provided for NBS to collect and analyze transmission data.

to BAMBI, but the BAMBI intercept requirements were generally more stringent in space-time resolution than those for TABSTONE.[18]

TABSTONE results and plans were coordinated and reviewed in a series of meetings throughout the project, notably the yearly AMRAC meetings. TABSTONE data and analysis had a major impact both on understanding the early MIDAS results and on the subsequent developmental efforts toward infrared warning satellites. The TABSTONE results were considered sufficient, at the end of 18 months, to understand the main quantitative features of signal and background noise and some of the characteristics of filters to obtain better signal to noise. In briefings at that time by the ARPA program director to PSAC and to DoD, a reasonable scientific case was made for the eventual operable utility of properly designed IR warning satellites. Some uncertainty remained, however, until the mid 1960s, and TABSTONE continued to provide important information to its end in 1965. A symposium was held on its results in that year.[19]

After TABSTONE had helped raise DoD confidence in IR for missile launch detection, the Air Force conducted related measurements programs, some using satellites.[20] A critical review of all existing information in 1967 affirmed the continued value of TABSTONE data and outlined areas where further work was needed.[21] In the late 1960's further experiments and development of a new infrared satellite system got under way. In the early 1970's the Air Force's geosynchronous-orbit satellite early warning system, (SEWS), including IR scanning sensors, became operational.[22] The present system includes three satellites in geosynchronous orbit, one over the Atlantic and two over the Pacific areas, including, besides IR warning sensors, systems for detection of nuclear explosions.[23]

Following TABSTONE, DARPA work in support of infrared strategic warning technology had a short hiatus. DoD and ARPA reviews in 1968 established objectives for a new ARPA Plume Physics program which got under way in 1970. Theoretical models of

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[18] BAMBI was eventually terminated for other reasons having to do with complexity and cost.

[19] Communication from Dr. A. Flax, IDA, 2/90. *J. Missile Defense Research*, classified issue, Vol. 4 #1, 1966, contains a preliminary review of the TABSTONE results and further references.

[20] History of Strategic Defense, ibid., p. 24. The subsequent Air Force IR satellite program was managed by the Aerospace Corporation.

[21] Discussion with Dr. H. Wolfhard, IDA, 11/88.

[22] "Warning and Assessment Sensors," By J. C. Toomay, in *Managing Nuclear Operations*, by C. Zraket and A. Carter, Brookings 1983, p. 306, and Aviation Week, Feb. 20, 1989, p. 34.

[23] Senate Appropriations Committee, Department of Defense Appropriations, FY 1975, part 1, p. 514.

the flow and radiation from launch and reentry plumes were formulated in this period. These were further developed by NASA and the AF into standard computer models, which were validated to a considerable extent by experimental data under the DARPA IREW program in the mid 1970's. Attentions turned in the late 1970's to measurements and theory of high altitude plumes phenomena, applications of new infrared technology to detection and tracking of plumes and other targets, and improvement of lifetime and reliability of space-based IR systems. SDI has contributed substantial support in these areas since its inception.

C. OBSERVATIONS ON SUCCESS

The motif for TABSTONE was the very strong high level interest in obtaining some 10 minutes or so extra warning time beyond horizon limited radar, by using an infrared satellite. There could be greater overall confidence in a warning picture developed by both microwave radar and infrared, which involved different physical phenomena. The Air Force IR MIDAS satellite was a very large program, on which ARPA's brief span of management had little initial impact. However, MIDAS experienced severe difficulties, which led to its cancellation. Doubts were publicly expressed by Mr. McNamara, then Secretary of Defense, whether any such IR system could be made to work. Some controversy continued, however, with the Air Force's Gen. Schriever contending that MIDAS could have been successful.[24]

TABSTONE was set up as a national program, under ARPA management, to go back to fundamentals to obtain an answer to the infrared satellites question, with an 18 months time limitation. TABSTONE was managed directly by an IR expert on ARPA's staff, R. Zirkind, and involved orchestration of existing technological capabilities and making improvements where necessary to achieve a coordinated IR measurements effort of unprecedented quality. The infrared community, in academia, industry and government laboratories apparently sensed the crisis caused by the MIDAS situation and cooperated fully. TABSTONE appears to be still regarded by this community as an IR measurements program of unique quality and breadth.[25] The data obtained from TABSTONE was carefully archived and is apparently still used by investigators in the IR area.[26]

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[24] Discussion with Dr. J. Ruina, 6/89.

[25] Discussion with Drs. J. Jamieson and H. Wolfhard, 11/88.

[26] Dr. H. Wolfhard, ibid.

TABSTONE achieved its objective in that results at the end of 18 months were good enough for ARPA to give, with reasonable assurance, a positive answer to DoD on the question of eventual workability of an infrared satellite, and continued to provide important information for OSD decisions on IR warning satellite systems, to the end of the project in 1965.[27] By this time also there was some relaxation of concern about the "missile gap," due to a recent information coming from the first surveillance satellites.[28] This plus the construction in the early 1960's of the 440L OTH missile attack warning system were "stop gap" measures, while further Air Force-developed IR infrared satellite programs were carried out and used to make measurements. TABSTONE can be credited with raising the level of confidence in DoD which led to a subtained effort toward developing the technology of the present DoD operational IR warning system, of its continuing improvements such as the Advanced Warning System, and possible future systems such as SDI's BSTS.[29]

The recorded ARPA outlay for the TABSTONE program up to 1965 was about $18M. The SEWS system cost is estimated as about $5 billion to FY 1988.[30]

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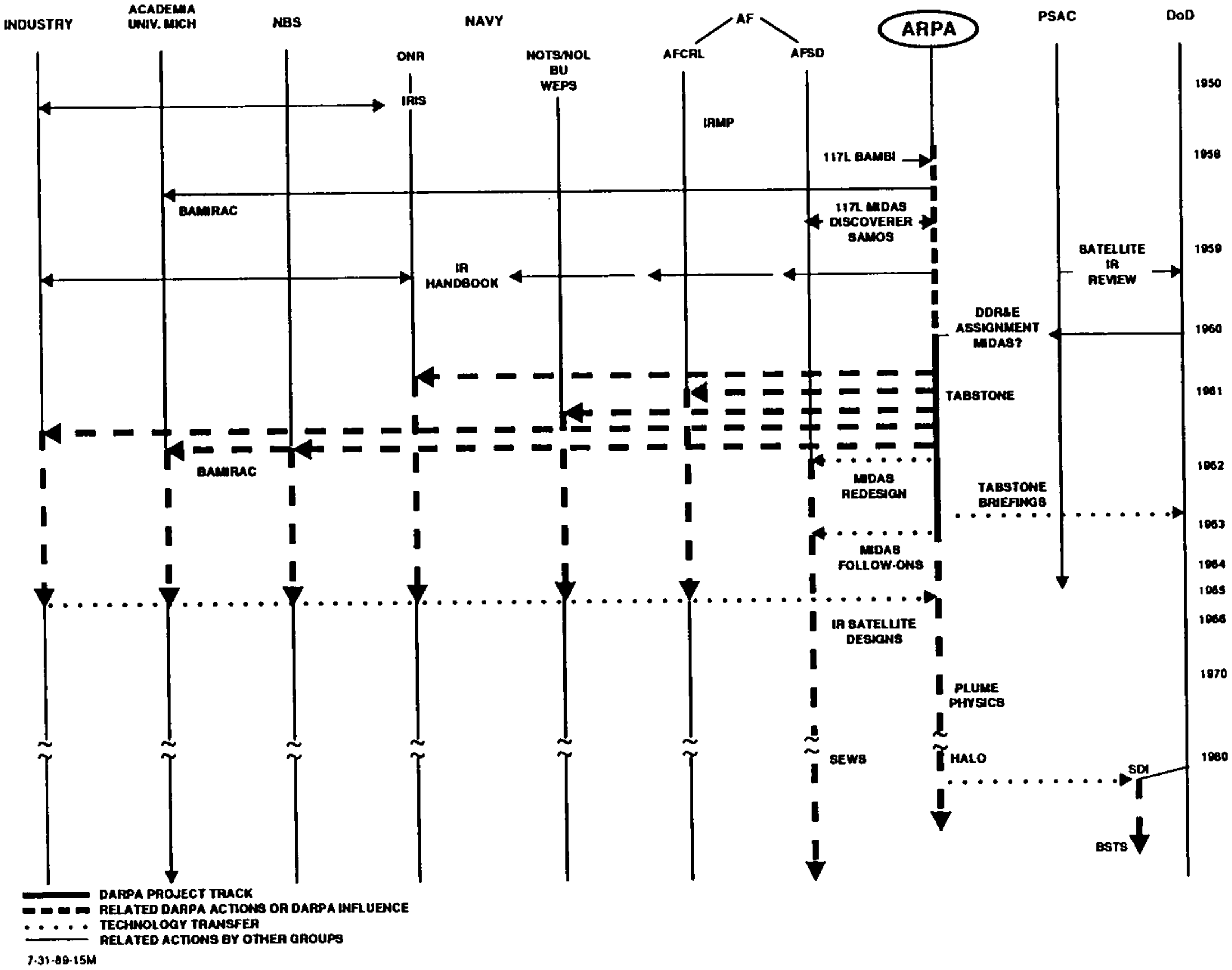
[27] Discussion with R. Zirkind, 7/88, and A. Flax, ibid.

[28] Klass, ibid., p. 176.

[29] Aviation Week, ibid.

[30] DoD Authorization Hearings before the House Armed Services Committee for FY 1984, R&D, p. 1304.

TABSTONE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VIII. HIGH ENERGY LASERS

A. BRIEF OVERVIEW

DARPA has developed much of the technology of high energy lasers (HEL) and has supported construction and test of state-of-the-art systems for military R&D, such as the ALPHA chemical laser. Most of this technology has been transferred to the SDI program. The DARPA effort also had significant impact on moderately high power lasers now used in industry, on the lasers used in the DoE Inertial Confinement Fusion (ICF) and Atomic Vapor Laser Isotope Separation (AVLIS) programs, and on the materials and components in lower energy lasers used by the military and industry.

B. TECHNICAL HISTORY

ARPA was involved in laser R & D from shortly after Townes' first publications on the laser concept in 1958. ARPA Order 6, task 12, of March 1959, provided substantial funding for "laser studies" in support of a broad exploration effort proposed by TRG, Inc.[1] In 1961, Ted Maiman, in a Hughes Company internally-funded project, demonstrated the first operating laser, using a ruby rod as the "lasing" medium.

Soon afterwards concerns rose about the question of high energy laser beam weapons and the ARPA laser effort was greatly expanded under project DEFENDER in order to explore its possibilities as a weapon for ballistic missiles defense (BMD).[2] While such a development could have a very high payoff, it was considered very risky, with much more demanding problems than low-energy applications such as rangefinders and targeting devices then pursued by the Army.[3]

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[1] "Laser Pioneer Interviews," *High Tech Publications, Inc.*, 1985, interview with Gordon Gould, p. 77.

[2] An account of the ARPA-IDA interactions leading to this expansion is given in "How the Military Responded to the Laser," by R. Seidel, in *Physics Today*, Oct. 1988, p. 41.

[3] The Army and Air Force also had high power laser programs beginning at about the same time as ARPA. Cf., e.g., "History of the U.S. Army Missile Command 1962-77," Historical Monograph, U.S. Army Missile Command, Chapter IX, p. 169. The Navy's Office of Naval Research, which did not have a large laser program, was used by ARPA as a main agent (AO 356 of 5/62, 9.3M.) for the first phase of high energy laser effort. Cf. also Physics Today, ibid.

After the early exploratory work, the ARPA HEL effort was conducted in four phases. The first phase, lasting roughly from 1962 to 1965, encompassed a broad exploration of laser mechanisms, materials, and techniques for high-energy lasers.[4] All prospective laser media: gases, liquids including dyes, crystalline and amorphous solids were investigated. This first effort was predominantly on solids because it appeared that only condensed lasing media could achieve high energy densities. The investigations included studies of optical and thermal properties and ways to improve them; damage mechanisms; gas flash lamps and semiconductor sources for pumping,[5] "Q switching" rapid energy dumping techniques, pulsed power sources, and propagation of high energy beams through the atmosphere. The interaction of intense laser beams with materials began to be studied with ARPA support, at the Air Force Weapons Laboratory.[6]

The properties of existing lasers were improved under the ARPA program, and the potential for high-energy applications of the many new lasers appearing at the time were investigated. Serious problems were soon uncovered, with respect to low pumping efficiency, thermal effects in laser generating media, and in high-energy laser beam propagation. An early JASON Summer Study indicated that the best candidate lasers, when scaled up to parameter ranges of interest for beam weapons, appeared to be very large and expensive. Further, any such beam weapon was weather-limited. It seemed clear by the end of this phase, 1965, that early development of a laser beam weapon was not likely.

One of the most important specific technological results of this phase was the technique for cleaning tiny platinum inclusions from glass, which could cause explosions at high energy densities. This technique has also eventually impacted development of all types of glass lasers, from low-energy systems such as range finders to medium energy industrial laser systems, and has been a major factor affecting the laser fusion research program: the high energy laser NOVA, at Lawrence Livermore Laboratory, uses glass technology in their Inertial Confinement Fusion program.[7]

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[4] Robert W. Seidel, "From Glow to Flow: A History of Military Laser Research and Development," in Historical Studies in the *Physical Sciences*, Vol. 18 #1, 1987, p. 111-147, and *Physics Today*, ibid., p. 36.

[5] To use semiconductors for pumping sources was not very promising 25 years ago; it seems now to be a serious prospect, see Robert L. Byer, "Diode Laser-Pumped Solid State Lasers," *Science*, Vol. 239, pp. 742-747, February 1988.

[6] As part of AO 356 of 5/62.

[7] The first high power glass system was apparently developed in France in the late 1960s.

In about 1965 a new phase of ARPA high-energy laser effort started which emphasized fundamental processes and problems of scaling new lasers, such as the CO_2-N_2 laser discovered by Patel of Bell Laboratories in 1964, to high energy. This phase of laser effort, however, was not as large as its predecessor.[8]

The discovery by AVCO of the high power infrared CO_2 gas dynamic laser (GDL) in 1966 demonstrated that rapidly flowing excited gases could provide a high energy laser source. The AVCO laser combined two concepts. One was the work of A. Kantrowitz in the late 1940's on delayed equilibration in the rapid expansion of hot molecular gases through an aerodynamic nozzle, which suggested a way of providing an excess population of excited CO_2 molecules. The other was the CO_2-N_2 laser mechanism discovered by Patel, mentioned above. The rapid gas flow also provided a mechanism for heat dissipation.

After some delay in acceptance of the potential of the AVCO approach, in the late 1960s another major phase of the ARPA effort toward a high energy laser began, with the "Eighth Card" program, under the Strategic Technology Office, classified partly because of the apparent potential of the gas dynamic CO_2 lasers to be scaled up in energy.[9] Besides investigation of technology and problems of the Gas Dynamic Lasers (GDL's) a number of new high energy gas lasers were developed with ARPA and other sources of support. Some of these were closed-cycle, including lasers based on flowing gases undergoing chemical reactions, or excited by electrical discharge or electron beams (e-beams), with improved efficiencies.[10] ARPA emphasis in this period was on the feasibility of scaling up these new types of continuous wave (CW) lasers, to achieve megawatt (MW) power levels,

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[8] A sampling: AO 744 of 6/3/65 called for an advanced scanning laser radar; AO 1279 of June 1968 for "Optical Radar," 1503 for "Ruby Laser," 2075 of March 1972 for a "Solid-State Laser Illuminator and 2165 of March 1972 "Laser Back Scatter Studies;" 2211 of 9/72 "Advanced Lightweight Laser Designator and Ranger; 2560 of 8/73 for a "Multipulse Laser Target Designator."

[9] The delay is described by Seidel, Ref. 3, p. 140. A brief history is also given in pp. S33-34 of *Reviews of Modern Physics*, Vol. 59, No. 3, Part II, July 1987. A.O. 1256 "Eighth Card", 6/68. In the mid 1960s also, in response to Vietnam, ARPA's project AGILE looked into low energy laser system applications. Much of this work was under the AGILE Advanced Sensor Office and produced several prototype laser radars, target designators, and illumination systems which differed from those developed by the Army and Air Force by being lighter, smaller, and achieving new levels of performance. Later, a number of similar systems were developed by ARPA's Tactical Technology Office.

[10] The United Technologies Research Center publication, *The Researcher*, October 1985, dedicated to the laser, gives a chronology of one major company's activity.

in a reasonably sized device.[11] Apparently, however, the first high-energy CO_2 laser of pulsed e-beam type was developed by Los Alamos, for their laser fusion program.

As a result of the intense efforts in the late 1960s by ARPA and the Services, expectations rose that some of these high-powered infrared lasers might actually be engineered into a weapons system. A Defense Science Board review of the progress recommended in 1968, a tri-service laser program with each service providing its own "test bed" related to its characteristic platforms, with ARPA initially in an overall coordinating role.

A little later, DDR&E undertook coordination of the large HEL programs, and ARPA's program turned more to investigation of limiting factors such as materials, optics, and atmospheric propagation. About this same time also several companies involved in the Eighth Card and other related programs began to make substantial investments in these new types of lasers for material processing applications.[12] These efforts, as well as those supported by the military, shared many problems of optical technology, notably windows for high energy infrared transmission. The damage mechanisms that had been investigated in a laser weapon context were important also for the industrial laser applications. A number of ARPA Orders from the Materials program addressed these problems.[13] Some of those involved in related optical work in industry at the time have given a good statement of the situation:[14]

> How much power can it take?" "What's the damage threshold?" "How many hours will it last?" -- these were the types of questions customers were asking. And the answers were not readily available. New substrate materials to transmit high energy beams, new methods to fabricate these materials and new coatings able to withstand high energy densities all had to be developed before this situation could even begin to be remedied.
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> In the late 1960s and early 1970s various government agencies realized that an enormous amount of work would be required to solve these problems, and the optical industry would not be able to handle the job without a large influx of funds and talent. The R&D programs thereafter established brought an impressive array of solid state, metallurgical, optical, and laser

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[11] Discussion with Dr. R. Cooper, 1/90.

[12] See e.g., "High Power, Short Pulse CO_2 Laser Systems for Inertial Confinement Fusion," by S. Singer, et al., in "Developments in High-Power Lasers and Their Applications," ed. C. Pellegrini, North Holland, 1981, p. 724.

[13] E.g., AO 2014 of 12/71 on Halides for High Power Laser Windows; 2138 of 2/72 on IR Laser Windows; 2980 on KBr for High Power IR Laser Windows, in 12/74.

[14] From "Transmission Optics for High Power CO_2 Lasers; Practical Considerations" by G.H. Sherman and G.F. Frazier, Optical Engineering Vol. 17 #3, May-June 1978, p. 225.

> specialists to bear on the important problems, and understanding of the critical parameters progressed quickly.
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> In this same time period, the CO_2 laser was just beginning to establish itself as a viable industrial tool. The new materials processes and coatings developed under the various government funded R&D efforts provided the optical industry enough background and direction to enable it to solve many of the optics problems facing high power CO_2 laser manufacturers and users. The increased laser reliability and stability resulting from improved optical components helped the industrial market expand rapidly, bringing us to the present time, where high power CO_2 lasers are being used in material processing applications in virtually every major industry. The hundreds of lasers operating thousands of hours in harsh industrial environments have generated a large amount of useful data and practical field experience which, when combined with the R&D efforts alluded to above, finally have built a solid foundation of knowledge and expertise from which the optical industry can draw.

Another JASON Study in this period indicated that practical implementation of high energy lasers for military use remained very difficult.[15] A significant proposal to ARPA by Lincoln Laboratory for a large scale demonstration and test facility, in 1969, was turned down by an outside review committee.[16] A high point of this phase of DARPA effort was the construction in 1975, in a joint program with the Navy, of the "Mid Infrared Chemical Laser" incorporating the most advanced chemical laser technology achieved at that time.[17] MIRACL eventually reached MW power range in continuous wave (CW) operation at near diffraction-limited output.[18]

Several demonstrations of lethality of the different Services' high powered gas lasers were also made in this period. The Airborne Laser Laboratory (ALL), initially a joint Air Force-DARPA effort, incorporating a United Technologies (UT) compact closed-cycle CO_2 laser, was one of the most advanced and the longest lived of these lasers, eventually achieving near-MW level power output.[19] ALL remained in R&D use until the mid 1980s. However, partly as a result of the JASON study, DARPA terminated its support of ALL in the mid 1970s.[20] There were many discussions and proposals for laser weapons system applications, but apparently none were sufficiently attractive to the Services.

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[15] Communication from Dr. E. Rechtin, 10/89.

[16] R. Cooper, ibid.

[17] AO 2607 of 8/73, MIRACL.

[18] *Reviews of Modern Physics;* ibid, p. S39.

[19] Ibid., p. S38.

[20] Dr. E. Rechtin, ibid.

Problems of efficiency, size, difficulty in handling chemical systems and changes in operational considerations seem partly responsible. However, the MIRACL has been upgraded and used for several R&D projects, for the SDIO. Fig. 1 is a depiction of the MIRACL beam director.

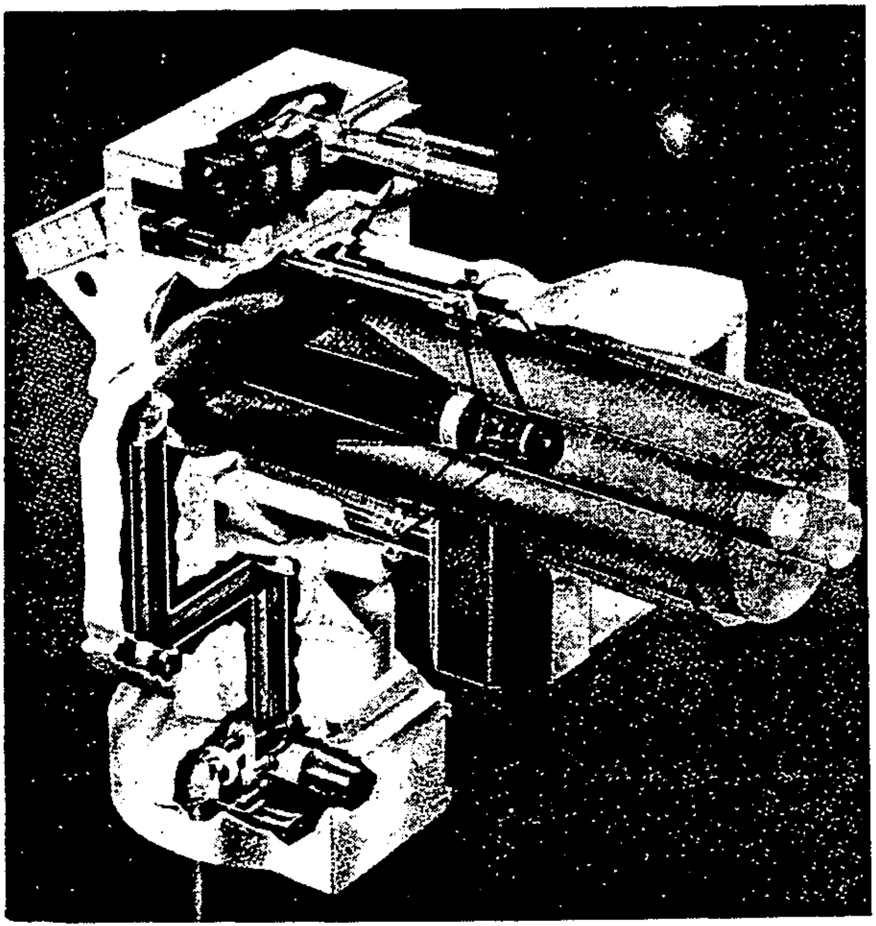

Figure 1. MIRACL and Navy SEALITE Beam Director

A major spin-off of this phase of the DARPA high energy laser effort has been to the industrial applications of the laser concepts and technology to materials processing applications as indicated in the quotation above. A more detailed perspective on industrial laser technology is given by some recent publications by LLNL and the National Academy of Engineering. The LLNL report[21] discusses the use of Nd-doped glass in the NOVA laser used in their inertial fusion research program, and also, more generally, the status of

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[21] "The Potential of High Average Power Solid-State Lasers," J.C. Emmett, W.F. Krupke, and W.R. Sooy, LLNL Report UCRL 53571, Sept. 1974.

industrial application of medium power lasers of which much of the technology was stimulated by the ARPA high energy laser efforts.

> Lasers are being used for cutting, drilling, welding, and heat-treating operations on metals, and, as relevant on wood, plastics, ceramics, fabrics, rubber, semiconductors, and paper. Despite early resistance by the usually conservative manufacturing community, these applications have grown, and they constitute the largest market area for production lasers and laser systems. The current market is roughly split between CO_2 and neodymium lasers, with cw CO_2 lasers the only entry for applications between 400 W (the upper limit on neodymium) and 25 kW (the upper limit for CO_2 lasers engineered for a manufacturing environment). Below 400 W neodymium is the major entry, but CO_2 competes in that range also, and a variety of other laser types are reaching sufficient maturity to enter the market. On the high-power side, experiments have been extended up to 100 kW but commercial interest is largely below 25 kW. It appears that for some time the advances in laser fabrication will be in the form of cost reduction, improved reliability, and expansion in the existing marketplace.

One of the most successful specific industrial applications seems to have been United Technologies Hamilton Standard laser welding system. While the power level of the welding laser system is considerably lower than for a weapon, the invention of this specific type of laser at UT (the high power forced flow, electric discharge CO_2 laser) appears to have been definitely stimulated by the Eighth Card program, under which a high power version was constructed in Florida and another was used in the AFWL ALL program. According to Dr. A.J. De Maria, head of UT's laser program, the ratio of company funding to DARPA funding was typically three-to-one in this period, but the DARPA funding was always vital to maintain the company's interest to continue the effort.[22]

A National Academy of Engineering publication celebrating the 25th anniversary of the discovery of the lasers points out that the material-working segment of the market for lasers was estimated as about $1/4 billion in 1984 with expansion expected to continue.[23] While the direct laser market is often taken as a measure of the worth of laser technology, the indirect value of the laser in reducing manufacturing costs, e.g., of the industrial medium power laser's use in making military turbine engines, providing more efficient

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[22] Discussion with Dr. De Maria 1/13/88. Dr. De Maria stated that the United Technology laser welding group is now one of their profit centers.

[23] "Lasers, Invention to Application," J.R. Whinnery et al., National Academy of Engineering, Washington, D.C. 1987, p. 22. By 1983, the overall (high and low energy) laser commercial market was dominant. See "Lasers the First Twenty-five Years," by A.J. De Maria, Optics News, Vol. 11, No. 10, Oct. 1985, p. 87.

machining and hole drilling, particularly in hard and exotic materials, is probably much greater.[24]

The fourth phase of DARPA high energy laser effort, beginning in the mid 1970's and lasting until recently, involved a return to exploration of advanced laser technology, along with a more directed effort toward laser systems for space applications. In the first part of this phase there was a strong push toward shorter wavelength, high-energy lasers, which could use smaller optics for the same beam quality, advantageous for space and other applications. Several other ARPA programs in this same time period also required lasers in the blue green, favorable for transmission in the sea: optical communication with submarines, detection of submarines from aircraft, and deep underwater imaging.[25] With ARPA (in this time frame becoming DARPA) stimulation, a number of high energy short wavelength lasers were developed, including, in the mid 1970's, excimer-type and free-electron lasers. This effort extended to X-ray lasers, also in the mid 1970's.[26] Much DARPA support in this phase went into developing other optical elements for use with the short wavelength lasers, such as pointing and tracking controls and techniques for space systems, and into optical compensation techniques for the effects of atmospheric irregularities. An adaptive mirror technique for atmospheric compensation was developed by Lincoln Laboratory under the DARPA program and has been tested using the AMOS (ARPA midcourse optical station) facility with SDI support.

Substantial efforts during this time period also went into developing compact efficient chemical lasers for use in space. A major product of this work was the ALPHA, a lightweight chemical IR laser system. The ARPA space laser system program, including ALPHA, large space optics, and pointing and tracking in space[27] eventually became the TRIAD program. This technology also was transferred to the SDI effort.

One of the main efforts under the SDI program to explore the potential of tunable high power free electron (FEL) lasers has used a induction accelerator generating a relativistic, high intensity electron beam, the Lawrence Livermore Laboratory's advanced

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[24] Dr. A.J. DeMaria, UT Inc., discussion January 1988.

[25] e.g., AO 1871, of 5/71 and 3588 of March 1978.

[26] e.g., AO 2694 of January 1974. The first successful X-ray lasers, however, apparently occurred in the early 80's, under the laser fusion program at the Lawrence Livermore Laboratory.

[27] AO's 2761 of 7/74, 3526 of December 1977 and 3945 of February 1980. ALPHA is briefly described in Reviews of Modern Physics, p. 539.

test accelerator (ATA).[28] The ATA accelerator was not funded by the ARPA Laser program but by a different ARPA effort which was aimed at exploration of the potential of particle beams for directed energy weapons. The ARPA particle beam program had its origins in 1958, and disappeared in the late 1960s, but came back in the mid 1970s and is still part of the DARPA long range Directed Energy Weapons Program.

Other potential, smaller space-based laser system applications, such as for air defense, were also investigated by DARPA in this period.[29] In the late 1970's, DARPA commenced a joint program with the Navy toward a blue-green laser system for communicating with submarines. Initially, this program was closely related to the short wavelength, high energy laser program. It included two approaches: a ground-based laser-satellite mirror combination, and a space-based laser. The ground-based laser system and adaptive mirror combination was tested at AMOS as mentioned above. This program was transferred to SDI. The space based laser approach continued and, after DARPA development and demonstration of a suitable narrowband filter optical receiver and a matched wavelength laser, (a modest energy ultraviolet excimer laser product of the DARPA short-wavelength effort) pumping a lead vapor "Raman" converter cell) and commencement of effort toward making the laser system qualified for space, this program, now named SLCSAT, was transferred to the Navy.[30] However, a recent Navy-DARPA MOU addresses continuing investigation of solid state lasers considered more suitable for space than the gas excimer lasers.

A significant spin-off of the DARPA short wavelength laser effort was the copper vapor laser. This laser was actually invented during the early TRG effort in the mid 1960's, and was further developed at GE in the late 1970's with support from the DARPA short wavelength laser program. The copper vapor laser is now a commercial product, and is the pumping laser for tunable dye lasers in the DOE's Livermore Laboratory atomic vapor laser isotope separation system (AVLIS), which was the preferred approach for the DoE nuclear fuels enrichment program.[31]

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[28] Very recently, however, SDIO has selected a different approach to the free-electron laser, based on a radio frequency driven accelerator. Cf., *Aviation Week*, Oct. 23, 1989, p. 21.

[29] R. Cooper, ibid.

[30] "Submarine Laser Communication," by Comdr. Ralph Chatham, *J. of Electronic Defense*, March 1987, p. 63.

[31] See Laser Technology-Development and Applications, Hearings before the Subcommittee on Science, Technology and Space of the Committee on Science, Technology and Space, U.S. Senate, 96th Congress, December 1979, p. 78-79; also, DoE Annual Report to Congress, 1986, p. 151. The Copper Vapor Laser was invented by Gould at TRG in 1966, see "Efficient Pulsed Gas Discharge

C. LESSONS LEARNED

ARPA's initial involvement with lasers was through an unsolicited proposal from a pioneering industrial group. This effort, however, did not yield any breakthroughs. After the first working laser was developed elsewhere, there were speculations in ARPA and IDA that this new area could have very high military potential and ARPA soon set up a sizeable effort in the high payoff and very risky high energy lasers area for weapons. Since this ARPA program began so close to the time of origin of a new idea in physics, it was a complex high technology effort with many players to more confidently determine and assess the payoffs, the limiting factors, and, importantly, the potential threat. The Army and the Air Force also had large laser programs, at about the same time, and the AEC developed a large high energy laser program for the inertial confinement fusion (ICF) program.

Some feel this early ARPA effort should have been curtailed earlier than it was. An early JASON assessment pointed out limitations due to propagation and the size of any prospective weapon system using the available technology. However, there were many uncertainties in propagation efficiency, pointing and tracking, lethality, and practicality of weapon systems. Many different kinds of lasers were being discovered--almost all outside the military programs. All this and the high potential payoff made such a program decision difficult. ARPA also had some of the best available advice for its early actions.[32] The reason for continuing a high level of ARPA effort at this time may have been that some felt that better glass cleanup might overcome the problems.[33] In fact, the glass laser technology developed in this phase under ARPA support has had a major impact on almost

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Lasers," by W.T. Walter, N. Solimene, M. Piltch, and G. Gould, IEEE Journal of Quantum Electronics, V. QE-2, Sept. 1966, p. 474-479, but significant further development was necessary to become practically useful. According to Dr. T. Karras of G.E., much of this development was funded by DARPA. Considerable further development for AVLIS occurred at Livermore. Discussion with T. Karras. A.O. 3650 of 7/78. Very recently, however, DoE has ordered a new review of all enrichment technologies, and has apparently put off further AVLIS development.

[32] C. Townes, the inventor of the laser, was at IDA during this period. Apparently, however, Townes did not seem to be a strong advocate of the high energy laser program. Discussion with Dr. C. Cook, 12/89.

[33] Discussion with R. Collins, IDA, June 1989.

all subsequent laser work involving glass. However, at one stage the French had produced the best glass, which was purchased by the U.S. programs. A number of key ideas over the years also came from the intensive Soviet efforts.

The invention of the gas dynamic laser, also from outside the ARPA program, was a surprise. The ideas involved were quite different from those of the previous program which emphasized solid laser media. There seemed good reason to "step on the gas" because the GDL technology appeared to be scalable to high energies. The large "Eighth Card" ARPA program, along with service and ICF programs, provided the climate for rapid developments of several derivative types of infrared lasers. Window and mirror materials were soon indicated as limiting factors. The ARPA materials program gave essential help to solve many of these problems, and ARPA's efforts to disseminate information on laser damage of optical materials was of great value to industry.[34] The three services became heavily involved. ARPA, besides supporting advanced technology and investigating limiting factors of possible systems, was given a coordinating role, which was later taken over by DDR&E and the DoD HELRG (High Energy Laser Review Group). Joining with the Navy, ARPA produced at the end of the 1970's a high power laser system, the MIRACL, which is still regarded as close to the state of the art, has been upgraded for use in SDI R&D, and may be again for ASAT application.[35]

Some feel that this expensive period of system oriented development could have been avoided if there had been agreement, in the late 1970s to prosecute a well coordinated program in a simple major facility.[36] Others point out that, during this period, because of the program's classification, contacts with the "outside" laser community, which were carrying on substantial efforts, were largely cut off, and that had it been possible to maintain these contacts, a more realistic program may have been pursued.[37] In fact, some contact was maintained through the HELRG. However, the impact of this phase of ARPA's effort on industrial use of moderately high energy gas lasers has been substantial.

ARPA was rather "responsive" to outside developments in the first phases. However, when the long wavelength technology had matured enough to make more realistic estimates of what would be required for weapons systems, DARPA began to support more directed work toward the objective of shorter wavelength lasers. This

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[34] See e.g., "Laser Induced Damage to Optical Mirrors," National Bureau of Standards, Dec. 1976.

[35] *Aviation Week*, December 19, 1988, p. 29.

[36] R. Cooper, ibid.

[37] R. Collins, ibid.

DARPA program helped develop several types of new short wavelength lasers, in the visible and ultraviolet, one of which, the "free electron laser" (invented sometime earlier outside the DARPA program), profited from the availability of the ASTRON accelerator facility at Livermore, partly developed under the separate ARPA particle beam weapon program. X-ray lasers were investigated under this program but abandoned a few years before success was reported by the Livermore ICF laser group. Some DARPA support was apparently given to the bomb-driven X-ray laser work at Livermore, before SDIO was formed.[38]

A joint program with the Navy for submarine laser communications profited greatly from excimer laser work, carried out under the DARPA short wavelength laser effort, and has led to demonstration of a workable, moderate power, laser-optical receiver combination. Recently, however, the Navy and DARPA have agreed that the risks and expenses in developing new solid state lasers for the blue-green, are perhaps more acceptable than those associated with going ahead with the gas excimer laser systems in space. The motif for communication needs also benefited the DARPA laser effort in providing a motivation which allowed atmospheric compensation experiments, relevant to the laser weapons program, to be carried out at more convenient lower laser powers.

The SDI has depended heavily on the DARPA laser technology, notably for the MIRACL, ALPHA, and the associated TRIAD pointing and tracking systems, and the ASTRON FEL facility.

The overall military high energy laser effort has been criticized generally as being overly ambitious and costly, with no resulting system in the inventory. Another criticism has been that limiting factors were soon discovered, which should have discouraged attempts to develop high energy laser weapon systems. Perhaps the problem of a "closed" community in which, because of the newness of the field, the contractors have a more deterministic role, led to excessive efforts. However, because of the wide "public" appreciation of the very high potential payoff, related concerns about potential threats, and the high unit cost of a R&D item in this field, it is difficult to see how DARPA could have done very differently. DARPA's role was to develop the new technology, and to construct state-of-the-art devices. Without a solid knowledge of the technology and its limiting factors, and of the practical difficulties in the construction and operations of high-energy

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[38] "Excalibur," A.O. #4557, 4/82, for $7.9 million.

lasers, it would have been very difficult to make a good assessment of potential threats in this area.

On the positive side, due to the DARPA program, state-of-the-art high energy lasers have been produced, and are being used by military R&D programs. There have been substantial spin-offs to lower energy military systems and to industry and the fact that the military R&D facilities and many of the spin-offs exist at this time, together with a strong technological community, can be largely credited to the DARPA program.

DARPA's total investment in lasers has been the largest in the military, estimated from project records as about $3/4 billion.[39] The direct value of the material-working medium power industrial laser market has been estimated as close to $1/2 billion. DoE expenditures for Copper Vapor Lasers in the development of the AVLIS technique are estimated at about $3/4 billion.[40]

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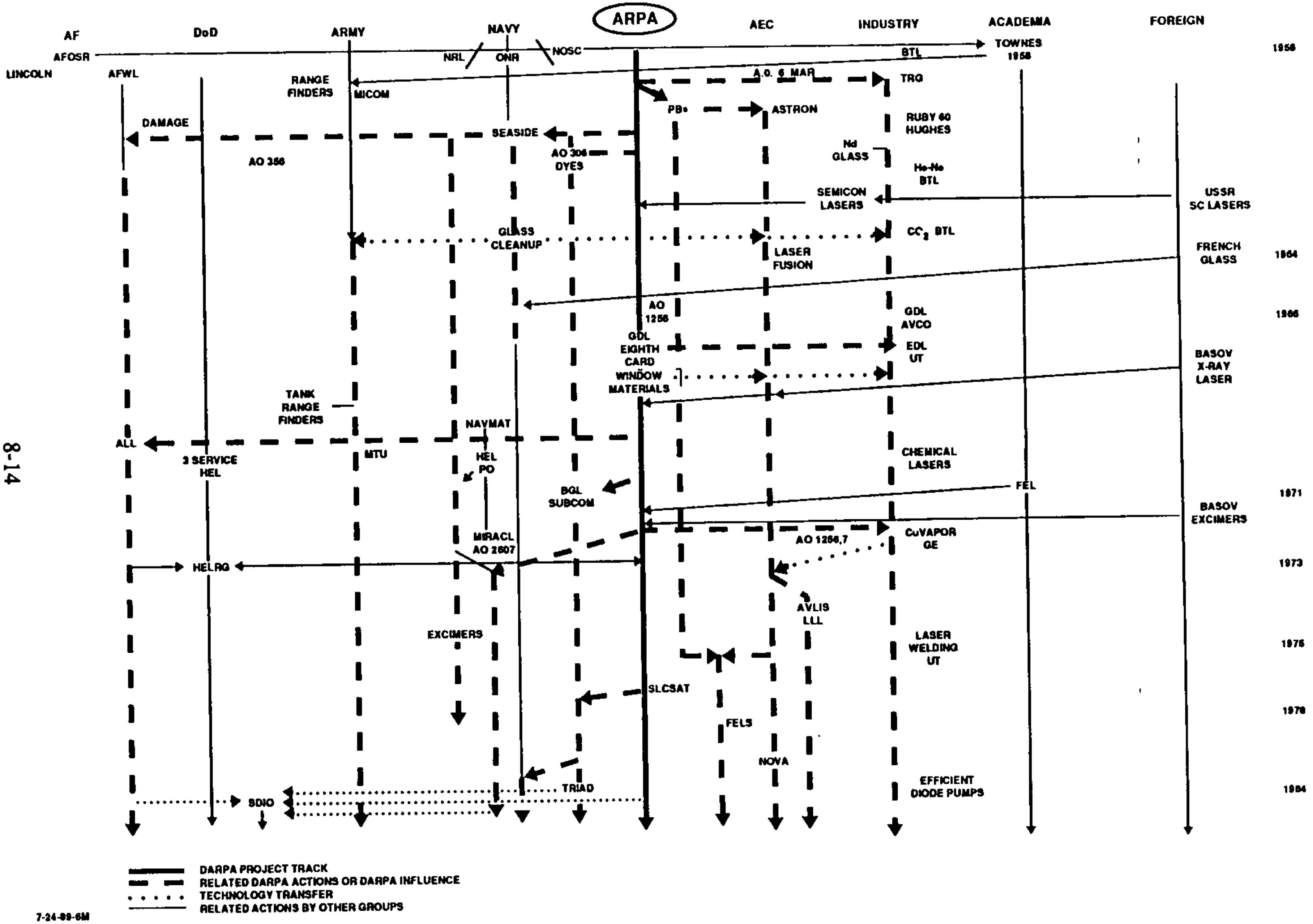
[39] Counting in the space mirrors work this approaches $1 billion.

[40] Lawrence Livermore National Laboratory, Institutional Plan FY 1985/90, pp. 118-19.

HIGH ENERGY LASERS



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IX. OTH RADAR

A. BRIEF OVERVIEW

The ARPA (and DARPA) involvement in Over the Horizon (OTH) high-frequency radar between 1958 and 1975 can be described as a successful effort in coordination, exploration and development of technology. One of the first payoffs was technology in the early 1960's for what became the Air Force 440L early warning system, which was deployed in 1966 and retired in 1975 when satellite systems for early warning became operational. Another spin-off was an oblique chirpsounder now in use in the AN/TRQ-35 frequency selection system for high-frequency military radio communications. DARPA-developed OTH technology had a major impact on the Air Force FPS-118 OTH-B radar system for CONUS air defense, approaching full operational deployment,[1] and on the Navy OTH-R system for air defense now in full-scale development.[2] DARPA OTH technology also provided much of the basis for the Australian OTH System for that nation's air defense.[3]

B. TECHNICAL HISTORY

Electromagnetic waves in the high-frequency band (with wavelengths of tens of meters) reflect downward when incident obliquely on ionospheric layers at hundreds of kilometers altitude. In this way electromagnetic energy can be propagated in a "guide" between earth and ionosphere to thousands of km range, a phenomenon long in use in high-frequency radio communications. This concept forms the basis for OTH radar.

The history of OTH radar apparently goes back at least to WW II, when an experiment during the development of the British CH (Chain Home) Radar Air Warning System, which operated in the upper end of the high frequency band, large diffuse echoes were observed and attributed to backscatter from the earth, after ionospheric reflection, at

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[1] "Backscatter Radar Extends Warning Times," David A. Boutacoff, *Defense Electronics*, May 1985, p. 71-83.

[2] "The Frontier of Sensor Technology," by LCDR J. Sylden, USN, *Signal*, March 1987, p. 73-76.

[3] *The Defense of Australia*, Australian Department of Defense, 1987, p. 4 and p. 35.

ranges up to several thousand miles.[4] Shortly after WW II there were studies and some Air Force-supported experiments in the U.S. to detect aircraft and V-2 missiles, without much success.

When ARPA began in 1958 there were several active military efforts under way. At the Naval Research Laboratory work had been going on since the early 1950's using a pulse-doppler radar with a great deal of signal processing to remove the large earth backscatter background for low-altitude targets and related propagation studies.[5] The "MUSIC" NRL effort was supported by the Air Force as an approach to long-range detection of aircraft, up until 1958 the highest priority. Another OTH effort had been conducted for some time by the Air Force's Cambridge Research Laboratory (AFCRL). A third, under project "Tepee" sponsored by ONR, had a later start in 1956, exploring initially the possibilities of using available equipment of the type then used in COZI (Communication Zone Indicator) studies during the IGY to detect, first, nuclear explosions and, later, ballistic missiles, both of which might have large radar cross sections and/or cause large ionospheric disturbances. Some of this ONR-supported work was done by a Stanford group under O.G. Villard, which had been conducting ionospheric studies with other ONR electronics research support for some time.

Because of the high priority of ballistic missile defense and ARPA's broad responsibilities and funds under project DEFENDER, OTH R&D began to be coordinated under ARPA.[6] ARPA also began to support exploratory, high-risk R&D on a wide range of OTH techniques and problems, such as antennas and receivers, ionospheric propagation, signal formats, management of interference, and ionospheric sounders.[7] Much of the research was done by the Stanford Group, which also served as advisors for the ARPA program.

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[4] "Radar Days," by E.G. Bowen, Hilger 1987, pp. 13-14. Apparently there was an identification of ground, backscatter echoes, called "Splash backs," in pulsed round the world propagation experiments at NRL in 1926. See "Evolution of Naval Radio & Electronics and contributions of the Naval Research Laboratory" by L.A. Gebhard, NRL Report 8300, 1979, pp. 45.

[5] "Over the Horizon Backscatter Radar," J.M. Headrick and I. Skolnik, *Proc IEEE*, June 1974, p. 664. Remarkable analog processing techniques were developed in the early NRL program.

[6] Earlier OTH coordination meetings had been conducted by ONR.

[7] E.g., AO #32 of 10/14/58 provided nearly $3.5 million to ONR for OTH radar measurements.

Many of the subsequent payoffs are traceable to this early ARPA-sponsored exploratory work, which extended through the early 1960's.[8] One of the earliest of these payoffs was the work by the Stanford research group, separately supported by ARPA, on an approach to long range ICBM raid detection.[9] These efforts formed much of the basis of the AF 440L "forward scatter" system, which began to be operational in the late 1960's, at a critical time when, because of the failure of the AF Midas satellite program, there was a need for an early warning system for detection of a massive missile attack. This relatively simple (and low cost) "forward scatter" system consisted of a set of transmitters in the Far East continually monitored by a set of receivers distributed in Europe. The main technical question regarding the 440L was the ionospheric stability and continuity over the propagation paths. Early field measurements, which incidentally detected some ballistic missile launches, showed that the stability was sufficient for a useful system and developed critical data on false alarms and failure to alarm. The 440L was retired in 1975, after infrared satellite early warning systems were deployed.[10]

Another early result from this same group was the Barry high-frequency sounder, using a low power, continuous-wave, digitally controlled, highly linear frequency-swept signal, (FM-CW). A significant achievement of this digital sweep, due to G. Barry, was that it preserved phase coherence.[11] This technique and the associated digital-processor and receiver equipment was used to obtain high range resolution and select favorable frequencies for OTH radar. Later it became a key part of the AN/TRQ-35V tactical frequency management system for HF military communications.[12] Later experiments by

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[8] Some examples of ARPA projects in this period include: AO # 90, of 5/2/60, for an OTH data collection and analysis center at SRI; AO # 160 for $1.6M to NRL for "Music Madre Radar Program," including modification of doppler processing to detect accelerating rockets and exploration of long range ducted propagation; AO #196 of 1/61 to explore the potential of longer range multihop HF backscatter; AO # 299 of 1/11/62 exploring "Sky Waves."

[9] AFCRL had similar ideas, and was conducting experiments under project CAME BRIDGE, but Dr. Fubini of DoD was more impressed with the Stanford approach and data, and prescribed that it be used. AFCRL news release 5/68 and discussion with Dr. Villard, 7/88.

[10] "History of Strategic Defense," by C.W. Maust, et al., SPC Report 742, 1981, p. 3.

[11] The digital sweep generator was originally suggested by Villard when the Hewlett-Packard digital frequency synthesizer became available. The modification to a coherent synthesizer by Barry was later adopted by Hewlett Packard. Communication from O.G. Villard 1/90.

[12] Acceptance of the Barry Sounder, which became a commercial product in the 1960's, was based on AF trials in the early 1970's. Cf. "Real Time Adaptive Frequency Management," by Robert B. Fenwick and Gerard J. Woodhouse, in "Special Topics in HF Propagation," ed. V.J. Cayce, NATO AGARD Congress Proceedings, # 263, 1979, pp. 5-1 to 5-14. Earlier Navy poor experience with a major investment in other HF sounders led to rejection of the Barry Sounder for nearly 10 years. Discussion with Dr. G. Barry 4/5/88.

the Stanford group demonstrated the advantages of this digital-linear FM-CW signal format for OTH backscatter radars, and the same signal format is now used in the OTH backscatter systems being deployed by the Air Force, Navy, and Australians.

During this same period, the NRL OTH group continued work on the MUSIC-MADRE experimental OTH pulse-doppler radar. In 1960, ARPA funds provided for modification of NRL doppler processing to improve detection of high acceleration missile targets, and for development of other techniques. ARPA support was very important to the NRL project because the air defense motif for the NRL work waned in the late 1950's and early 1960's due to the priority attention then being given to ballistic missile defense.[13] The long-range air-defense motif returned strongly, however, in the late 1960's. This motif was largely responsible for the fact that OTH remained in ARPA when DEFENDER was transferred to the Army in 1967.

In 1963 the Air Force proposed and OSD accepted, in principle, a future Air Defense modernization program, including AWACS and OTH backscatter radars.[14] In 1967 also, a DoD DSARC decision affirmed CONUS air defense as an objective for OTH.

In the mid 1960's to early 1970's, performance limits of wide aperture non-rigid HF antenna technology were tested by the Stanford group with ARPA support. The NRL-OTH radar, which made most of the earliest backscatter detections, used a rigid antenna to avoid spurious doppler effects during long integration times. It was not certain how much could be done with wider but less rigid antennas. The Stanford Wide Aperture Research Facility (WARF), with a 2.5 km aperture, much wider than any before attempted (see Fig. 1) was constructed in 1966, mainly with ARPA support.

The WARF width was determined after a number of experiments, together with practical enginering considerations.[15] Initially, the low-powered WARF was not expected to detect aircraft.[16] However, high resolution in azimuth and range was found possible using the WARF, which, together with sophisticated digital processing of the highly linear digital FM-CW signal, allowed detection and tracking of aircraft and the systematic study of this capability as functions of radar parameters. The WARF experiments established

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[13] A.O. 160 of 6/60 to NRL for Music Madre. The additional support is credited with getting the MADRE system completed in Gebhard, ibid., p. 126. See also "History of Strategic Defense," ibid., p. 9.

[14] Communication from Dr. A. Flax, IDA, 2/90.

[15] Support of WARF was also given by ONR.

[16] Discussion with Dr. L. Sweeney of SRI, 4/6/88.

many benchmarks for performance for later systems, and also laid the basis for automatic detection and tracking techniques. This technology was transferred effectively, and informally, in the regular OTH symposia run by the ARPA program director. In particular, the Air Force adopted the FM-CW signal format and separate transmitter and receiving antennas for its future OTH radars in the early 1960s, for their 441B and 118L systems.

In 1967 ARPA began to plan project BIG PUSH, aimed at an experimental system embodying the state of the art of pulse doppler and FM-CW technology, with flexible characteristics enabling detection and tracking of a variety of targets, including ballistic missiles at long ranges, and aircraft. BIG PUSH incorporated high

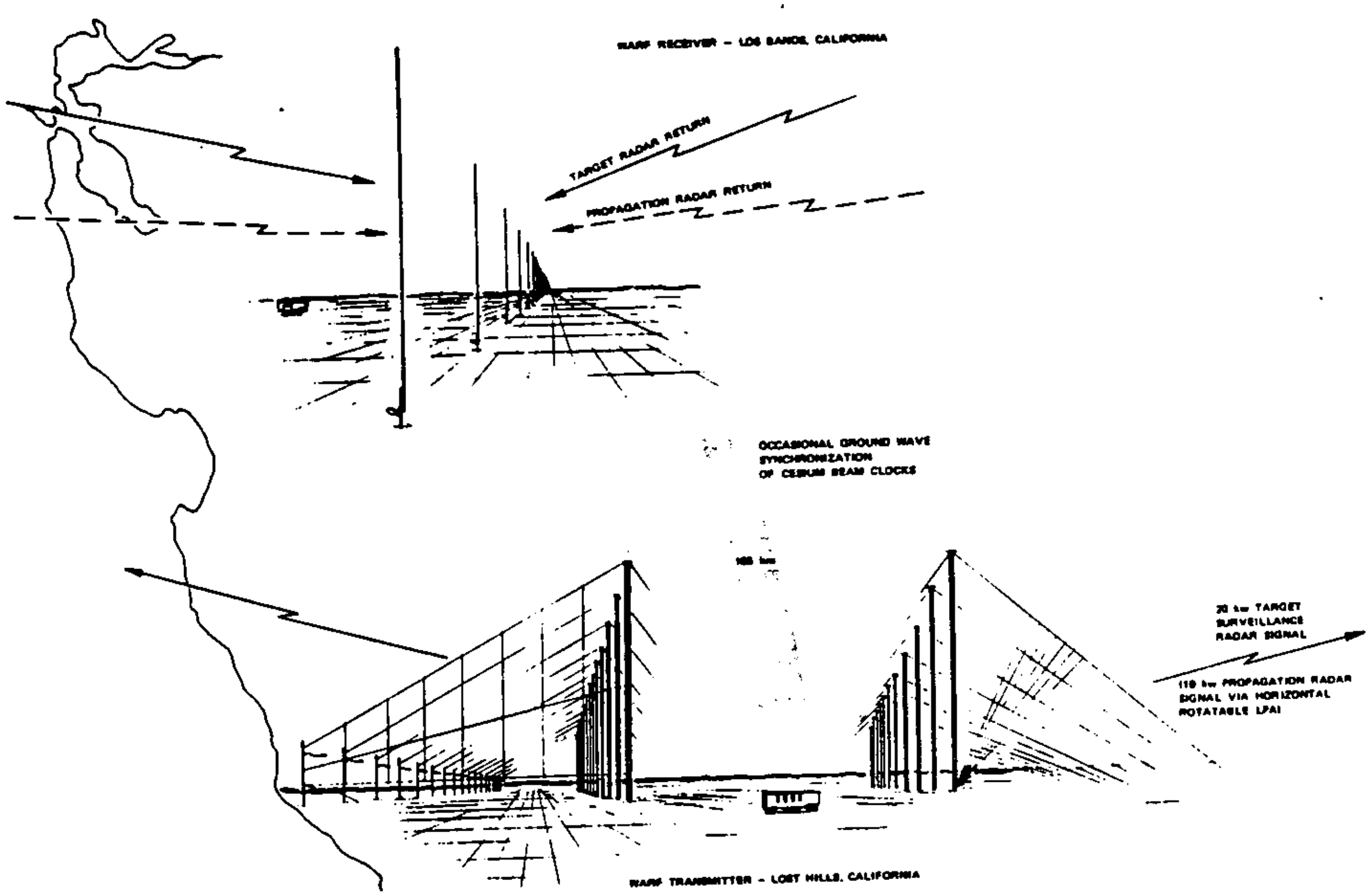

Figure 1. WARF System

power and a variety of waveforms, the highest aperture achievable and up to date digital processing. However, BIG PUSH was not approved by DoD, on the grounds that the Air Force's large FPS-95 radar project was then under way, and DoD could not have two large competitive OTH research projects at the same time. The FPS-95 was a high power pulse doppler system with a unique antenna, and was turned off after a short period of unsuccessful operations. The FPS-95 experience had quite a negative impact for some time on much DoD thinking about the eventual utility of OTH.[17] ARPA, however, continued its OTH program, albeit somewhat reduced, despite the unfavorable climate.

In the early 1970's WARF experiments also examined the potential of OTH for sea state and wind patterns determination. This led to demonstrations in the late 1970's of the WARF's ability to remotely track hurricanes in the Gulf of Mexico.[18] Later, taking advantage of HF propagation management possible with new processing capabilities to isolate single propagation modes, ships were detected using the WARF.[19]

The ARPA program turned, in the early 1970's, to the problem of evaluating risks for OTH for detection of aircraft in the higher latitudes, with the singular auroral and polar cap ionospheres. A strong motive for this investigation was the fact that CONUS air defense would have to deal with this northern section. A number of experiments were performed, and analyzed under the joint ARPA-Air Force "Polar Fox"[20] experiments, which explored the capabilities of OTH backscatter radars, both pulse-doppler and FM-CW, in the mid to higher latitudes, and auroral ionospheric regions marked by spurious reflection and propagation. A somewhat later project, "Polar Cap," explored these capabilities in the polar ionospheric region, within the Auroral ring, marked by irregularities and absorption. The results of these experimental projects were used for the assessment of the statistical probability of detection in these regions by OTH systems, which because of the large scale coverage would have many opportunities during a large air attack. The results affected the later decisions on siting and orientation of CONUS OTH air

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[17] Discussion with Dr. C. Cook, ex-ASD for Defensive Systems, 12/89.

[18] "High Frequency Sky Wave Radar Measurements of Hurricane Anita," by Joseph W. Maresca and Christopher T. Carlson, *Science*, Vol. 209, 12 Sept., 1980, p. 1189.

[19] "Ships Detection With HF Sky Wave Radar," J.R. Barnum, (IEEE) *Ocean Engineering*, Vol. OE11, No. 2, April 1986. Large ship detections were first demonstrated by NRL in 1967, See Ref. 4. The ARPA support to NRL was key to development of a digital filter that was used for these detections. Discussion with J. Headrick, NRL 6/88. During WW II, U.K. researchers apparently considered OTH radar for detecting convoys. Communications from O. Villard, 1/90.

[20] E.g., AO 1765, of 1/71.

defense radars generally away from the auroral regions.[21] Data from these northern experiments were also valuable for assessment of effects of high altitude nuclear explosions on military HF systems for communications and OTH. Increasing appreciation of the air threat to CONUS provided motivation for the Air Force finally going ahead with OTH backscatter systems for CONUS defense in 1975.[22]

DARPA formally transferred their OTH program to the Air Force in 1975. After its FPS-95 experience mentioned above, the Air Force decided to adopt the DARPA-generated FM-CW signal format with high average power and large bandwidth together with a wide aperture for their OTH backscatter radars. With General Electric as contractor, RADC built and operated a demonstration model OTH radar in the early 1970s, which detected and traced aircraft at long ranges over air and water.[23] In 1975 the Air Force awarded a contract to General Electric for construction of an experimental OTH radar which was a prototype for continental air defense. Tests with this OTH radar were successfully completed in 1981. Since then several sections of the Air Force CONUS OTH FPS-118 systems have been constructed and are approaching operational status.[24] Figure 2 shows one of the hardened FPS-118 prototype transmitter antenna fields.

In the early 1970s, because of growing appreciation of the BACKFIRE threat, the Navy began to be interested in long-range detection for fleet air defense. Later a number of Navy Integrated Tactical Surveillance System (ITSS) studies were conducted which indicated that satellite capabilities for this purpose were not likely to be available before the 1990's, but that OTH B backscatter radar technology, deployed to forward areas, might satisfy the need until then. In the late 1970s, after demonstration of ship detection, the Navy interest increased, and DARPA technology, especially in antenna systems, signal format and signal processing, played a major role in the design of the Navy relocatable ROTH-R system now in full-scale development. Figure 3 shows an ROTHR transmitting antenna field, similar to that of the WARF.

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[21] However, the Air Force now plans to deploy an OTH backscatter radar in Alabama to cover the "North Slope" BACKFIRE attack corridor.

[22] Discussion with Dr. C. W. Cook, ex-ASD for Defensive Systems, 2/89.

[23] Communication from Gen. J. Toomay, 1/90.

[24] See Ref. 1, and also "Warning and Assessment Sensors," by MG. John C. Toomay, USAF (Ret.) p. 292, in *Managing Nuclear Operations*, by Ashton B. Carter, et al., Brookings, 1987.

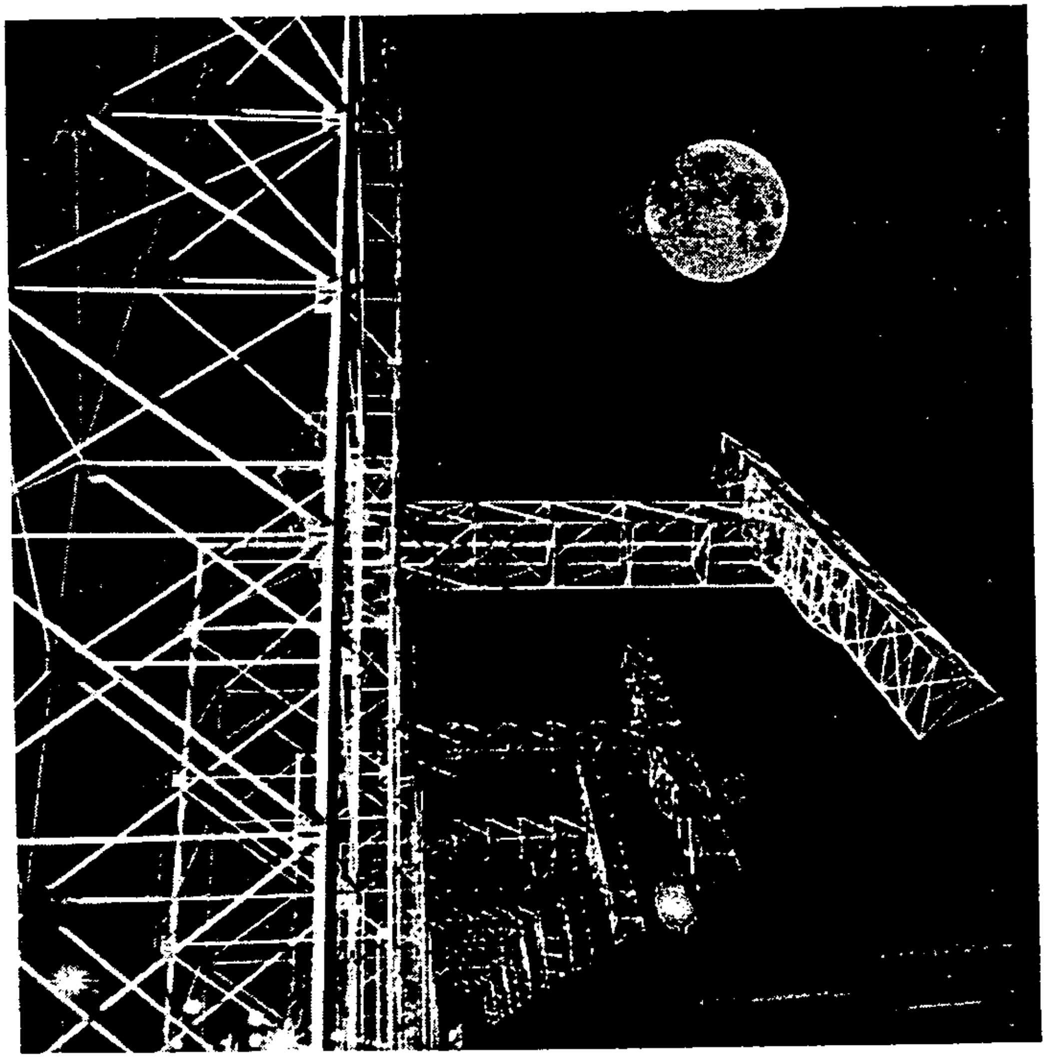

Figure 2. FPS-118 Antenna

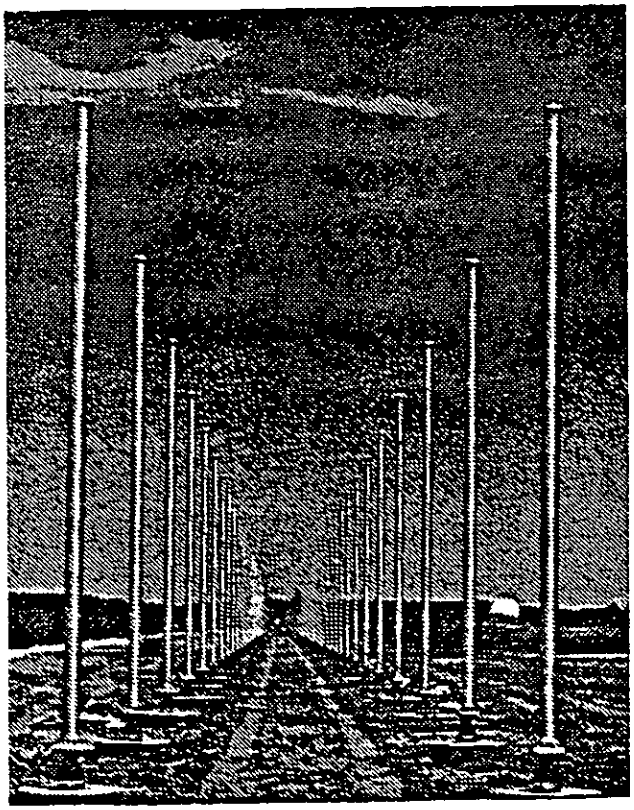

Figure 3. Relocatable Over-The-Horizon Radar (ROTH-R) Transmitting Antenna Field (From Director, OTE, Report to Congress, FY 1987)

Australia had a small OTH program dating from the late 1950s. Early experiments using bistatic HF CW radar systems took place in the joint ARPA-Australian ballistic missile experiments in the early 1960's at the Woomera test range. As a result of an initiative by the Australians, a specific U.S.-Australian cooperative program in OTH began in the early 1970's,[25] and DARPA established an office in Australia to facilitate the transfer of OTH technology to that nation's JINDALEE experimental OTH radar. Construction of the Australian operational OTH system based on JINDALEE is planned for Spring 1990.[26]

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[25] "The Development of Over-the-Horizon Radar in Australia," by D.H. Sinnott, Australian Government Publishing Service, 1988.

[26] See Ref. 3, and "The JINDALEE Over-the-Horizon Radar System," by R.H. Sinnott, paper at the conference on Air Power in the Defense of Australia, 14-18 July 1986, Australian National University. See also *Aviation Week*, May 11, 1987. JINDALEE means "Bare Bones" in Aborigine, which Sinnott says characterizes the effort.

There were also unsuccessful attempts by ARPA to explore use of other parts of the electromagnetic spectrum for OTH purposes, including the VLF and VHF range. Ionospheric modification by high-power HF transmitters was also tried in the attempt to generate or modify reflecting ionospheric conditions.

OTH technology, while now considered mature, is still undergoing some development, paced again by advances in data processing and networking technology, and by improvements in understanding of the complexities of the ionosphere.

C. OBSERVATIONS ON SUCCESS

DARPA's OTH program began as an approach to early warning of missile attack under project DEFENDER. It was built on earlier Service programs. While it began under DEFENDER, it did not receive as much attention as the terminal defense DEFENDER programs. Like HF communications, OTH was widely regarded as partly unreliable, particularly in the event of nuclear exchanges, which were a major consideration in DEFENDER. However, it seems to have been one of only two DEFENDER programs that led directly to a deployed system for warning of ballistic missile attack, in this case the 440L.[27]

Sustained support of a very strong Stanford (later SRI) Group under Villard proved highly productive. Timely ARPA support was provided for the 440L and related developments in a period of crisis for ICBM attack warning. Later ARPA provided continuous backing through a long period of OTH technology development for air defense, which returned to high priority in the late 1960's. Out of this sustained effort came two of the key technologies used today, although these were considered risky for many years.[28] The first of these were digital linear frequency sweeping to generate a coherent frequency modulated-continuous waveform (FM-CW), (applied also with some delay, in the TRQ-35V system). Secondly, the program demonstrated the utility of high resolution obtained by very wide aperture, less than rigid antenna systems. This demonstration took many years, which was necessary to get statistical information on propagation stability. Not only the frequency sweeping, but all the processing technology in OTH was greatly assisted by the general advances in digital processing technology which occurred during the same time period, and were quickly applied to OTH by Stanford and the other ARPA contractors.

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[27] The other was ESAR, which led direcly to the Air Force FPS-85, still used partly for SLBM warning.

[28] Communication from T. Croft, 1/90.

The productivity of the Stanford (now SRI) group is attributed by them largely due to ARPA's continuous long-term support and "light handed" management.[29]

The ARPA BIG PUSH OTH program was an attempt to construct a state of the art research system. Apparently, part of the motif was to test the relative performance of FM-CW versus pulse doppler technology. It was stopped by DoD because of the large Air Force (pulsed) FPS-95 OTH radar program then under way. The FPS-95 was a result of a "parallel" RADC OTH program, which was recognized as a dangerous competitor, but apparently not strongly opposed by ARPA.[30] Because of BIG PUSH's cancellation the ARPA program transferred key technologies, and not a system.

The long series of ARPA's OTH coordination meetings led to an effective, if informal, transfer of these technologies to the Air Force and later to the Navy. There were always some elements of competition in the DARPA OTH program, between pulse doppler (NRL, Industry) and the FM-CW techniques assessed by the Stanford group. Eventually the Stanford combination of FM-CW waveform and wide aperture was agreed on by the community involved as the preferred approach. The unsuccessful experience with the FPS-95, a pulse doppler system, was crucial to the final decision by the Air Force to adopt the FM-CW waveform approach. ARPA's POLAR experiments provided opportunities to demonstrate the capabilities of OTH technology, both pulse doppler and FM-CW, and provided and key ionospheric information for Air Force decisions on OTH for CONUS air defense in the early 1970's.

The Stanford-ARPA WARF technology, while not itself a prototype for the Navy's ROTHR systems, provided most of the essential technology for that system. The Navy's interest in long range air defense was in reaction to the BACKFIRE threat, and its decision to go ahead with ROTHR came only after its extensive ITSS studies indicated that adequate satellite systems would not be available until nearly the end of the century.

Increased appreciation of threats to CONUS from aircraft which could launch cruise missiles provided an additional challenge to this technology. The OTH air defense technology appears to be meeting a timely need, at least until satellite systems such as TEAL RUBY also largely developed with other DARPA-support, can be tested and deployed. The Air Force estimates its 118L system to be useful for more than 25 years.

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[29] Discussion with L. Sweeney and T. Croft, 5/88 and O.G. Villard of SRI, on 7/88.

[30] Discussion with J. Kane and E. Lyon, 1/90. ARPA's Navy agent, however, did express opposition to the FPS-95.

In retrospect, the dedication and management skill of a single ARPA (and DARPA) OTH program manager, Alvin van Every, throughout the 1958-1975 period, can be credited for much of the program's success.[31]

DARPA-developed technology formed the basis for the Australian air defense system, facilitated by van Every's going there personally as DARPA's representative in 1975. Some experts feel the Australian system has profited from more recent data on performance of the U.S.' OTH radars, and may be a more advanced system when built.

The total ARPA expenditures for OTH appear to have been about $100 million. The Air Force 118L east and west coast systems cost exceeds $1 billion, and the ROTHR cost is estimated as more than $1 billion dollars.[32] The fact that the ARPA programs had a large academic component, which was low cost, and that there was a single ARPA manager throughout, may have had an impact on the scale of the expenditures. Not everything tried in the DARPA-OTH program worked, but "poor horses" were generally soon abandoned.

The Soviets have published two books on OTH technology, the latest of which has been transcribed in the U.S. and refers extensively to results of U.S. OTH research.[33] The Soviets large "WOODPECKER" OTH radar system, however, apparently does not use FM-CW signal modulation technology, and causes much interference in the HF radio bands.[34]

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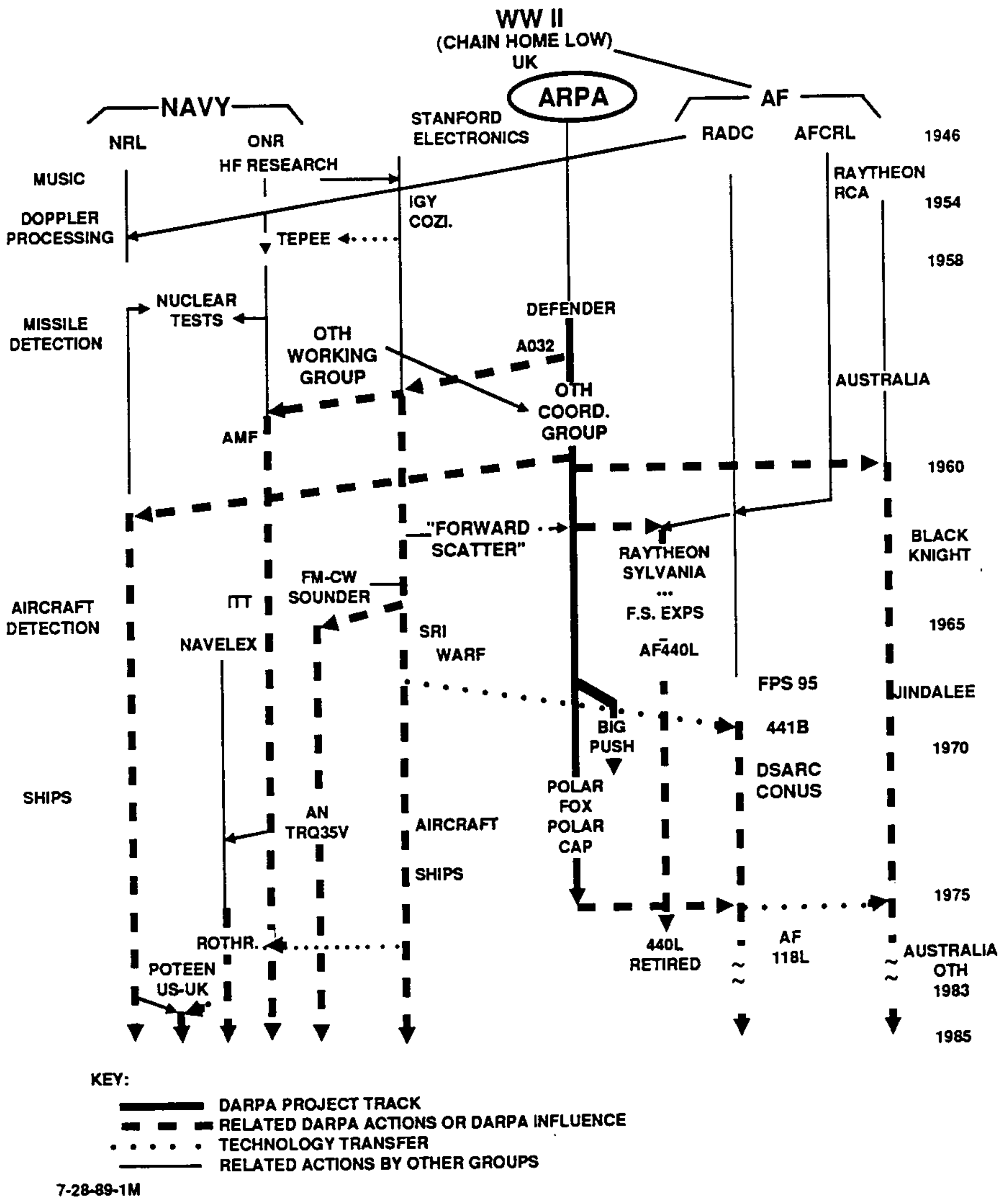
[31] Van Every had also been a graduate student under Villard.

[32] HASC DoD Appropriations Hearings, 99th Congress, 2nd Session, Part 3, 1987, p. 620.

[33] *Over the Horizon Radar*, by A.A. Kolosov, et al., Artech House, 1987.

[34] *Short Wave Listening With the Experts*, by Gary L. Dexter, H. Sams Co., 1986, p. 181.

OVER-THE-HORIZON RADAR



X. AMOS: ARPA MIDCOURSE OPTICAL STATION

A. BRIEF OVERVIEW

AMOS (ARPA Midcourse Optical Station) was initiated by ARPA in 1961 as an astronomical-quality observatory to obtain precise measurements and images of reentry bodies and decoys, satellites and other space objects in the infrared and optical spectrum. Located at nearly 10,000-ft altitude atop Mt. Haleakala, Maui, Hawaii, AMOS served as a unique facility for operational measurements and R&D from the early 1960's. AMOS' twin infrared telescopes were transferred to Air Force in the late 1970's as MOTIF: the Maui Optical Tracking and Identification Facility, now regarded as one of the primary sensors of the Air Force Space Tracking System. Transfer of the optical telescope and the remainder of a highly automated AMOS to the Air Force took place in 1984.

B. TECHNICAL HISTORY

The concept of AMOS was originally proposed in 1961 by R. Zirkind of the ARPA staff as an astronomical-quality facility for imaging reentry bodies and other space objects in the infrared, and for performing research in infrared astronomy. Information on the infrared emissions from reentry bodies in midcourse, expensive to obtain in space, was needed particularly for assessment of detection and discrimination systems then under study in the BAMBI and PRESS projects under ARPA's DEFENDER program. The location selected for AMOS, at about 10,000 ft altitude near the top of Mt. Haleakala, the largest dormant volcano crater in the world, was above most clouds and most of the infrared-absorbing water vapor in the atmosphere. The site was also expected to have very good astronomical "seeing." For similar reasons the site had been selected previously for one of the Baker-Nunn Satellite Cameras used to track satellites during the IGY.[1] The AMOS location was favorable for observation of reentry vehicles and decoys, missile bodies and other objects over a considerable portion of the midcourse range of sub-orbital trajectories between the Vandenberg missile launch site and the main reentry location at

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[1] "Trackers of the Skies," by E. Nelson Hayes, Howard Doyle, Cambridge 1968, p. 33-34. The University of Hawaii operated the Baker-Nunn telescope for the Smithsonian Astrophysical Observatory.

Kwajalein. The low-latitude location was also advantageous for observations of satellites. AMOS was conceived initially to include two high quality telescopes, one for use in the infrared and the other in the visible spectral region, with precision mechanical mounts and computer-controlled drives.

Zirkind had a strong desire also to exploit, part-time, the capabilities of such a system to open a new field of astronomical research in the infrared.[2] Dr. J. Ruina, ARPA director at the time, gave his approval to the project, provided the astronomical community agreed it was a good idea, and would actually do research with AMOS. A meeting of several prominent astronomers was held at Harvard's Smithsonian Astrophysical Observatory in Summer 1961, at which it was agreed that AMOS' planned infrared observing capabilities and its location further south than then existing U.S. observatories, were indeed of interest in astronomy. The conclusions of this meeting, and the results of a careful investigation of astronomical "seeing" a little later by one of the participating astronomers (G. Kuiper), which indicated that resolution of the order of 0.1 seconds of arc was often attained, led to further plans for an additional, somewhat larger telescope at AMOS for use in the optical spectrum.

The AMOS effort formally began with Amendment No. 2 to an existing ARPA Order 236, to the University of Michigan's Institute for Science and Technology, for telescope design, construction, and eventual operation of the observatory.[3] The ARPA order amendment stated the AMOS objectives as: (1) "Identification and signature of space objects; (2) an active program to advance the state of the art of infrared technology and high-resolution imagery; (3) a research program in geophysics and astrophysics including the astronomical community." The Department of Astronomy of the university was involved in the initial design studies for AMOS. The previously mentioned "seeing" investigation was one of the first subcontracts, and was facilitated by the existence of the existing IGY-Smithsonian Baker-Nunn telescope at the site. The AMOS site was leased from the University of Hawaii. The original terms of the lease provided for operation of the AMOS Observatory facility by the University of Michigan, and after 10 years use when

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[2] "Project AMOS: An Infrared Observatory," by R. Zirkind, *Applied Optics*, Vol. 4, 1965, p. 1077, and discussion with R. Zirkind, 11/88.

[3] AO 236 of 6/61 for BAMIRAC had been set up with the University of Michigan previously for a broad set of responsibilities connected with data for ballistic missile defense largely in the infrared. Amendment # 2 was for $8.3M.

construction and shakedown were expected to be completed, it would be turned over to the University of Hawaii.[4]

Soon after these initial steps by ARPA, a directive arrived from Harold Brown, then DDR&E, giving space object identification (SOI) and tracking a high priority in DoD. Since AMOS' capabilities were designed for this purpose, its funding was increased. The University of Michigan undertook the design of two 48-in. infrared telescopes, on a common mount and shaft, one mainly for tracking and the other for special observations, and of a 60-in. telescope separately mounted, mainly for work in the optical spectrum. Design was completed in 1963 and construction of the foundation and buildings commenced by the Army Corps of Engineers.[5] The Corps constructed the entire facility except for telescopes and domes. The three high quality mirrors were completed to diffraction limited tolerances, successfully and at quite low cost. Special coatings were added to the IR mirrors to enhance reflectivity over the 1-30 micron range. Telescope mounts were of cast steel, a bit unusual, since most astronomical mounts involve welded pieces. This decision was made by ARPA, and the risk accepted to reduce costs. Successful casting saved $1M.[6] The bearings were formed with very close tolerances, in order to allow the desired pointing and tracking accuracy of ~ 1" arc at angular rates required to track satellites and reentry objects. No telescopes of this size and weight had previously been constructed to the tracking specifications of AMOS.[7] However, the only hitch that developed in the construction occurred in the domes, which also had to have rapid motion capabilities, something new for such structures. A separate contractor made the first domes, but these were found to vibrate excessively. The previously helpful astronomers pitched in again to correct the problem.[8] Considerable re-work was involved, which caused an overrun, in turn forcing cancellation of plans for advanced instrumentation, which included, in 1964, an interferometric spectro-radiometer and computer-controlled articulated mirrors.[9]

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[4] The initial lease was for 25 years from the University of Hawaii, beginning in 1963, R. Zirkind, ibid.

[5] AO 389 of 8/62 and 482 of 5/63 to the Army Corps of Engineers.

[6] Discussion with R. Zirkind 11/88.

[7] The Baker-Nunn satellite tracking camera was smaller and lighter with 20" aperture, and achieved a tracking accuracy of about 2". "The Baker-Nunn Satellite Camera," by Karl Heinze, *Sky and Telescope*, Vol. XVI, Jan. 1957, p. 3. This system also had several successes in SOI, see e.g., Hayes, loc. cit., p. 121-2.

[8] A. Meinel of the University of Arizona was particularly helpful. Discussions with R. Zirkind 11/88.

[9] R. Zirkind, ibid.

Construction of AMOS was completed by 1967. Between then and about mid-1969 there was an initial phase of evaluation, calibration and testing of the telescopes' computer control and tracking algorithms, and of the associated infrared arrays, radiometric, photometric and imaging equipment. A data link with a radar at another location in the Hawaiian area was established, to facilitate tracking.[10] As originally envisioned, astronomical objects were used for calibration. Initial attempts were made with some success to acquire and track satellites and other space systems. An early success was a photograph and tracking of one of NASA's APOLLO modules.[11]

Figure 1, from a current Air Force brochure,[12] shows pictures of the telescopes, housed in the largest dome shown in Fig. 2, which also exhibits other features of the AMOS facility as it is today. The optical systems provided for several instrument mounting platforms for different detection and imaging systems. Both IR and optical systems had long focal lengths to allow fine image definition.

A second data link with a tracking radar on another island was established, and this and other radars were relied upon, together with information from the NORAD network for initial tracking inputs. A low-power ruby laser was also installed, as a first step toward a laser radar target illumination technique.

By 1969 the quality and potential of AMOS had been demonstrated and a second phase began in which the Air Force became the ARPA agent. The Air Force also began to support projects to measure properties of reentry bodies at the facility under its ABRES project. The University of Michigan was replaced, as AMOS manager and operator, by industrial contractors, AVCO and Lockheed.[13] Computer and software advances further improved tracking capabilities. In the early 1970's advances in semiconductor state of the art allowed a much improved, larger infrared sensor array to be combined with a contrast

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[10] AMOS Advanced Electro-Optical Program, RADC TR-86-215, Feb. 1987, p. 2. This report contains a brief history of AMOS since 1963.

[11] Discussion with Glen Rogers, AMOS, 11/88.

[12] AMOS/MOTIF brochure, undated.

[13] A.O. 2320 of 11/22 and RADC, ibid.

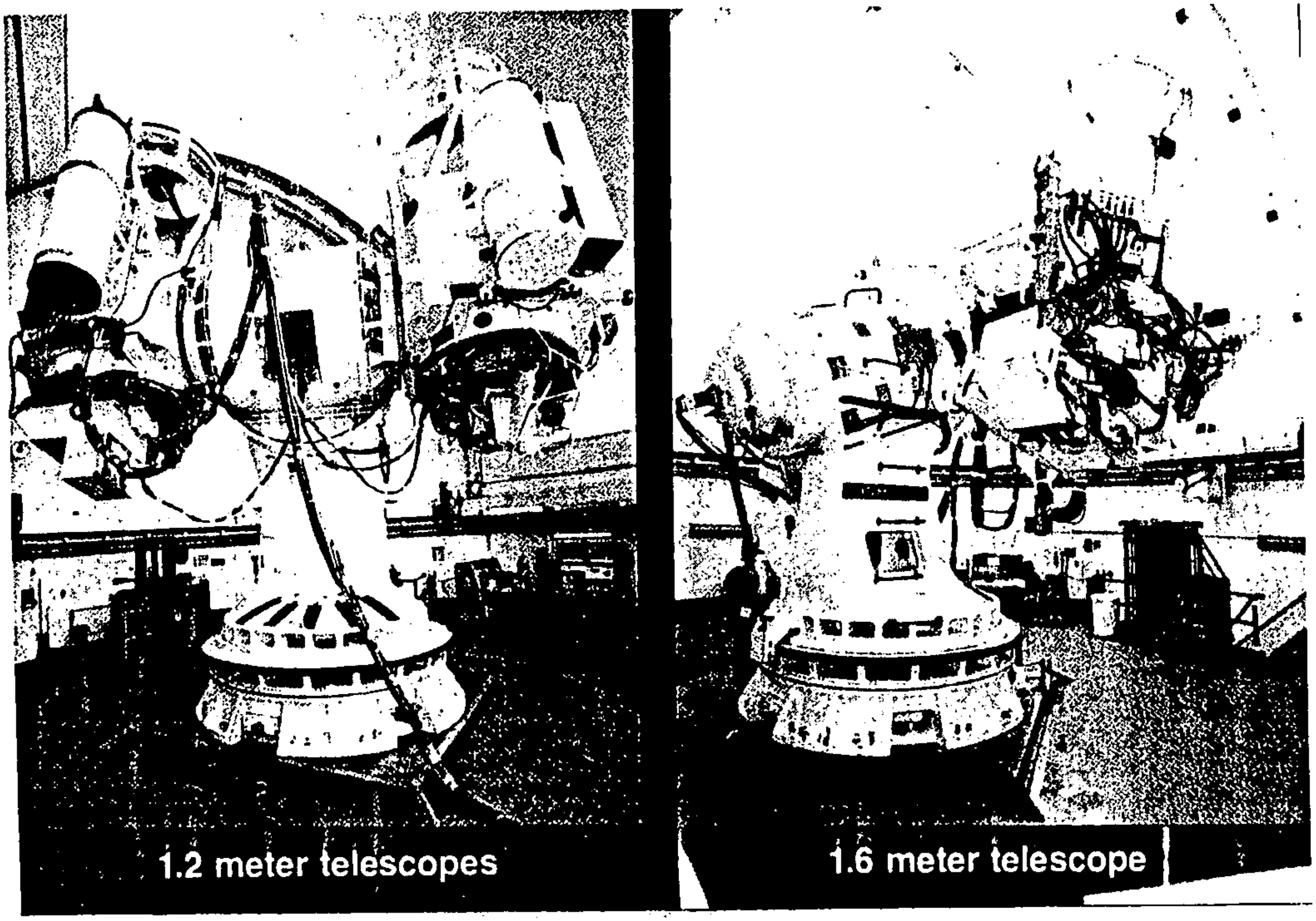

Figure 1. First AMOS Telescopes

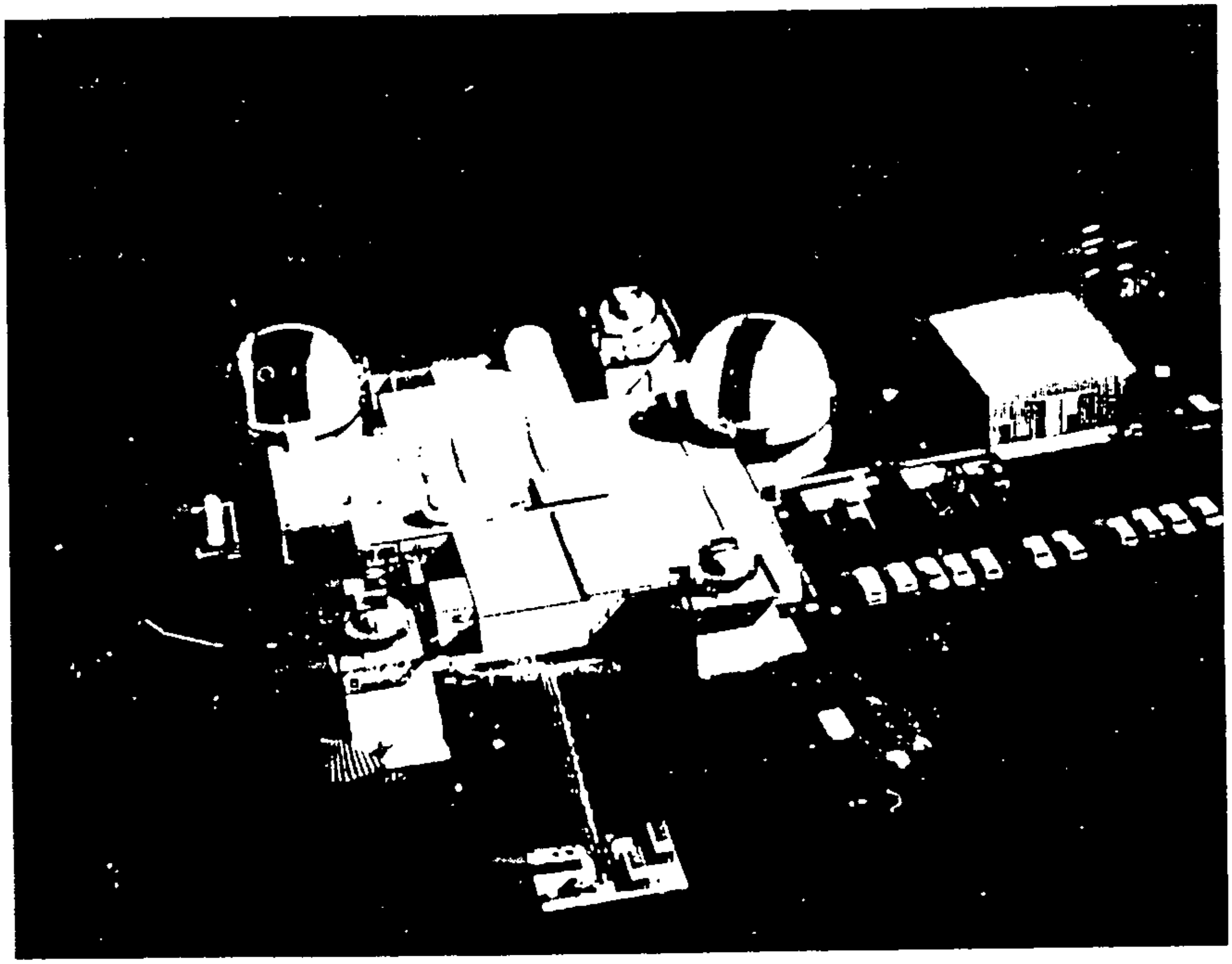

Figure 2. AMOS/MOTIF/GEODSS Observatory Buildings

photometer and television camera in an "Advanced Multicolor Tracking" system. A higher power ruby laser was designed and installed to work with one of the infrared telescopes, to conduct initial ranging experiments. These improvements allowed IR and visible measurements to be obtained on reentering vehicles and penetration aids of the Minuteman Series and on several satellites.[14] Assistance was also provided to NASA to help with problems on the SKYLAB.

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[14] RADC, ibid.

In the late 1970's successful space object measurements continued in the infrared and visible, and laser ranging and illumination experiments began.[15] Eventually, a dedicated laser beam director was constructed. Preparations began for the installation of the ITEK compensated imaging system (CIS) which had also been developed by DARPA, to be used with the 60-in. telescope on low-altitude space objects because of the limited effective field of view.[16] A number of measurements of high atmosphere turbulence related to CIS performance were made. Precision tracking improvements continued, particularly in characteristics affecting hand-off to local and distant tracking systems.

A higher power CO_2 laser was installed and used for experiments for ranging and illumination of more distant objects. In 1979 AMOS' twin infrared telescopes and associated systems became part of the Air Force Space Track Network and was renamed MOTIF: Maui Optical Tracking and Identification Facility.

In the early 1980's DARPA-supported AMOS activity included more detailed measurements of background, high cirrus cloud properties and atmospheric turbulence. Measurements were made on meteor trails in the infrared, and on the core of the M-87 galaxy in the visible.[17] Atmospheric compensation experiments began using Lincoln Laboratory deformable mirror technique for directing a laser through the turbulent atmosphere. Several supporting experiments have been made for SDI in the atmospheric infrared windows.[18] The compensated imaging system was tested and installed on the 60-in. telescope. A LWIR capability was also added to the 60-in. on a side mount, and the 60-in. mirror was coated to improve its IR reflection.

By 1984 AMOS had become a highly automated system, and DARPA transferred AMOS to the Air Force. RADC is now responsible for AMOS' R&D and the Air Force Space Command for the operation of MOTIF. A summary of current AMOS-MOTIF capabilities is routinely issued by the Air Force. SDI now supports a substantial fraction of AMOS' activity.[19]

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[15] E.g., A.O. 2837 of 7/74.

[16] A description of this Itek system is given in the chapter on "Adaptive Optics," by J.R. Vyce and W. Hardy, Chapter 8, p. 101 of *Arms Control Verification*, Pergamon 1986.

[17] *Direct Infrared Measurements of Thermal Radiation From the Nucleus of Comet Bennett*, by James A. Myer, Ap. L., V. 175, 1972, p. L49.

[18] RADC, ibid.

[19] Summary of AMOS-Technical Activities - 1987, RADC TR-87-301, May 1988.

One of the original objectives for AMOS, astronomical infrared research, has been carried out only to a very minor extent.[20] However, academic IR astronomy is now beginning to flourish with several telescopes in the U.S. and also at Mauna Kea (near the active volcano). What has caused this area to bloom is the availability of larger IR focal plane arrays, developed largely with DARPA support. Some of these arrays had been tested at AMOS.[21]

Suggestions have been made by some members of the astronomical community, notably the Meinels (who have been involved with AMOS from the beginning) to begin planning for larger (10-meter range) aperture, computer-controlled, articulated mirror telescopes for the next-generation AMOS.[22]

C. OBSERVATIONS ON SUCCESS

AMOS was an ARPA initiative to construct an astronomical-quality facility for observations of satellites and for astronomical research. The Air Force had used the IGY's Baker-Nunn telescope-camera for satellite observations, but AMOS was to be a larger, more complex and heavier telescope, with angular tracking quality at least as good as the Baker-Nunn. The step to construct AMOS was considered risky at the time, but not excessively so by competent astronomers, who were interested enough to provide help with design at the early and later stages of the project. The sudden increase in priority for satellite observation techniques enabled AMOS construction and use to proceed quickly. An academic contractor, University of Michigan, built the telescope. Initial plans were to turn AMOS over to the University of Hawaii, after ten years operation. After its construction, however, operational use of AMOS became predominant, and the plans for academic uses were on the one hand awkward, and on the other hand academic groups were, at the time, distancing themselves from military-related programs. Industrial operation of these facilities was therefore considered more appropriate.

Over a nearly 20-year period AMOS has met its primary objective of serving as a unique facility for electrooptic R&D and operational use, and is now considered a national asset. During this time many advances in electrooptic and related technology developed by DARPA have been efficiently tested and used at AMOS. A key feature was that

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[20] Discussion with James Myers, Photon Research, Inc. 11/80. See Fn. 17.

[21] See e.g., "Astronomical Imaging With Infrared Array Detectors," by I. Gatley, et al., *Science*, Vol. 242, 2 Dec. 1988, p. 1264.

[22] "Summary of AMOS Technical Activities 1987" ibid., p. 16.

astronomical objects of known brightness and spectral characteristics could be used for calibration purposes. The success of AMOS is attested to by its past and current use for reentry and penetration aids studies by the Services and SDI, and as a part of the AF Space Track Systems. While DARPA support is now in the mode of support of "users," the challenges in the operational areas do not seem to have diminished.

While the original objective for AMOS also included astronomical research, this has occurred only to a very minor extent, for reasons outline above. AMOS, however, has been a unique test bed for focal plane arrays developed by DARPA, which have made a substantial contribution to the presently blooming field of IR astronomy.

After its initial demonstration of operational capability, transfer to the Air Force occurred gradually. The Air Force has collocated at the AMOS facility three of its GEODSS systems, developed also partly with DARPA support,[23] to automatically detect and track satellites at geosynchronous distances.

The initial AMOS facility cost appears, from project records, to have been approximately $12M. The cost of the later phases, including operations and improvements such as the CIS, and support of AMOS operations for some DARPA R&D projects, appears to be about $90M.

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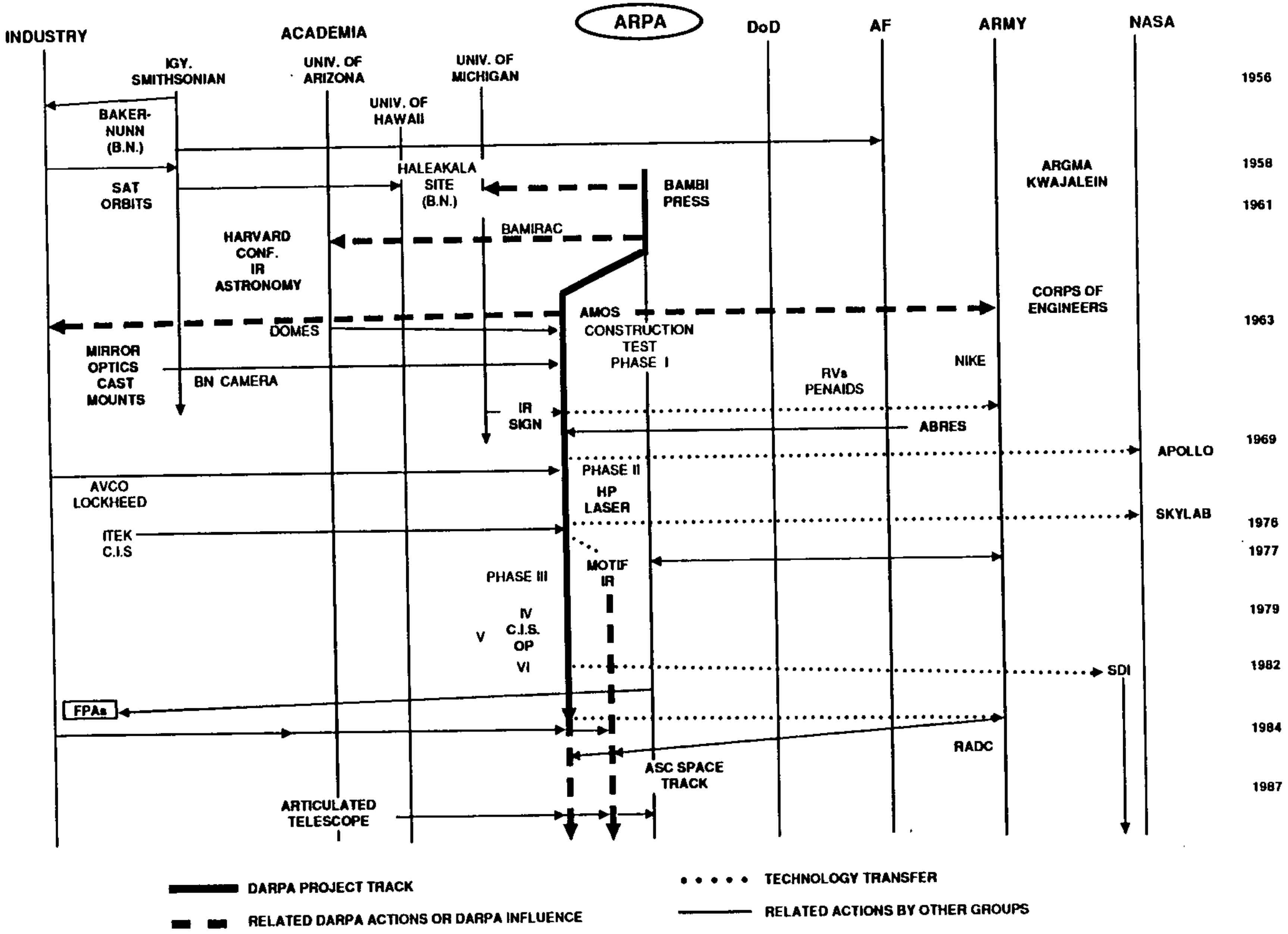
[23] AMOS user's manual, RADC.

AMOS



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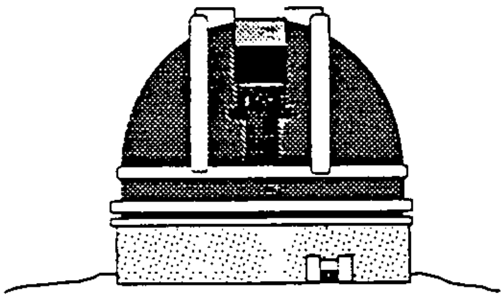
ANNEX
AMOS/MOTIF FACILITY CAPABILITIES



U.S. AIR FORCE OBSERVATORY
MT. HALEAKALA, MAUI, HAWAII

AMOS/MOTIF FACILITY CAPABILITIES

The Air Force Maui Optical Station (AMOS), and the Maui Optical Tracking and Identification Facility (MOTIF) are co-located at an altitude of 10,000 feet on the crest of Mt. Haleakala, located on the island of Maui, Hawaii. This high altitude location is characterized by a relatively stable climate of clean, dry air. The low levels of particulate matter and absence of significant scattered light from sea-level sources provide excellent conditions for the acquisition and viewing of space objects. The facility was constructed during a two year period beginning in 1963. During the past twenty years, the site has evolved to its present configuration, which includes four primary optical testbeds: the 1.6-meter telescope, the dual 1.2-meter telescopes, the Laser Beam Director (LBD), and the Beam Director/Tracker (BD/T). These four optical telescope systems, along with the facility's sensors and computer resources, form the basis for both the Air Force Systems Command's (AFSC) AMOS Program, and for the Air Force Space Command's (AFSPACECOM) Spacetrack MOTIF program. Both organizations share the facility. AFSPACECOM maintains and operates the site as facility host; and AFSC, through it's executive agent, the Rome Air Development Center (RADC), is the tenant supporting measurement programs, special testing, and visiting experiments.

The AMOS 1.6-meter telescope is one of the finest optical instruments of its size in the world. In the absence of atmospheric-induced image distortion, the telescope permits diffraction limited performance (approximately 0.1 arcsecond resolution, or 1 ft. at a distance of 500 miles) at all mount attitudes above the horizon. The clear aperture is 1.57m and the effective focal length is 25m. Broadband mirror coatings (Al plus an SiO overcoat) allow spectral coverage from the visible through the LWIR. The telescope is attached to an equatorial mount on an azimuth turntable. The mount has hydrostatic bearings, 23-bit shaft angle encoders on each axis, and is servo-driven by direct current torque motors under control of a Harris 500 computer. This system allows absolute pointing to ±2 arcseconds and tracking to ±1-3 arcseconds (depending on target velocity) at tracking velocities up to 2 degrees/sec and accelerations to 2 degrees/sec^2. An acquisition telescope with three switch-selectable fields of view is mounted piggyback on the north face of the 1.6-meter telescope.

Two instrument mounting surfaces are available for sensor packages on the 1.6-meter telescope. The rear surface is currently dedicated to the Compensated Imaging System (CIS), an adaptive optical device that compensates in real-time for atmospheric turbulence-induced distortion of satellite images. The side surface supports a sensor package which currently includes the Enhanced Longwave Spectrometer/Imager (ELSI), which is a dual infrared acquisition/imaging array, and the AMOS Spectral Radiometer (ASR), which is a 26 detector element MWIR/LWIR radiometer. An 8000 element Platinum Silicide (PtSi) infrared Charge Coupled Device (CCD) is also included for infrared imaging in the 3-5 micrometer spectral band. A sensitive Intensified Silicon Intensifier Target (ISIT) Camera is also present in the package.

The AFSPACECOM 1.2-meter telescope complex represents a unique capability which functions as a fully integrated sensor in the Spacetrack Network. Two 1.2-meter telescopes are mounted on opposite sides of a single polar axis, and are fixed to a common declination axis. The mount shares the same operating systems and performance parameters as the 1.6-meter mount. Both 1.2-meter telescopes are classical Cassegrain optical systems, having parabolic primaries and hyperbolic secondaries. One telescope (B29) has a back focal distance of 29 inches, a relative aperture of f/20, and a focal length of 24.5m, while the other (B37) has a 37 inch back focal distance, a relative aperture of f/16, and a focal length of 19.8m. Both telescopes have primary mirror support systems which incorporate air bags for axial support and mercury filled belts for radial support. An acquisition telescope is mounted piggyback on the B29 telescope.

There are three mounting surfaces on these telescopes, one on the B29 telescope and two surfaces on the B37 telescope. The B29 houses the Advanced Multicolor Tracker for AMOS (AMTA), a square array of 25 cooled Cadmium-doped Germanium (Ge:Cd) detectors. The sensor is fitted with seven remotely programmable spectral filters that operate in the 3-22 micrometer band. The system is used to collect low dispersion infrared spectral data on targets of interest, and to perform manual or closed-loop tracking of non-solar illuminated targets. Sharing the light beam with AMTA is the Contrast Mode Photometer (CMP), which provides visible photometric signature data simultaneously with AMTA infrared signatures.

The rear instrument surface of the B37 telescope houses the Low Light Level TV (LLLTV) Package, for detecting and imaging resolved targets, and for detecting very faint, unresolved deep space objects. The LLLTV consists of a high-gain, astronomical quality Intensified SIT camera with narrow and wide field of view optics. The package also contains a 16 mm cine camera for a classical imaging capability. The camera has a variable frame rate (2-100 frames/sec), a tri-mode shutter providing consecutive exposures in the ratio of 1:3:9, and a filter wheel for color spectral filters. The side instrument surface of the B37 houses an atmospheric turbulence measuring device, and additional mounting space is available for visiting experimenters. Mounted on the B37 telescope housing is a small 1 Joule pulsed ruby laser used as a Cirrus LIDAR Probe (CLIP), and an 18 inch receiver telescope is used to detect backscattered light from the atmosphere.

The Laser Beam Director is an optical system which provides precise laser beam pointing and tracking. The system utilizes a series of fixed mirrors and beam expanders to take the output of a laser system, expand it to 24 inches, and direct it to a 36 inch azimuth/elevation gimbaled tracking mirror, from which it is projected into the atmosphere. The 24 inch beam expander and the 36 inch tracking mirror are mounted on an azimuth turntable which is locked prior to a tracking operation. The LBD has supported the AMOS pulsed ruby laser system, a three stage Q-switched and conventional mode laser producing pulse energies of about 8 and 80 Joules, respectively, for laser ranging and illumination of objects in space. The beam director has been designed to enable user agencies to mount their own laser in the sub-dome area and utilize the existing optics and pointing to conduct measurement programs tailored to a specific laser system.

The new 0.8-meter Coudé Beam Director/Tracker is a versatile system that can accept up to a 15 cm. beam from a variety of lasers, and project it to an object being tracked. The beam may be projected from the BD/T without expansion, or be expanded up to 0.6 meters. In addition to the Coudé path, the system includes a Cassegrain mounting surface. The BDT mount is an altitude-altitude configuration with a Coudé path to bring the laser beam to the projection optics from a fixed point on the observatory floor below. The mount can track at velocities up to 5 degrees/sec and angular accelerations up to 4 degrees/sec^2. The BD/T is operated with a variety of lasers, including systems installed by visiting user agencies. The LIDAR Acquisition/Sizing Experiment (LASE) system is currently in use with the BD/T. This bistatic CO_2 laser transceiver is designed to provide measurements of target range and range rate at ranges in excess of 2 Megameters, independent of time of day. The system was designed to serve as an experimental test bed for precision dynamic measurements, Doppler imaging and micro Doppler measurements.

In addition to the large optical systems and sensor capabilities at the AMOS/MOTIF site, extensive computer facilities have been installed as well. The Mount Control System (MCS) Harris 500 computers direct the operation of the 1.2-meter, 1.6-meter, LBD, and BD/T mounts. The MCS allows each mount to independently acquire and track targets with a high degree of precision, and to employ data from remote sensors, such as off-site radars, to achieve acquisition when necessary. In addition, two MODCOMP computers provide the capability for collecting, recording, displaying, editing, processing, and transmitting AMOS/MOTIF data. One MODCOMP is part of the Data Transmission System (DTS), which is capable of simultaneous, real-time acquisition and storage of metric, photometric, and infrared data. The second MODCOMP is part of the Communication System (CMS), which takes information from the DTS and formats and transmits the data via AUTODIN to AFSPACECOM. Other computers at the facility perform digital image storage and transmission, data analysis, and database management at the site.

Extensive support systems exist at the site to operate and maintain the complex and unique optical systems and sensors at AMOS/MOTIF. These include a satellite-based Global Positioning System (GPS)-referenced timing system, secure 2400 BAUD worldwide AUTODIN, and a secure voice system. A separate support building adjacent to the observatory facility contains a mirror re-coating laboratory with a vacuum tank capable of holding the telescope primary optics. The support building also houses a machine shop, electronics shops, welding shop, carpentry shop, and parts storage.

C. VELA: NUCLEAR TEST MONITORING

XI. VELA HOTEL SATELLITES

A. BRIEF OVERVIEW

The VELA HOTEL Satellites were part of the ARPA VELA program assigned by DoD.[1] The objective of the VELA HOTEL project was to develop satellite technology and global background data to detect nuclear explosions taking place in space, and eventually also in the earth's atmosphere. The first such experimental satellites were launched in 1963 and were very successful, with performance, cost and lifetime far better than expected, which allowed progressive improvements to be made rapidly in the detection systems and related satellite technology. This success also provided interim monitoring capability in support of the Limited Test Ban Treaty in 1963, banning nuclear tests in the earth's atmosphere and in space. In 1970, after six VELA HOTEL Satellite pairs had been launched without failure and operated successfully in orbit, the program was taken over by the Air Force. The current Air Force operational nuclear test detection system includes improved detectors of the type developed in the VELA Hotel program, incorporated into the GPS/NDS integrated navigation and nuclear explosion detection satellites. Six of a planned constellation of 18 are, so far, in orbit. The VELA-type instrumentation in the HOTEL and later satellites have been credited with detecting: "every nuclear event set off above ground that it has been in a position to see."[2]

B. TECHNICAL HISTORY

In May 1959, the High Altitude Detection panel (Panofsky Panel) of the President's Science Advisory Committee, recommended a satellite system be used to detect nuclear tests in space and in the atmosphere, as part of the overall basis for verification of a future nuclear test ban treaty. This panel also considered it possible, but difficult, to hide even

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[1] VELA means watchman in Spanish. Hotel was apparently, not an acronym. Other parts of the VELA program were: VELA UNIFORM, detection for underground explosions, and VELA SIERRA for ground-based methods to detect nuclear explosions in the atmosphere and in space.

[2] "Satellite Verification of Arms Control Agreements," Harold V. Argo in *Arms Control Verification*, Pergamon Press, 1985, p. 292. However, an apparently controversial incident occurred off S. Africa, in Sept. 1979. See "Monitoring The Tests," *IEEE Spectrum*, July 1986, p. 63-64, and *Alvarez*, by L.W. Alvarez, Basic Books, N.Y. 1987, p. 249.

small nuclear tests in space. To succeed in this would require special measures, such as hiding detonations behind the moon, using heavy lead shielding, or conducting the tests at very great distances. Technical Working Group I of the Geneva Conference on Discontinuance of Nuclear Weapons test recommended, in July 1959, "placing five or six large satellites in earth orbit at a distance of 180,000 miles to detect radiations from nuclear explosions in space." The satellites would be supplemented by special equipment placed in the 170-odd ground-control points of the recommended Geneva system for monitoring nuclear explosions underground and in the atmosphere.[3]

ARPA was assigned overall responsibility by the President, in late 1959, for project VELA, aimed at developing technology for detection of nuclear tests and verification of a nuclear test ban treaty. ARPA began immediately to plan for the required launchers for VELA HOTEL, the space segment of VELA, and with the assistance of the AEC laboratories at Los Alamos and Sandia, design of a satellite system commenced in the summer of 1959.[4]

As prescribed by the Geneva Technical Working Group, earth-based technologies to detect nuclear explosions in space were also investigated under the VELA SIERRA ground-based nuclear detection project, including an optical system to detect air fluorescence caused by X-rays,[5] nuclear-burst-caused ionospheric effects on VLF radio propagation and absorption of cosmic radio noise.[6]

Some felt that the costs of an adequate satellite system could be very high, particularly if the possibility of lead shielding of X-rays from the explosion and other possible evasion methods were taken into account, along with the lack of relevant

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[3] *Kennedy, Khruschev and the Test Ban*, by Glenn T. Seaborg, U. Cal. press 1981, p. 19.

[4] AO 102, "VELA" of 9/59 to Sec. AF for nearly $70M, and AO 140 "Project VELA" of 4/60 to AEC, $4.4M. The AEC labs had already been working on the problem with AEC support. See, Developments in the Field of Detection and Identification of Nuclear Explosions, Summary of Hearing on July 25-27, 1961, Journal Committee on Atomic Energy, April 1962, p. 5.

[5] Ground-based optical systems for detection of nuclear explosions in space were apparently field tested and used beginning in 1961, but were, initially, rather costly. See, e.g., "The Los Alamos Air Fluorescence Detection System," by D.R. Westervelt and H. Hoerlin, *Proc. IEEE*, VA 53, #12, 1965, p. 2078.

[6] OTH radars to detect nuclear explosions in the ionosphere were proposed by the U.S. but rejected by the Soviet Union. See testimony by W. Panofsky, in "Technical Aspects of Detection and Inspection of a Nuclear Weapons Test Ban," hearings before a Subcommittee on Radiation JCAE, 86th Congress, 2nd Session, April 1968, p. 48.

background data and the possibility of unreliability of the space systems involved.[7] Because of the controversy, a joint agency technical group was set up by ARPA to plan and steer the VELA HOTEL project, with AF Space Division chairmanship.

A number of instruments were also flown piggy-back on other early U.S. Defense and NASA satellites to test instrument performance and make preliminary background measurements.[8] Estimates were soon made that 3 to 5 launches of satellites, in a five-year program, would prove adequate for defining a prototype system.[9] Detection experiments were also performed by launching rockets from Hawaii during the 1962 high-altitude nuclear test series.[10] Under the DARPA program six pairs of VELA satellites were put into orbit, the first pair in 1963, and the last pair in 1970. Table 1 gives a summary of the launch dates, and information on the satellites' equipment and stabilization.

Table 1. VELA HOTEL Satellite Launches

Satellite Pair Number	Date in Orbit	Detection Equipment	Stabilization
1	16 Oct 1963	Nuclear (space explosion)	Spin (fixed axis)
2	27 July 1964	Nuclear (space explosion)	Spin (fixed axis)
3	20 July 1965	Nuclear, Bhangmeter (atmospheric explosion)	Spin (fixed axis)
4	28 April 1967	Nuclear, Bhangmeter	Earth-oriented (gravity)
5	23 May 1969	Nuclear, Bhangmeter	Earth-oriented (gravity)
6	8 April 1970	Nuclear, Bhangmeter	Earth-oriented (gravity)

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[7] See *A Scientist at the White House*, by G. Kistiakowsky, Harvard, 1976, pg. 76 and "Scientists and Politicians," by H. Jacobson and E. Stein, U. Mich. Press, 1960, pp. 191-2

[8] Some early results are described in the testimony of Dr. A. Schardt, ARPA Vela Hotel program manager and "Developments in Technical Capability for Detecting and Identifying Nuclear Weapons Tests," hearing before the JCAE, 88th Congress, 1st Session, 1963, p. 331.

[9] Schardt, ibid., p. 321.

[10] Seventeen rocket payload measurements were successful out of seventeen launched. See testimony of James H. Coon, in "Developments in Technical Capabilities for Detecting and Identifying Nuclear Weapons Tests," hearings before the JCAE, 88th Congress, 1963, p. 390.

The first pair of VELA satellites were successfully launched in Oct. 1963, spaced 180 deg apart in a circular orbit at about 115,000 km,[11] beyond the outer Van Allen Belt. The second and third pairs were launched in July 1964 and 1965. All of these contained X-ray, neutron and gamma-ray detectors designed by the AEC Labs., which could measure the very characteristic signals of these types from a nuclear explosion. Figure 1 shows a photograph of the first two VELA HOTEL satellites mounted in tandem, and ready to be mounted on their booster rocket. Each satellite had an internal injection motor used to position it in final circular orbit of 115,000-km radius, approximately 180 deg apart. These satellites had an icosahedral configuration, with cubic shaped X-ray detectors at each apex. The gamma-ray and neutron detectors were inside. The second and later satellites carried instruments to measure background radiation to which the nuclear explosion detectors might be most sensitive.[12] With this background information, coincidences of multiple detectors of the same type and time histories of the different signal types could be used in the design of logic systems in the satellite[13] to identify explosions with greater confidence. While the first VELA HOTEL satellite detection payloads were constructed by Los Alamos and Sandia, the satellite frame, solar cells, etc., had been built by TRW under a success-oriented performance incentive fee contract, one of the first of a long series of this type in the military satellite business.[14] Because of the excellent TRW performance, a sizeable fee had to be paid by ARPA, which was done without objection.[15] The lifetime of these first satellites had been expected to be nine months at most, but turned out to be years. Taking

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[11] The Limited Test Ban Treaty, including provisions against nuclear tests in space and in the atmosphere, had been signed before this, in April 1963.

[12] "The Vela Satellite Program for Detection of High Altitude Nuclear Detonations," by S.F. Singer, *Proc. IEEE*, Vol. 53, 1965, p. 1935, "Vela Satellites Measurements of Particles in the Solar Wind and the Distant Geomagnetosphere," by James H. Coon, in *Radiation Trapped in the Earth's Magnetic Field*, B. M. McCormack, ed., Reidel 1966, p. 231-236.

[13] Considerable effort went into the design of the logical systems at Sandia because of the strong desire to avoid false alarms. See Jacobson and Stein, ibid., p. 191. For the situation as of 1965 see, "A modular System of Logic for the Vela Satellite Program," by W. McGoldrick, et al., *Proc. IEEE*, Vol. 58, 1965, p. 1959.

[14] Discussion with Dr. C. Cook, 12/89.

[15] Discussion with Dr. R. Sproull, who had been ARPA director at the time, 12/87. Sec. Def. McNamara cited the VELA Hotel contract in his 1964 report to the President on Cost Reduction. The success of this CPIF contract can be credited partly to the clear technical description of requirements by ARPA, see Richard J. Barber Associates, DARPA History, ibid. The success in later contracts of this type can be credited, in part, to their heavy "incentivation" possible due to the "special handling" of the satellite program. Dr. C. Cook, ibid.

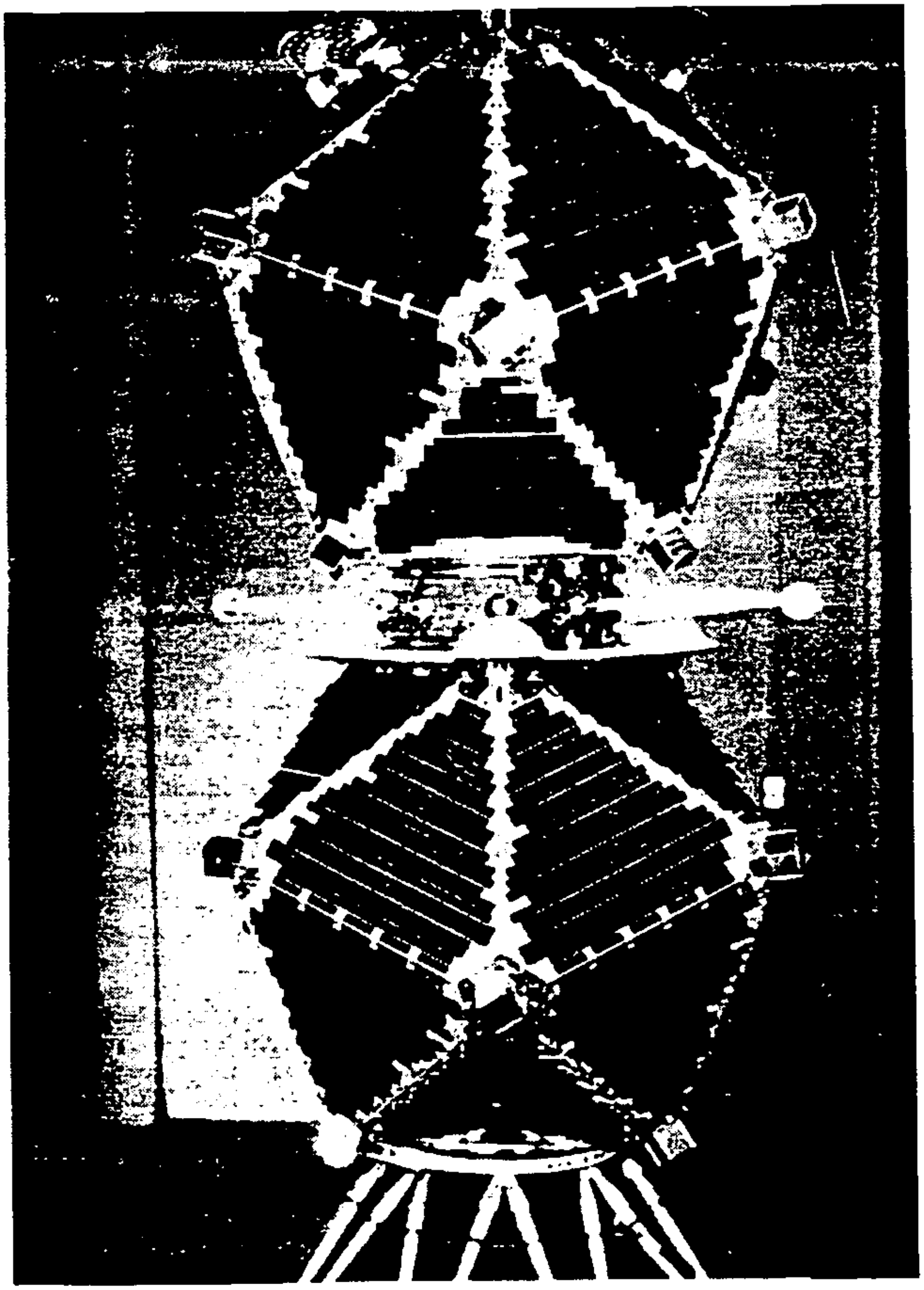

Figure 1. First VELA HOTEL Satellites

advantage of the remarkably successful launch and successful payload performance together with lower costs and longer lifetimes, ARPA changed the schedule and payload, as things went on, to progressively incorporate improved nuclear detection systems.

The test ban treaty of 1963 gave incentives to extend the satellites' capability to atmospheric explosions. The multistation Geneva ground-based system was becoming appreciated as being very costly and a large, difficult burden on the U.N. (or some other international body), and the satellites offered a way to provide a substitute for the atmospheric detection role of these stations.[16]

The key technology for this purpose was the "bhangmeter," a version of an optical instrument that had been used previously by the Los Alamos Laboratory for measurement of the light emitted by atmospheric explosions and proposed by the laboratory for this application. In order for the bhangmeter to detect the characteristic optical signature of nuclear explosions in the atmosphere, it was necessary to first use it to obtain some preliminary data on the brightness background characteristics of the earth. The third satellite pair contained a bhangmeter, but limited earth background data was acquired because of the spin-stabilization then used. To detect nuclear explosions in space, no particular directional characteristics were required for the other instruments.

When the fourth VELA satellite was launched in 1967, space technology had advanced enough to allow its axis to be oriented towards the earth's center so that a bhangmeter looking downward could detect and measure the double-humped optical signature characteristic of an atmospheric nuclear explosion, which could also be used to estimate yield.[17] The last two satellites pairs of the VELA series also contained electromagnetic pulse detectors for nuclear explosions in the atmosphere.

The early gamma-ray detectors, which like the X-ray detectors employed scintillators, were improved to have better time and spectral resolution and in 1967 the fourth pair of VELA satellites detected, for the first time, gamma-ray bursts identified as

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[16] Seaborg, ibid, p. 147, discusses the probable impracticality of the Geneva Systems as first proposed. Costs estimates were given by C.M. Beyer of ARPA, in testimony before the Joint Committee on Atomic Energy in 1963. See "Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Tests Ban." Hearings before a subcommittee on Radiation of the JCAE, 86th Congress, 2nd Session, April 1960, p. 367 ff.

[17] Argo, ibid., (Ref. 1), p. 298.

coming from distant collapsing star events.[18] The sixth and last VELA HOTEL Program satellite pair was put into orbit in 1970. Several of these satellites are still operating.

When the Air Force (at first SAMSO, and later AFTAC) took over the satellite nuclear detection responsibility after 1970, the nuclear explosion detection payloads (beyond the existing VELA HOTEL systems) were at first combined with other instruments, for reasons of economy, in geosynchronous satellites.[19] Since July 1983, the nuclear test detection responsibility has been given mainly to the GPS/NDS combined navigation and nuclear test detection satellites systems, planned for 18 satellites at 20,200 km altitude (within the outer Van Allen Belt) and 55 deg orbits, and now being built up as launch capabilities allow. Six are presently in orbit. Most of the GPS/NDS systems include X-ray, bhangmeter and an EMP detector, as the VELA satellites did, and some also contain a dosimeter to assess damage to on-board systems and to detect magnetically trapped electrons and ions from a nuclear explosion. The recent GPS/NDS systems do not include gamma or neutron detectors, but this capability is apparently still available on other satellites.[20] The accurate timing inherent in the GPS system is used also for locating the source of signals detected by the X-ray, bhangmeter or EMP detector, allowing correlation of the times of arrival at different GPS/NDS satellites. Signals received at a number of satellites are analyzed at ground stations for positive detection, identification, location and yield estimation of a nuclear explosion, useful not only for monitoring nuclear tests but also for wartime assessment of nuclear attacks.

C. OBSERVATIONS ON SUCCESS

The VELA assignment was given to ARPA by the White House and DoD. A rough prescription of the technology involved was available from the Geneva Technical Working Group I and the Panofsky Panel. However, there was still considerable confusion over how much detection capability would be required, and at what cost. Confidence was also not high, until about 1963, in launch success or in payload lifetime. In retrospect the VELA HOTEL satellites benefited very greatly from a combination of what was, at the time, an unusually successful launch series, together with the high quality nuclear test

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[18] "Gamma Ray Astronomy," G. Ramaty and H. Lingenfelter, in *Annual Reviews of Nuclear and Particle Science*, Vol. 32, 1982, p. 242.

[19] Panofsky, ibid., where it is pointed out that beyond detection of a nuclear explosion, identification of the test violator would need additional information from other surveillance sources.

[20] ARPA, ibid., p. 302.

instrumentation and rigorous logic control technology available from the AEC laboratories. The logical subsystem was considered very important, in order to give high confidence in any detection made by the satellite. There were many technical risks: launchers and payload design, overall payload reliability and lifetime, and importantly, the radiation backgrounds on which information had to be built up over time. On the basis of the sequential accumulation of information on nuclear system performance and background and the rapid advance of space technology, ARPA's working group changed the technical specifications as the series went on.

The main features of the nuclear components of the satellite system to detect high altitude nuclear explosions were clear after three successful launches, as had been estimated after some background data had been attained. But the 1963 treaty banning nuclear explosions in space and in the atmosphere, and the high cost for the Geneva ground-based, multi-station system then under discussion for monitoring, gave strong incentive to have satellite systems to detect atmospheric tests worldwide. This required new technology on the satellite, which again was available from previous AEC programs. The bhangmeter, an optical instrument developed previously by Los Alamos, was added to the payload, and satellite technology now allowed an earth orientation to look downward with it. Addition of the bhangmeter for the detection of atmospheric tests required a new and different kind of background and discrimination logic. Proving out this technology required three more experimental payloads which again were successful. The phenomenal run of successful launchers can largely be credited for the success-oriented progress of the project.

The Air Force apparently was impatient at first to take over responsibility, but eventually recognized the cost savings in the project and in its CPIF contract with TRW.[21] Some known risks to avoid, which would have required a larger number of detection satellites and consequently high costs, were accepted for economical and political reasons. The early satellites' remarkable success provided an interim operational capability for test detection, and also for diagnostics and rough location of nuclear explosions occurring in the atmosphere. The experimental VELA HOTEL satellite system was actually operational for many years. When the Air Force took over, detection packages similar to those in the VELA satellites were combined, partly for economy, with other payloads on the Air Force geosynchronous satellites. These were in a different radiation environment from the VELA satellites, but information was available on this background from "piggyback"

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[21] The Richard J. Barber ARPA History quotes a letter from Gen. Shriever to this effect. Ibid., p. V-32.

experiments on other geosynchronous satellites. Apparently the ARPA program envisioned eventual use of its product in the geosynchronous satellite.[22] Now a somewhat modified version of the VELA HOTEL system is carried on the GPS/NDS satellites, which provides a wartime attack and damage assessment capability as well as nuclear test detection and location.

ARPA expenditures for VELA HOTEL, from available records were approximately $150 million, including six launches, payloads, and data analysis. The incentive contract to STL was estimated to have saved $26 million.[23] Expenditures for the successive generations of detection systems, including ground stations, from the early 1970s through the GPS/NDS, are estimated as about $2 billion.[24]

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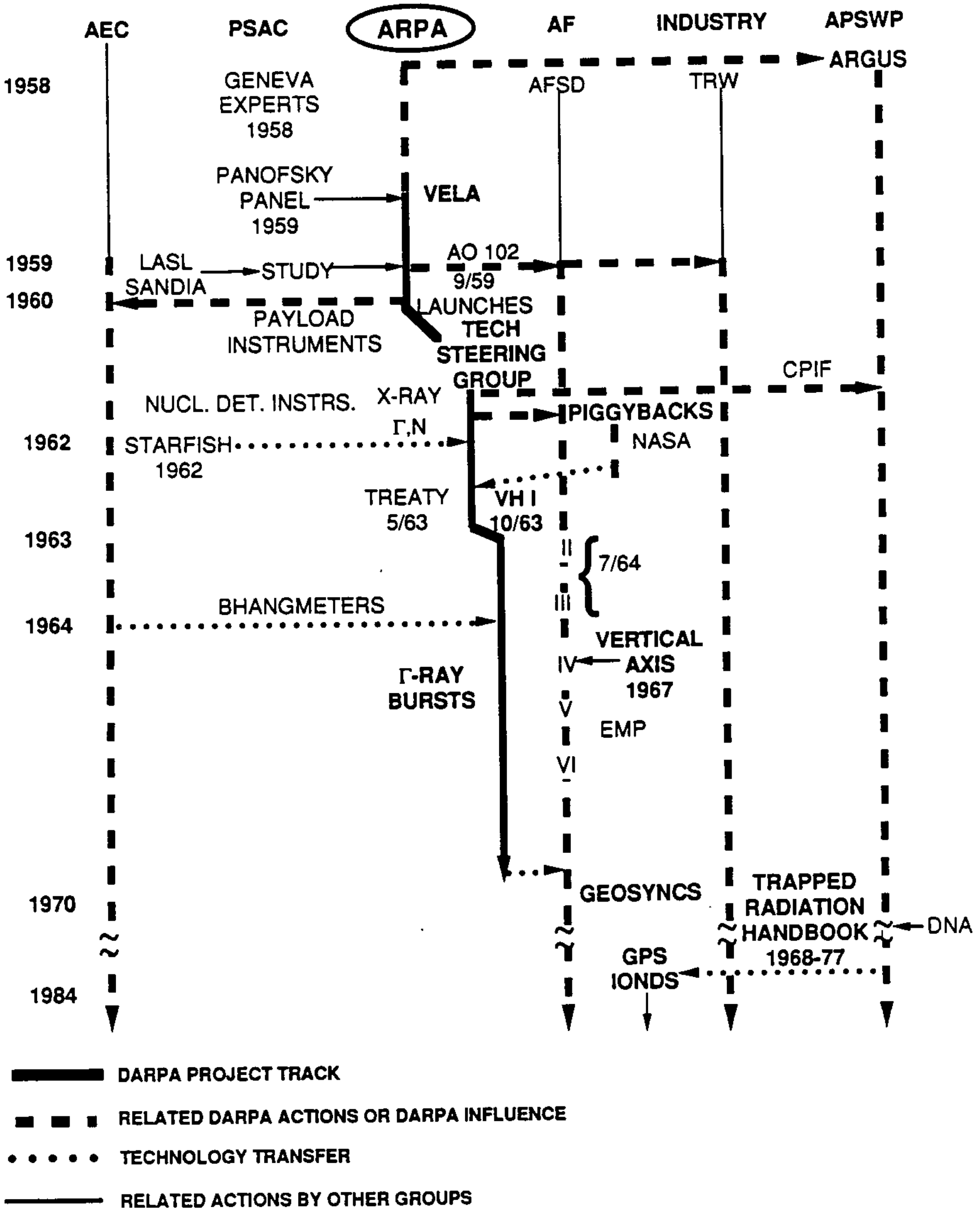
[22] Discussion with Gen. H. Dickinson, 7/88.

[23] Ibid., p. 29. See testimony of Dr. A.W. Schardt, in "Developments in Technical Capabilities for Detection and Identifying Nuclear Weapons Test," hearings before the JCAE, 88th Congress, 1st Session 1963, p. 322.

[24] Dr. C. Cook, ibid.

VELA HOTEL



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XII. VELA UNIFORM: WWNSS

A. BRIEF OVERVIEW

As part of project VELA, assigned to ARPA by the Secretary of Defense in 1959, VELA UNIFORM was a program of research in seismology and other techniques toward improvements in the detection and identification of underground nuclear explosions. As one of its first activities, VELA UNIFORM set up the first worldwide network of standard seismograph stations, the WWNSS, which has had a very great impact on seismology and its applications to our understanding of earthquakes and to geology, as well as to the problem of detection and identification of underground nuclear explosions .

B. TECHNICAL HISTORY

In 1958 an international committee of experts met in Geneva to define technical characteristics of a control system to monitor a possible nuclear test ban.[1] However, seismic data from ongoing underground nuclear tests in the U.S. soon indicated that the capabilities of the system recommended by the Geneva Experts was considerably less than they had estimated. In the same period the "decoupling" theory was put forward, according to which a large explosion in an underground cavity could appear to be much smaller to a distant seismic monitor. These events led, in early 1959, to the formation in the U.S. of the Berkner panel on seismic improvement, which was asked to review the situation and recommend what changes would be needed in the Geneva system to bring its capabilities more nearly to the level the experts had originally estimated. The Berkner panel recommended several such improvements in March 1959, and in a special report emphasized the urgent need for, and outlined the desirable content of, an accelerated research program in seismology to better deal with the problems of detecting and identifying underground nuclear explosions.[2]

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[1] "VELA Overview--the Early Years of the Seismic Research Program," by C.F. Romney, in "The VELA Program," DARPA 1985. Vela in Spanish means "watchman."

[2] "The Need for Fundamental Research in Seismology," report of the Panel on Seismic Improvement, U.S. Department of State, 1959.

The recommendations and the rather comprehensive outline of needed research in the report of the Berkner panel led to and guided the early stages of ARPA's VELA UNIFORM program, established in Sept. 1959.[3] One of the first steps suggested by the Berkner panel's report was to equip, as soon as possible, selected seismographic stations worldwide with a standard set of seismographs, and equipment for accurate time and data recording, together with a central data repository.[4] ARPA, which was not strong in the seismology area at the time, depended on AFTAC, the Air Force Technical Applications Center, which had been active in the nuclear detection and seismology area since 1946, and had developed a detailed plan along the lines of the Berkner panel report.[5] ARPA then proceeded to implement this plan, one important aspect of which was assigning the task of installing the equipment and managing the WWNSS and its central data repository to the U.S. Coast and Geodetic Survey (USC&GS), an agency which had been involved in seismological activity for some time and was known worldwide.[6]

The USC&GS undertook the task with enthusiasm.The WWNSS instruments were to become the property of the stations or institutions in the different nations where they were installed, and voluntary cooperation in data exchange, as had been the custom in seismology, was assumed. A committee of the National Academy of Sciences assisted the USC&GS on the choice of instruments and the selection of recipients.[7] Proven, reliable instruments were recommended, one short and one long period type, each measuring three components of motion. Direct light-beam photographic recording was used. A single contractor, the GeoTechnical Corporation, supplied the instruments for the 120 stations distributed around the world. This was the first relatively large-scale industrial seismological instrument production of its kind. Figure 1, from Farrell,[8] shows a picture

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[3] A.O. 104 of 9/59: "Vela Uniform," to AFTAC.

[4] Frank Press and David T. Griggs, "Improved Equipment for Existing Seismic Stations," Appendix I of the Berkner report, ibid., p. 17 and 18. Besides making a very great improvement in seismology, it was envisioned that the distribution of seismographs could make it possible for other nations to identify attempts at cheating on the test ban. Discussion with R. Sproull, 10/89.

[5] IDA TE 212 of Dec. 2, 1959: "AFTAC Development and Funding Plan: VELA," by R.S. Warner and F.C. Hazen.

[6] A.O. 173 of 9/60 to USC&GS.

[7] "Specifications for a World-Wide Network of Standardized Seismographs," a report by the Committee on Seismological Stations, National Academy of Sciences, Washington, D.C., June 1960.

[8] W.E. Farrell, "Sensors, Systems and Arrays: Seismic Instrumentation Under Vela-Uniform," in *The Vela Program*, ARPA 1985, p. 489.

of one of the WWNSS systems, and Figure 2, from Oliver and Murphy,[9] indicates the station locations. Each station was supplied with a standard crystal controlled clock, and a radio system to receive and record time signals. Provision was also made for periodic calibrations of the WWNSS systems. A Seismology Data Center to copy and distribute the data was formed first in Washington and later in Asheville, N.C, under the USC&GS and finally in Boulder, CO under the U.S. Geological Survey.

The WWNSS' installation involved many problems, technical, logistical and political.[10] The installation was essentially complete by 1963, with over 100 stations in 54 countries, at a cost of about $9 million. The only notable non-recipients were Canada, which agreed to share data from their own system, and the Soviet Union.

The WWNSS transformed seismology and became the main source of data for that science. In a 1979 National Academy Report, seismologist Jonathan Berger describes the impact of WWNSS (or WWSSN):[11]

> Until the mid-1960's a seismologist had to rely on a diverse set of seismograms that he had culled from various organizations and individuals throughout the world. Network analyses were, at best, extremely tedious and usually impossible, because in many, even the most rudimentary calibration (which way is up?) was unknown. With the deployment 15 years ago of some 120 stations of the World Wide Standardized Seismograph Network (WWSSN), a large quantity of graphically recorded seismic data became available to the world's seismologists.
>
> When the WWSSN was established in the mid-1960's, the world's intermediate and larger earthquakes were routinely and accurately located, and it was soon discovered that the vast majority of earthquakes were confined to narrow zones spanning the globe. Further, certain parameters describing the source could be established. Using the model of an earthquake as a fracture of the rocks over a plane, scientists could determine the orientation and direction of motion on this plane. This seismological evidence, on a global scale, contributed significantly to the development of the theory of plate tectonics in the late 1960's.

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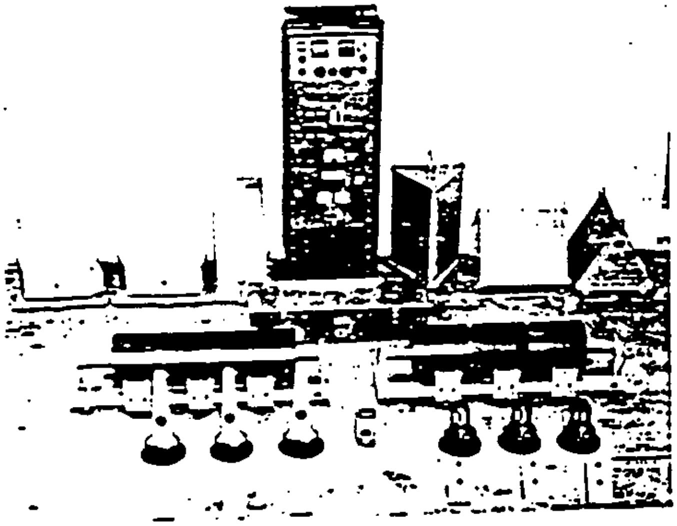
[9] J. Oliver and L. Murphy, "WWNSS: Seismology's Global Network of Observing Stations," *Science* V. 174, 1971, p. 257.

[10] Oliver and Murphy, ibid.

[11] "Impact of Technology on Geophysics," National Academy of Sciences, Washington, D.C. 1979, p. 65-66.



The WWSSN instrumentation system shown here uses photographic recording exclusively and is earth-powered. The three Sprengnether long-period seismometers are displayed to the left of the cabinet that holds the timing and calibration apparatus. The three massive Benioff short-period seismometers are shown to the right.

Figure 1. The WWSSN

(from Farrell, Fn. 8)

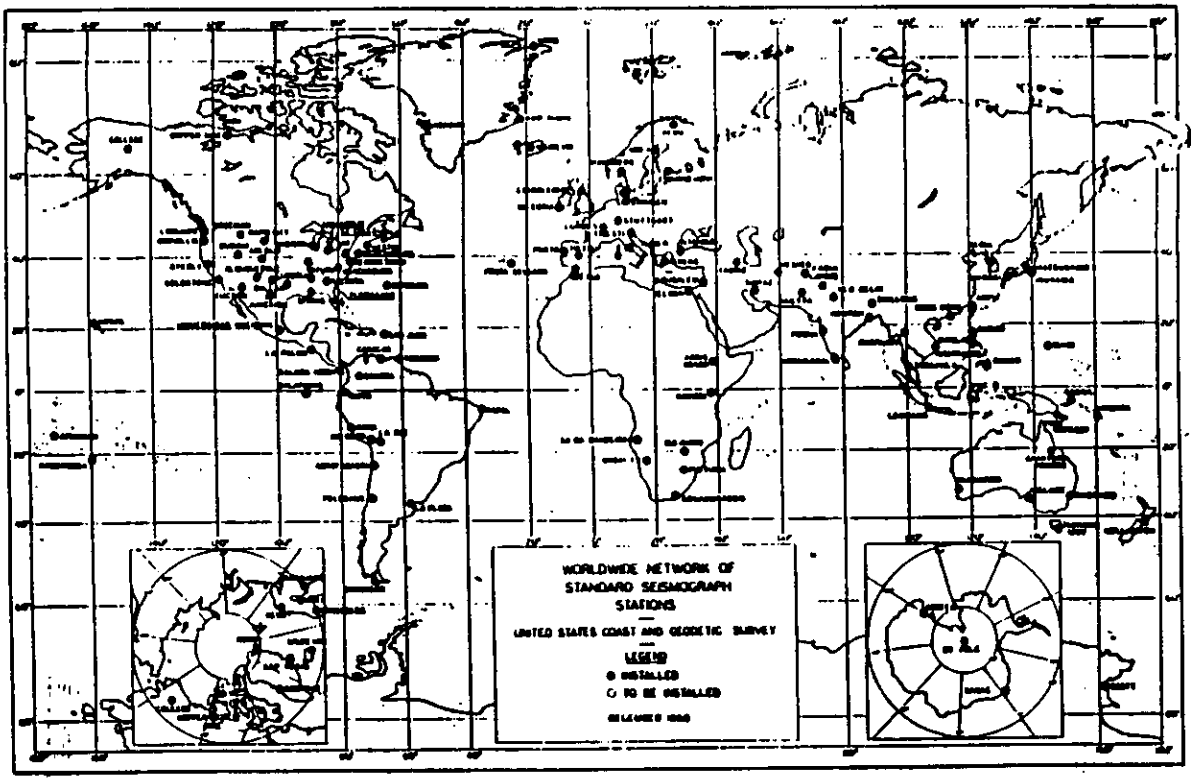


Figure 2. Worldwide Network of Standardized Seismograph Stations Established as Part of the Nuclear Test Detection Program (USC&GS)

According to Oliver and Murphy, the WWNSS arrived "just in time" for the new development in geological concepts:[12]

> In part, the success of the WWNSS has resulted from the increase in the quantity, quality, and means for distribution of the data. To some extent successes occurred because the new data became available at the "right" time in history, just when the concepts of sea-floor spreading, continental drift, and plate tectonics were appearing, or reappearing, and undergoing development.
>
> The very earliest stages of the development of the sea-floor spreading hypothesis depended in only a limited and secondary way on seismology, for it was geomagnetism that held the key. Seismic activity was used to map the spreading zones, but the linear magnetic anomalies were the source of information on spreading and rates of spreading. Very shortly, however, the contributions of seismology grew in importance, and this discipline was able to play an important role in the testing and development of the hypothesis.

Providing from three to five times as much data as previously available, data of much greater reliability from standardized, calibrated instruments, WWNSS allowed a drastic clarification and improvement of the delineation of seismic activity, earthquake focal mechanisms, and seismic wave propagation.[13]

A 1977 report of the National Academy states:[14]

> In a little more than a decade, the WWSSN significantly increased our knowledge of earthquakes and of the earth structure and dynamics, while performing its initial mission of providing basic scientific information for the detection and identification of underground nuclear explosions anywhere in the world. These major scientific advances provide important new input toward solutions of such national problems as the monitoring of nuclear tests, earthquake hazard reduction, understanding the origin and location of minerals and geothermal energy sources and the siting of dams and nuclear power plants.

Regarding the nuclear test monitoring problem, Farrell says, more specifically:[15]

> The WWSSN project has undoubtedly delivered more seismograms to seismologists than all other networks combined...Although set up as a research tool for studying fundamental problems in seismology, it can be argued that studies conducted on data from this single network have been

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[12] Oliver and Murphy, ibid., p. 257.

[13] Ibid., p. 18. Oliver and Murphy illustrate this progress with several examples, Ref. 9, p. 255-6.

[14] "Global Earthquake Monitoring," National Academy of Sciences, 1977, p. iii. Chapter IV of this report outlines the history of seismological networks and the accomplishments of WWNSS.

[15] Farrell, Ref. 8, p. 487.

> comparable in importance to that provided by all other seismic systems for the problems of source identification and yield estimation.

DARPA continued to upgrade the technology of the WWNSS, notably toward being more "digital," to complement its capabilities with other stations having different and improved instruments, and to arrange for central processing of the digital seismic data. Most of this was done through the U.S. Geological Survey (USGS). In the late 1960's, DARPA also sponsored the development and installation of 10 high-gain, long-period (HGLP) seismographs which were later augmented with short-period instruments and outfitted with improved digital recorders, and managed by the USGS as a complementary part of the WWNSS. In 1973 DARPA and the USGS jointly developed and deployed 13 Seismic Research Observatories (SRO), which included a new broadband borehole seismometer and an advanced digital recording system.[16]

Berger describes the important characteristics of this upgrade from the standpoint of nuclear test discrimination.[17]

> When established in the mid-1960's, the WWNSS was confined by the sensor and associated electronics principally to periods shorter than 20 sec. Later in the decade, Pomeroy and others at Lamont-Doherty Observatory developed the high-gain long-period (HGLP) instrumentation that successfully modified seismometers to extend their useful range to 60-100 sec. An outcome of their studies and those of others was the discovery of an optimum period at which to discriminate between nuclear explosions and natural earthquakes. Based on this knowledge, two global arrays of seismic instruments "tuned" to this period were deployed -- the Seismic Research Observatories (SRO) network and the HGLP systems.

In parallel with the upgrade of instruments in the field, and the increase of digital data in quantity and quality, a new seismic data center has been set up to process and manage this data for the benefit of both geophysical research and international data exchange for treaty support.[18]

Since the beginning of the WWNSS, it has been recognized that[19]

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[16] ARPA Order # 2880 of 6/74. Cf. also "Seismic Research Observatories. Upgrading the Worldwide Seismic Data Network," by J. Peterson and N. Orsini, EAS, American Geophysical Union, 1977, p. 548.

[17] Berger, Ref. 9, p. 67.

[18] "Tools for Seismic Data Analysis and Management for Research and International Data Exchange," by Ann U. Kerr, in *The Vela Program*, DARPA, 1985.

[19] *Seismographic Networks, Problems and Prospects for the 80's*, National Academy Press, 1983, p. 7.

> ...DARPA has been responsible for virtually all advances in global seismographic networks...

However, the support required for the continued operation of the WWNSS has been precarious since about 1967 when ARPA funding for it ceased due to Congress ruling that earthquake research was irrelevant to the ARPA mission.[20] The responsibility for WWNSS was then eventually transferred to the U.S. Geological Survey. A similar event for the GSDN, the global seismological digital network, occurred in FY 1979, and as a result these networks have been reduced in size somewhat. However, much seismological research supported by DARPA depends on data from the routine operation of the GDSN and WWSSN.[21]

At the present time it seems likely that the National Science Foundation and the USGS will have a dominant role in any future upgrading and operation of the WWNSS, and the construction and operation of a "next generation" digital network, linked via satellite. Such an advanced system will also consist, largely, of technology generated through DARPA support .

C. OBSERVATIONS ON SUCCESS

ARPA was given the VELA program responsibility by the White House and DoD. AFTAC, at the time technically much stronger in the underground and atmospheric nuclear test detection areas, had prepared a comprehensive plan to carry out the Berkner Committee recommendations. However, AFTAC was not given VELA responsibility, probably because of its more direct military and intelligence connections. ARPA used the AFTAC plan to help guide its initial activity.

F. Press of the Berkner panel had put forward the idea that a global "standard" set of seismographs and recording instruments was needed for VELA, actually could be carried out inexpensively, and would be very beneficial to seismology. It was also envisaged that a worldwide distribution of seismographs could help other nations to identify attempts at cheating on the test ban.[22] The Berkner panel recommended that VELA carry out this WWNSS project, and this was included in the AFTAC plan. A National Academy Panel was formed to provide technical specifics for guidance of the WWNSS project. WWNSS depended entirely on international data exchange and cooperation of the

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[20] Communications from Dr. E. Rechtin, 10/89.

[21] Seismographic Networks, ibid., p. 11.

kind that had been prevalent in seismic research. The U.S. Coast and Geodetic Survey (USC&GS) was an appropriate choice of agent in view of its international connections. The C&GS had both recognized expertise and enthusiasm, and did a remarkable and difficult job in installing WWNSS and shepherding it through its early stages.

WWNSS involved proven technology. The risk was in whether the network, based on an expansion of existing seismological voluntary practices, would work. It did, and the payoff was very large, both as a foundation for understanding the problem of detection of underground nuclear tests and to seismology as a science. WWNSS arrived at a time to have a very great impact also on geology, not in originating, but in confirming and extending the ideas of plate tectonics.

It seems most unlikely that WWNSS, and its consequences, would have existed without the ARPA program. On the other hand, while responsible for getting it started and profiting immensely from its results, it was difficult for DARPA to continue support for a data collection effort such as WWNSS, even though equipment was updated and the data were still useful for nuclear test detection research. The ACDA could have operated WWNSS, according to its charter, but was unable or unwilling to do so, lacking funds and staff. Congress terminated ARPA funding for earthquake research as irrelevant in 1967, thus forcing a transfer out of ARPA. The U.S. Geological Survey (USGS) then undertook responsibility for WWNSS. So far it has been difficult to find the necessary funding for WWNSS despite increased interest in earthquake research, at NSF and USGS.

If and when a nuclear test treaty is initiated, the responsible U.S. agency might be involved to some extent in continuing to operate the WWNSS. But the treaty responsibilities would likely involve a network of modern digital seismological instruments and computers, linked by satellites, building on DARPA-developed technology, for international test monitoring and also for seismological research.

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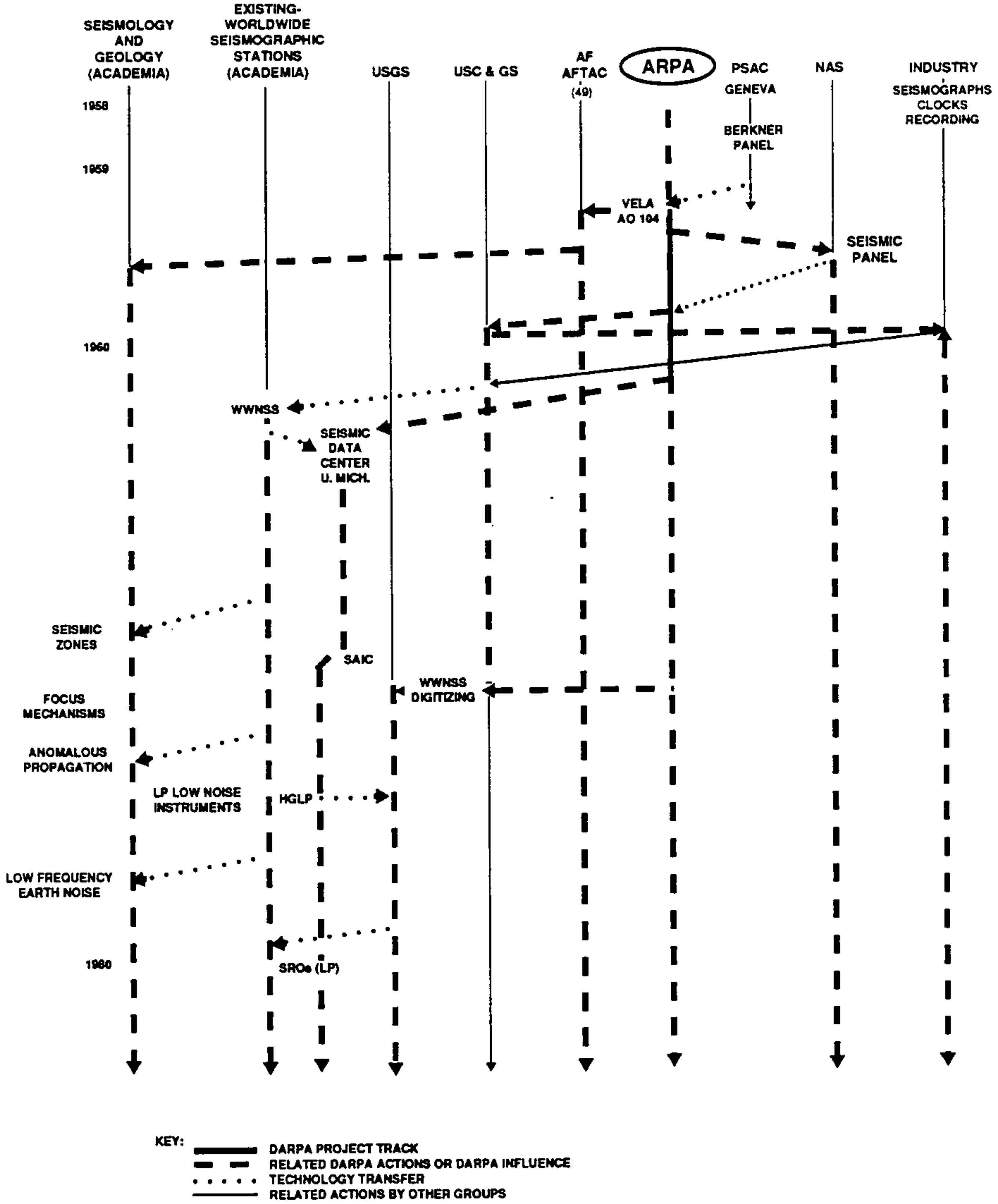
22 Communication from Dr. R. Sproull, 10/89.

WWNSS (WWSSN)



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XIII. VELA UNIFORM: THE VERY LARGE ARRAYS, LASA AND NORSAR

A. BRIEF OVERVIEW

Motivated by the recommendations of the Berkner Panel, a treaty climate indicating reliance might have to be placed on long distance detections, the progress in digital data processing and some early array experiments,[1] ARPA began construction in 1964 of LASA, a "large aperture seismic array," an array of subarrays extending over 200 mi. in diameter. LASA contained more than 500 instruments, with digital outputs transmitted and processed on a large scale for the first time using modern telecommunications and computing techniques. The construction of LASA was completed in five months, in early 1965, under severe winter conditions. LASA was operated until 1978.

In 1967 ARPA undertook the cooperative construction, with the Norwegians, of the Norwegian Seismic Array (NORSAR), a "second generation" large array at a location outside Oslo. NORSAR commenced full operation in 1971 and is still being used for research on detection and discrimination of nuclear explosions. A subarray of NORSAR, NORESS, has been outfitted with the most modern seismographs and data handling systems and may be regarded as a prototype international seismographic monitoring station.[2]

B. TECHNICAL HISTORY

In 1958, the Geneva Conference of Experts suggested that about 170 nuclear test detection stations be constructed to monitor compliance with a test ban treaty, the number

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[1] E.W. Carpenter, "An Historical Review of Seismometer Array Development," *Proc. IEEE*, Vol., 53, Dec. 1965, p. 1816.

[2] "Nuclear Testing Issues," Hearing before the Committee on Foreign Relations, U.S. Senate, 96th Congress, 1986.

and spacing of which were determined mainly by the estimated range of detection of possible underground explosions.[3] Each such seismic station was to include approximately ten short-period vertical seismographs spaced over a few kilometers and interconnected with a recording system by cable. No sophisticated processing was envisioned. In a 1959 reappraisal stimulated by new data, the Berkner panel on seismic improvement stated that some stations should have a hundred or so instruments to bring capabilities up to a level approximating that estimated originally by the Geneva experts, and that processing and array design could offer potentially great improvements in signal-to-noise:[3]

> Of great importance in the detection and identification problems is the degree of signal enhancement that may be gained through instrumental and computational operations on the improved sampling of the seismic data made possible by the use of large arrays of seismometers. When the operations incorporate the elaborate complex signal enhancement techniques that can be performed on special-purpose digital data processing equipment, they may realize an improvement in signal-to-noise amplitude ratio in excess of $n^{1/2}$ where n is the number of seismometers in the array.

The panel further recommended the investigation of techniques that had been developed for electromagnetic antennas and communications data sampling, and the establishment of a computer center to move towards the automatic processing of seismic data from monitoring stations.

In 1959, ARPA set up project VELA Uniform, which began to carry out most of the Berkner panel recommendations, and about the same time the U.K. began to investigate the possibilities of larger arrays. The development in arrays and associated signal processing proceeded rapidly:[4]

> Between 1959 and 1963, five array stations were built in the United States by the Air Force Technical Applications Center (AFTAC) for the Advanced Research Projects Agency (ARPA), which operates the VELA program. Each of these VELA arrays had 10 to 31 elements and 3 km aperture. Beginning in 1960, the group under Thirlaway and Whiteway at the United Kingdom Atomic Weapons Research Establishment began to urge the use of larger aperture seismic arrays, and built several 21-element arrays in which the elements were arranged in two crossed lines, using various apertures up to 25 km.

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[3] Report of the Panel on Seismic Improvement, Ref. 1, p. 11.

[4] "Experimental LASA Principles," P.E. Green, R.A. Frosch, and C.F. Romney, *Proc. IEEE*, Vol. 53, Dec. 1965, p. 1825. AFTAC, mentioned in this quotation, had been active in seismic detection work since 1949, when it was given a national responsibility in this area. Early VELA Uniform efforts depended extensively on AFTAC assistance.

The U.K. approach was to record broad band, on tape, and use "velocity filtering," or "delay and sum," of signals from array elements to improve signal to noise.

In about 1962 the treaty climate worsened, and in the same time frame the Soviet and French underground nuclear explosions occurred and were detected at several distant seismographic stations, indicating low-loss propagation of compressional P-waves to large distances. The U.K., followed by the U.S., then began to look into the possibilities of detection at large "teleseismic" ranges (greater than 2000 km), which might not require stations in each country, and for "quiet" sites in remote locations where large arrays could be installed.

At Yellowknife in Canada, a joint Canadian-U.K. 25-km array was built, and the Tonto Forest Seismological Observatory (TFSO), in the U.S., was enlarged to a 10-km "Mills Cross" array. Related advances in signal processing were pursued, including correlation techniques to exploit signal coherence across the array aperture. At about the same time, new developments in small geophones and in low noise amplifiers occurred, allowing installations deep in boreholes in an attempt to reduce wind noise. Green et al., give some details of these first steps toward larger arrays.[5]

> Backus, Berg, and their colleagues at Texas Instruments (T.I.) led in developing sophisticated techniques of combining the *N* seismometer outputs into one output.
>
> Acting on the realization that signal coherence over long distances must be insured in considering an expansion of array aperture, AFTAC, under the initiative of C.F. Romney, set up a network of eight independent mobile stations in the TFSO area to form a network having an aperture of 300 km. A system of phone line and microwave telemetry leading to a central digital multiplexing and recording system was installed in the summer of 1964 by AFTAC for Lincoln Laboratory to facilitate data collection and the study of equipment techniques required for large arrays.

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[5] Green, et al., ibid., p. 1826.

From the experiments with the Geneva-type arrays, some information had been obtained on noise correlation lengths.[6] The instrument spacing in LASA was initially smaller than these lengths.[7]

Methods were also worked out to alleviate some of the anticipated computing difficulties of the large arrays:[8]

> One of the major criticisms of the large arrays was simply that to use their high resolution in an on-line system required the provision of many simultaneous processed outputs (or beams). This, it was shown, could not be achieved without three Stretch computers running in parallel! Of course, no one wants to look at multichannel noise, and in the U. K. work on trigger clusters began. These clusters, at the center of each array, would act as coherent energy detectors, and provide the "bulletin" data from which the choice for subsequent off-line processing could be made. They could also provide a trigger pulse to switch on auxiliary processing equipment designed to give more detailed on-line analysis.

In 1963 the first VELA Uniform results were announced and had a strong impact on the U.S. negotiations for a comprehensive test ban treaty.[9] However, no "breakthrough" had occurred. Carpenter summarizes the technical arguments then developing for a large array,[10]

> Statistics were accumulating, but of breakthrough for explosions identification there was no sign. Was it time for a new look, a big step forward in technology with the hope that something new would result? The early doubts about digital computing had been overcome by the introduction of special purpose computers, and a whole range of new possibilities in processing were thus opened up. The velocity filtering properties of the large arrays, particularly their directional resolution, continued to receive attention, particularly since the detection of smaller events increased the chances of interfering signals.
>
> National networks, particularly the Canadian net, and then the international Worldwide Seismic System Network (WWSSN) were contributing more to

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[6] In his 1971 statement to the Subcommittee on R&D and Radiation of the Joint Commander on Atomic Energy, Dr. S.J. Lukasik, Director of ARPA, discusses seismic noise correlation lengths. Hearings before the Subcommittee on R&D and Radiation of the Joint Committee on Atomic Energy, 92nd Congress, 1st session, on the status of current technology to identify seismic events as natural or man-made. Oct. 1971, p. 23.

[7] C.F. Romney, ibid., p. 90. LASA spacings were eventually increased by decreasing the numbers of short-period seismometers. NORESS spacings are smaller, with higher frequency instruments.

[8] Carpenter, ibid., p. 1720.

[9] Glenn T. Seaborg, *Kennedy, Khruschev and the Test Ban*, Berkeley, CA; University of California Press, 1981, p. 162.

[10] Carpenter, ibid., p. 1020

> seismology. Regional networks, essentially arrays with fewer seismometers but larger spacings than the conventional arrays, telemetered their data to a central recording point. Such networks in Tasmania, California, New England, Arizona, and France all began to produce seismological data whose value derived largely from the velocity (including azimuth) resolution they could command.
>
> In trying to elucidate source mechanisms, it was found that geology still appeared to be the controlling factor. Perhaps if we could see the signal in the microseismic band "the glass would lighten and we would see the source less darkly," but this could only come from much larger arrays.
>
> Then some strange new noise appeared. Texas Instruments doing *f, k* noise analysis found significant noise power near the origin: high velocity noise. On quiet days, Yellowknife showed nothing like the $\sqrt{N}$ signal-noise improvement of noisier days. Here, apparently was "mantle P wave noise," probably the minimum noise level possible anywhere on earth. Only by increasing the array dimension could this noise be effectively reduced: and it would have to be a big increase.
>
> We were also reminded that aftershocks were a feature of earthquakes. Perhaps instead of going to the site of an event we could steer an array to look at it, but again only a large array could provide the required resolution.
>
> Thus there arose the project for a large array.

The treaty climate favoring distant observations had persisted, and there was increasing appreciation of the large costs that would be involved in a Geneva-type system with 170 monitoring stations. Thus,[11]

> R.A. Frosch of ARPA proposed in March 1964 that an effort be made to capitalize on existing array art to the extent of actually building a very large experimental array. Under his direction, a study group was formed to oversee such a development.

The "array art" included not only that of radar antennas mentioned by the Berkner Panel, but also some of Frosch's own previous experience with construction of large underwater arrays, and the associated signal processing.[12] Responsibility for LASA construction was given to AFTAC, and for the communications and data processing to the Lincoln

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[11] P.E. Green et al., p. 1825, and "The Concept of a Large Aperture Seismic Array," by R.A. Frosch, P.E. Greene, *Proc. R. Soc. A*, Vol. 290, 1966, p. 368-384.

[12] Discussions with Dr. H. Sonnemann, ARPA, LASA Program Manager, 5/31/88. Frosch previously had been at Hudson Laboratories in charge of the Navy's Project Artemis, involving a large underwater array, which posed similar processing problems on a smaller scale. Sonnemann, who was also in charge of engineering for Artemis, stated that LASA was much less risky.

Laboratory.[13] Lincoln had participated in some of the early U.S. array experiments, as mentioned above, applying digital processing techniques and theory based on their experience in radar and communications.[14]

Green, et al., gives further details about LASA:[15]

> The LASA study group was aided considerably at the beginning by the ideas on overall system organization presented to it by the T.I. group and by the Geotechnical Corporation's comparative evaluations of seismometers and preamplifiers. An initial rough design was worked out by the study group, involving 525 sensors and 200 km aperture, and a site in eastern Montana was tentatively chosen on the basis of recommendations by T.I., together with noise intensity measurements made earlier in various parts of the U.S. by the Geotechnical Corporation. This location had many desirable properties. It was sparsely populated, relatively uniform geologically, remote from oceans, not too distant from known overseas test sites, and convenient to transcontinental long-haul microwave facilities, should these be needed.
>
> In October 1964, T.I. began installing the first two 25-element, 7-km diameter subarrays, and in December, after it was decided to accelerate the program, Teledyne Inc. began installing the remaining 19 subarrays, and the local telephone companies began open wire line installation. Both these efforts proceeded at a rapid rate in the face of the most severe difficulties due to the winter weather.

"Speedups" ordered by DoD telescoped the originally anticipated path of LASA R&D.[16]

> System specifications which had been established were altogether preliminary and conceived LASA as a huge breadboard which would be evaluated in the field on a limited scale prior to installation of the total of 21 subarray systems. The final design was to evolve from this step, but much experimentation and a considerable amount of systems engineering remained to be completed.
>
> A decision by the Department of Defense to accelerate the experimental program appreciably foreshortened the operational date. Thus it was that a contract was written on December 1, 1964 requiring full operational status on June 1, 1965.

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[13] A.O. 599 of 7/64 for "VELA Large Arrays," and A.O. 624 of 10/64 for "VELA Uniform" to AFTAC; A.O. 670 of 2/65 for study of LASA signal processing to the AF ESD (contractor for Lincoln Laboratory).

[14] "Seismic Discrimination," Final Report, Lincoln Laboratory, 30 Sept., 1982, ESD TR. 82-099.

[15] P.E. Green, et al., ibid.

[16] "The LASA Sensing System Design, Installation Operations," C.B. Forbes, et al., *Proc. IEEE*, Vol. 53, Dec. 1965, p. 1834.

Apparently the speedup occurred sometime after Secretary of Defense McNamara was briefed in late 1964, and was impressed with the potential for a global test ban monitoring system.[17] An additional reason for speedup of LASA was to be ready in time for the nuclear explosions in Amchitka.[18] ARPA was then asked to estimate the number (and cost) of arrays required for global coverage, which turned out to be eleven to obtain 2 to 3 good directional "cuts," at a total cost of several hundred millions. DoD soon decided, however, not to go with eleven but eventually settled for two.[19]

LASA was a state-of-the-art system in its seismic components, many of which had been developed under the VELA Uniform program, and a major step in large-scale real time processing. LASA was the first large seismographic system to have digital recording with both online and offline data processing.[20] There was a new order of magnitude in quantity of data flow, and the overall LASA operation was under computer control from a central station. Testing and calibration of the field instrumentation could also be done remotely. Fig. 1 shows a "seismic view of the world" from LASA, and Fig. 2 indicates the scale of and nature of the installation. Fig. 3 displays a signal flow diagram for LASA.

The main objective, apparently, was to achieve higher signal-to-noise, and obtain clearer signals for detailed study.

According to Davies:[21]

> When LASA was being built, it was not known to what extent $\sqrt{N}$ (signal/noise) improvement would hold up. The central problem was not whether noise would be incoherent at 200 km seismometer separation but whether signal would be coherent over these distances...the array was denser in the middle so that if the signal was coherent only across 50 km, more than half the seismometers could contribute.

While there was considerable argument about what the LASA performance would be, when turned on, the majority of statements appear to be that the gain of the array was roughly as expected, within a few dB of $\sqrt{N}$.[22] With a randomized distribution of

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[17] Discussion with Dr. H. Sonnemann, 6/7/88. See also "The Advanced Research Projects Agency," 1958-1974; Richard J. Barber Associates, 1975, p. VII-18.

[18] Discussion with Dr. R. Sproull, 10/89.

[19] H. Sonnemann, ibid.

[20] Digital seismographic recording was pioneered by the oil industry. Cf. Sykes, Ref. 4, p. 246.

[21] "Seismology with Large Arrays," by D. Davies in *Reports on Progress in Physics*, Vol. 36, 1973, pp. 1233-1283.

[22] H. Sonnemann, ibid., see also Lukasik, ibid., p. 29, and P.E. Green et al., ibid.

instruments, simple delay and sum processing turned out to be about as good as could be obtained with much more sophisticated processing approaches.

Real-time beam forming to quickly locate epicenters of seismic sources was achieved, and it was possible to issue a daily worldwide earthquake bulletin. While the beams were narrow, the uncertainty of location in the Soviet Union was about 50-100 km, too large to be useful for efficient follow-up inspections.[23] In 1967 about a third of the LASA instruments were removed, since increased instrument spacings in the subarrays reduced short-period noise correlations, and there was no loss of signal-to-noise with delay and sum processing.[24] No new discriminant between explosion and earthquakes appeared, but known discriminants, for sources giving good signal to noise, stood out due to the higher degree of signal clarification. The quality of LASA signals allowed discovery of new reflections of seismic disturbances from inside the earth's core, and also indicated large-scale roughness of the core boundary.[25]

Originally it had been planned to construct two large arrays, partly because of the need to check one another at what was expected to be a new level of sensitivity, unachievable by any other smaller group of instruments. Also, at that time it seemed desirable, on the one hand, to have a capability for nuclear detection of tests anywhere on the globe, which required use of more than one location to obtain a first "fix," and on the other hand to make measurements closer to the Soviet main test site. Consequently, in 1967 ARPA proposed that another large array, "NORSAR," be constructed, as a cooperative project, in Norway. The geology of the NORSAR site also appeared to offer potential advantages for seismic signal propagation and bandwidth. This array was to be a "second generation" LASA, incorporating lessons learned in instrumentation and processing as well as automatic detection capability. The instruments removed from LASA in 1967 were used to start NORSAR. The Norwegian government approved the

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[23] However, when monitoring known nuclear test locations it was possible to calibrate arrivals and to do fine-grained location of new tests on the site, H. Sonnemann, ibid.

[24] Early statements, cf. Frosch and Green, ibid., p. 383, indicate early hopes that threshold (Richter) magnitudes of 3-3.3 were expected. However, later statements give a figure of 3.5 to 3.8. Romney, ibid., states that the overall gain of LASA was not, in fact, better than that of a smaller array at a very quiet location, 3.9. P.E. Green, et al., discuss the tradeoff of gain and computing costs.

[25] F. Ringdal and E.S. Husebye, "Application of Arrays in the Detection, Location and Identification of Seismic Events," *Bull. Seismol. Soc. of Am.*, Vol. 72, No. 6, pp. S-201-224, Dec. 1982.

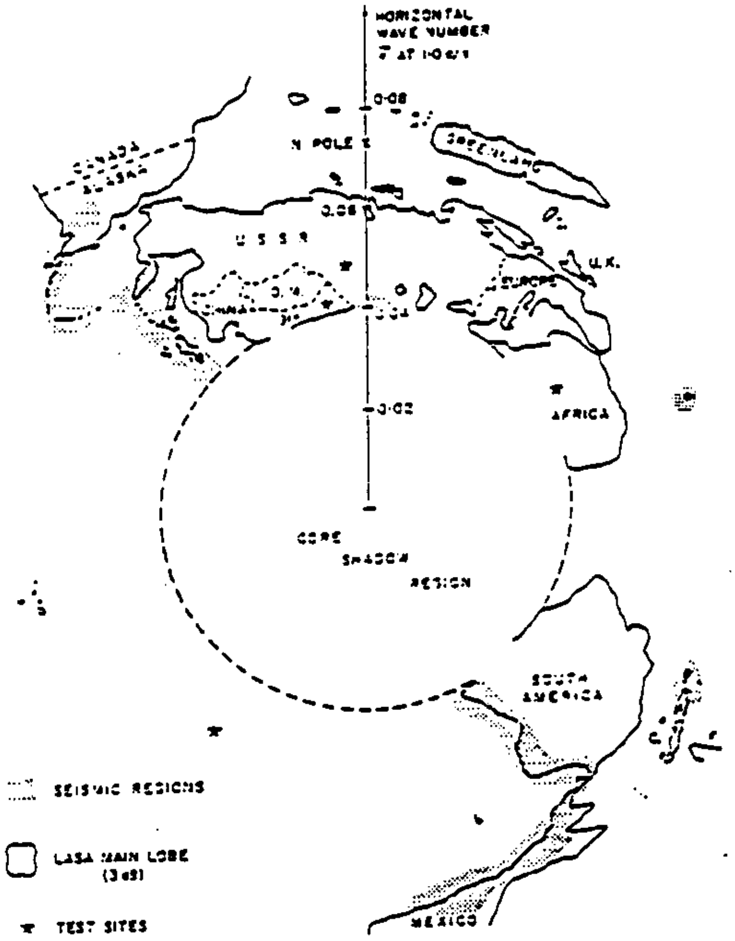

Figure 1. The Earth as Seen From the Center of LASA

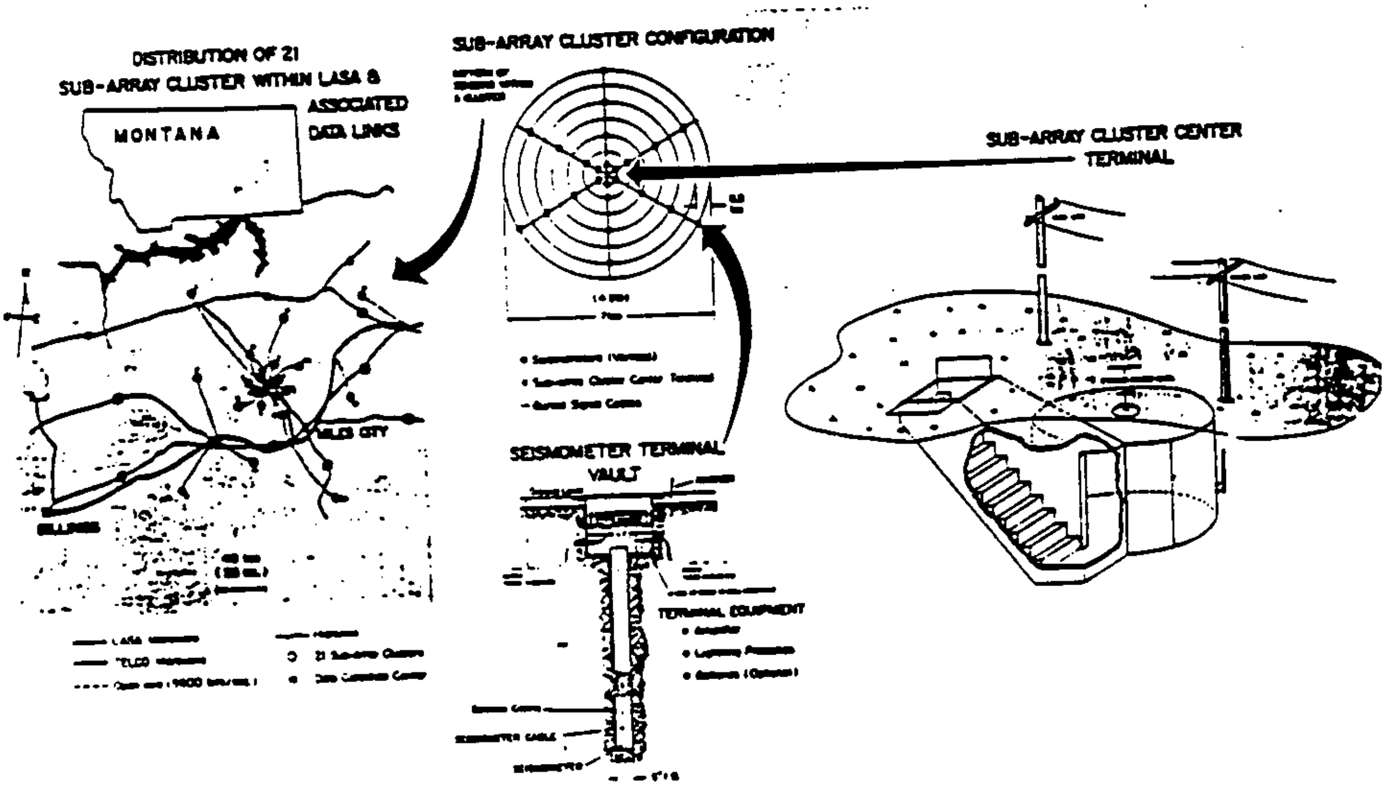

Figure 2. Large Aperture Seismic Array (LASA)

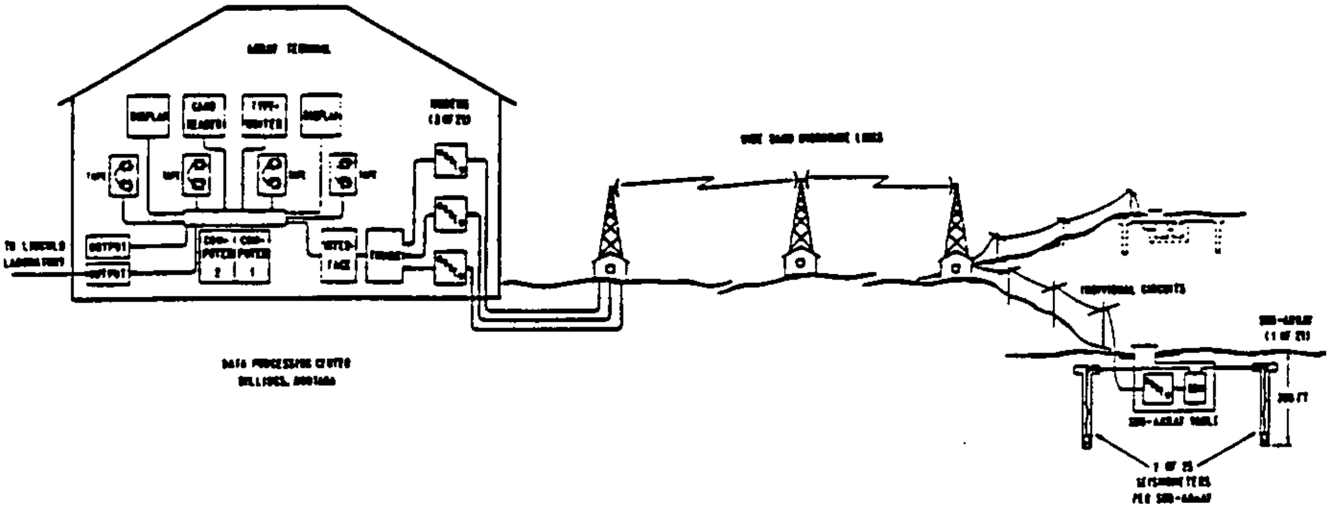

Figure 3. Signal Flow Diagram

project in 1968, and NORSAR became operational in 1971.[26] Data links through ARPANET connect NORSAR with DARPA's Seismic Analysis Center in Alexandria, VA. NORSAR initially was somewhat smaller, about one-half the size of LASA, and with improved understanding of true array gain, and of computing expense, the array has also been gradually "thinned out."[27]

In 1968 an array of new, low-noise, long-period seismometers was developed under VELA Uniform. The Alaskan Long Period Array (ALPA), with 19 such instruments and an 80-km aperture, was installed near Fairbanks, Alaska. Digitized data was transmitted by radio to a local control sensor, and eventually all the large arrays transmitted to the ARPA Seismic Data Center in Alexandria, VA.[28] ALPA operated until late 1970.

NORSAR is still operating. However, Husebye, et al., state that the large arrays were in full operation only for about 5 years, during which time a large volume of high quality data were accumulated.[29]

In a review article, Husebye and Ringdal state that:[30]

> ...the event detection capability of arrays has proved superior to that of simple stations, but event locations, while readily available, are seldom very accurate (not < 50 km) .... the implied two-dimensional wave field sampling provided by arrays has been instrumental in understanding phenomena like the ambient noise field, the extent of mantle heterogeniety, and their effect on short wave propagation. It is somewhat unfortunate that due to limitations in handling the enormous amounts of data involved, only a relatively small number of seismologists has had access to the high quality array recordings; recent advances in computer technology might eliminate such problems in the near future. New technology also makes possible a new trend in array seismology, involving on the one hand worldwide deployment of small- and medium-sized arrays, and on the other hand opening up array processing techniques for a global network of such stations...
>
> ...interest has shifted more to small and medium high arrays, primarily because of cost but also because it has been realized that a few large arrays cannot by themselves solve the problems in monitoring a nuclear test ban.

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[26] A.O. 1852 of 4/71 for NORSAR computer, to the Air Force Electronic Systems Division.

[27] A review of the status of NORSAR is given in "Seismic Arrays," by E. Husebye and S. Lugati, Chapter 28, *Arms Control Verification*, Boston, MA., Pergamon, 1986.

[28] W.E. Farrell, "Sensors, Systems and Arrays," in *The VELA Program*, DARPA 1985, p. 495. Farrell gives details of the instruments in the large arrays.

[29] E.S. Husebye, et al., "Seismic Arrays for Everyone," in *The VELA Program*, DARPA 1985, p. 527.

[30] F. Ringdal and E.S. Husebye, ibid.

Ringdal and Husebye also critically appraise the degree to which the large arrays, mainly NORSAR, have been successful in achieving their objectives. A more recent appraisal of seismic verification of nuclear testing treaties by the Congressional Office of Technology Assessment credits the full NORSAR array, when operated at higher-than-usual frequencies, with an instantaneous detection threshold of very small explosions in selected locations in the Soviet Union.[31] Recent results obtained at NORESS, an updated dense subarray of NORSAR, at higher-than-ordinary seismic frequencies, have also indicated a new possibility of detection and identification of small explosions, even if decoupled.[32]

The same OTA appraisal discusses the relative worth, in current thinking, of arrays versus the use of many distributed single seismographs for treaty verification.[33]

C. OBSERVATIONS ON SUCCESS

The LASA initiative was taken by ARPA. The Berkner Committee had made a recommendation to look into large arrays. The engineering risks taken in the expansion of seismic array size to LASA dimensions were not regarded as high by the program managers. However, there was uncertainty about the results of processing the noise, and to what degree signal coherence would be useful across the full aperture. AFTAC, on which ARPA had previously relied heavily, apparently did not favor the project, and put forward an alternative proposal which ARPA did not regard as involving state-of-the-art processing.

At the time, it seemed very important to answer the questions of what capability could be achieved by pulling together the state of the art in seismic instruments and in digital signal processing capability in a really large array. It was envisaged that doing so would transform seismology.[34] The treaty climate seemed unfavorable and it appeared that monitoring of underground nuclear tests, then considered as possibly occurring in many locations on the globe, might have to be done from locations under U.S. control. A very large array could give directional indications, and several such arrays were initially

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[31] "Seismic Verification of Nuclear Testing Treaties," Congress of the U.S. Office of Technology Assessment (OTA), USGPO, May 1988. The magnitudes quoted here are about 2.5.

[32] Ibid., p. 70. Cf. also Sykes, Ref. 4, p. 286. The bandwidth required for the high frequency NORESS data is larger than can be accommodated by the ARPANET line to NORSAR. Discussion with C.F. Romney, 7/88.

[33] Ibid., p. 74.

[34] Communications from C. Herzfeld, 1/90.

discussed to provide localization. Even with several LASA's, however, the localization uncertainty was understood to be so large that the problem of follow-on inspection would be formidable.

LASA was successful in demonstrating a new level of data processing capability, which has affected all test detection systems since. However, no new "discriminant," for nuclear tests versus earthquakes, emerged from the LASA experiments. The increase of LASA sensitivity seemed to go as the square root of the number of instruments, which was less than some had hoped.

NORSAR, originally thought of as a "second LASA," was closer to the Soviet Union, where most explosions of interest were expected to occur. NORSAR was started with instruments taken from LASA, as a result of discussions between ARPA and seismologists from Norway, and has been quite successful, indicating the continuing utility of the large array concept as a research tool. While no new discriminants were forthcoming also from NORSAR at first, recently the use of high frequencies appear to show some promise. NORSAR has also offered a means to assess the cost-effectiveness of smaller arrays, of different sizes, and to help define the NORESS subarray. NORESS may be regarded as a state-of-the-art monitoring array and a prototype for a international monitoring station under a test-ban treaty.

It is most unlikely that research facilities such as NORSAR and NORESS and their implications for nuclear test detection systems would exist, without the VELA program. A full "transition" of this DARPA technology has not yet occurred, however, partly because no agency has the ability to carry out an adequate follow-on responsibility. This problem may be cleared up if and when a more complete ban on underground nuclear tests comes into effect.[35]

The ARPA outlay for the LASA facility was apparently about $20 million. The follow-on research using the facility is estimated to have been about $25 million, for a total of $45 million.[36] Costs of building NORSAR, including its computer, are estimated as about $8 million.[37]

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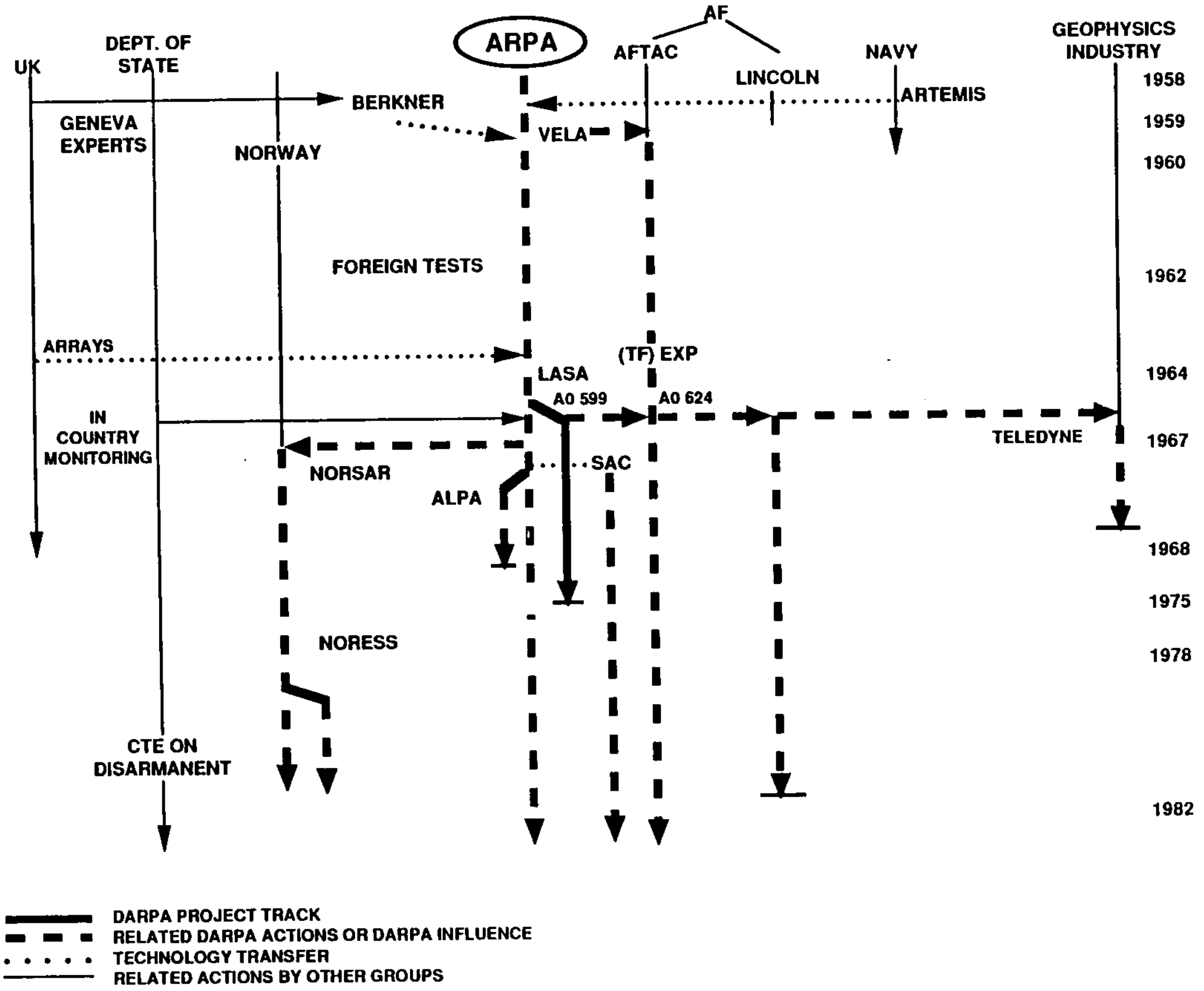
[35] "Intelligence Support To Arms Control," Report of the Permanent Select Committee on Intelligence, House of Representatives, USGPO 1987, p. 54.

[36] Discussions with H. Sonnemann and R. Lacoss, 8/89.

[37] "The NORSAR Array and Preliminary Results...." by H. Bungum et al., Geophys. J.R. Astro Soc. (1971) Vol. 25, p. 115 and AO 1852.

LASA



7-31-89-1M

D. AGILE: VIETNAM WAR PROGRAMS

XIV. IMPACT ON M-16 RIFLE

A. BRIEF OVERVIEW

ARPA bought a number of lightweight ArmaLite AR-15 rifles under project AGILE in 1961 and 1962 to evaluate in Vietnam. The very positive evaluation in August 1962 had a major impact on the DoD studies leading to a decision, in early 1963, to purchase AR-15's in quantity for use in Vietnam, and eventually on the Army's adoption in 1967 of the follow-on M16 as its standard rifle.

B. TECHNICAL HISTORY

The lightweight, high-velocity .22 caliber AR-15 rifle was originally developed by Eugene Stoner of ArmaLite division of Fairchild Industries in response to a request in 1957 by Gen. Wyman of the Continental Army Command.[1] The background of this request came from earlier studies by the Army's Aberdeen Laboratory going back to the 1920's, and in the 1950's by Army supported studies by a contractor, the Operations Research Office (ORO), which indicated that a rapid fire, high-velocity, small-caliber weapon could be very effective at ranges at which rifles appeared most likely, from recent experience in Korea, to be used in ground combat.[2] It was also argued that lighter rifles could allow a soldier to carry more ammunition, and increase combat effectiveness.

While the ArmaLite AR-15 had undergone a number of tests and had some support within the Army, initially it met with opposition from the Army Ordnance Corps. The Ordnance Corps favored the heavier, larger caliber, M14, which was designed for use primarily in the NATO theatre and had influenced the caliber and choice of and agreement on NATO standard ammunition. The semiautomatic M14's were being produced in large numbers in the late 1950's and early 1960's, and were expected to gradually substitute for

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[1] E.C. Ezell, *The Great Rifle Controversy*, Stackpole Books, 1984, p. 162.

[2] Notably, the ORO report "Operational Requirements For an Infantry Hand Weapon," by Norman A. Hitchman, June 1952; see also *The Black Rifle*, by R. Stevens and E.C. Ezell, Collector Grade Publications, Toronto, 1987, p. 9. The Viet Cong gave the name of "The Black Rifle" to the M-16.

several weapons: the M1 rifle, the Browning Automatic Rifle (BAR) and the carbine, as these were phased out of the inventory.

The AR-15 had also been taken on a "World Tour" demonstration in 1959 by Mr. Bobby MacDonald of Cooper MacDonald Company, affiliated with Fairchild.[3]

In July 1960, an informal demonstration of the AR-15 was given to Gen. Curtis LeMay of the Air Force. This led to Gen. LeMay's recommendation for Air Force use of the AR-15 to replace their older carbines. After three tries, the Air Force was able to get approval for procurement of AR-15's in May 1962.[4]

ARPA's project AGILE had a mission of rapid development of material for use by Vietnamese forces, and had set up a field R&D unit in Vietnam. The ARPA field unit reported that the small-statured Vietnamese soldiers were having problems with the M1 and other weapons they had been given by the U.S. due to weight and recoil.[5] Bobby MacDonald, now affiliated with Colt Industries, which had bought out rights to the AR-15 from Fairchild, urged ARPA's project AGILE to test the lighter AR-15 in Vietnam. According to Stevens and Ezell:[6]

> It wasn't long before the tireless Bobby MacDonald had convinced Col. Richard Halleck, on loan to the AGILE team from the Army, that the light, lethal but soft-recoiling AR-15 was just the rifle ARPA was looking for. By late summer ARPA had officially requested over 4,000 AR-15s to support a proposed full-scale test of the AR-15 in conjunction with special US advisor-guided units of the South Vietnamese Army. This request was denied, on the grounds that M2 Carbines were just as suitable for small-statured troops, and were available from storage. Undaunted, ARPA boiled the whole idea down to what they could afford: a limited range of tests in Saigon, in October 1961, with ten Colt AR-15s. The number of rifles might have been small, but the enthusiastic reaction of the Vietnamese and their American advisors alike who handled and fired the AR-15s was just as Bobby MacDonald had predicted.
>
> Armed with these positive results, ARPA resubmitted its original request, clearly stating that the AR-15s required were to be used to arm special US advisor units and their Vietnamese allies only, and were not to be considered as a general issue item for regular U.S. troops.

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[3] Stevens and Ezell, ibid., p. 83.

[4] Stevens and Ezell, ibid., pp. 87-97.

[5] Richard J. Barber Associates, ARPA History, p. V-44. According to S. Deitchman of IDA the equally small Viet Cong seemed to have fewer problems with captured M1's. However, R. Sproull pointed out that the differences of operational discipline of the Viet Cong and ARVN also mattered. Communication with R. Sproull 10/89.

[6] Stevens and Ezell, ibid., p. 100.

This ARPA request came through Military Assistance Advisory Group (MAAG) channels. The MAAG had been trying to provide M-1's, which came "free" as war surplus in Vietnam.[7] In December 1961, Secretary of Defense Robert S. McNamara approved purchase of 1000 AR-15's for this field test. ARPA responded quickly, procuring the rifles and arranging for shipment.[8] The test was to be under combat conditions, and involved experienced Vietnamese soldiers and U.S. military advisers. In August 1962, the AGILE field test report was in, stating that the Vietnamese much preferred the AR-15's and recommending that the AR-15 be considered for adoption by all Vietnamese forces, especially for jungle combat. Stevens and Ezell, in their recent history of the M16 state that "this (report) was the most influential yet controversial document so far in the history of the already controversial AR-15."[9] Because of its interest, most of the field report is reproduced in the Annex to this chapter. Immediately after the AGILE field test, the MAAG Vietnam requested 20,000 AR-15's. Apparently, the Army Material Command, which had absorbed the Ordnance Corps, agreed with the AGILE report that the AR-15 was more suitable for the small-statured Vietnamese troops. However, it was three years before AR-15's were made available in quantity for use in Vietnam, and nearly six years before they were made available to the Vietnamese forces.

A follow-on study, by C. Hitch of DoD's Systems Analysis Group, based partly on the ARPA field unit study, was issued in late September 1962 and was highly favorable to the AR-15. Stevens and Ezell describe the background:[10]

> Over this same period (summer 1962) ARPA staffers back in Washington had introduced the ubiquitous Bobby MacDonald to others in the OSD's Systems Analysis Directorate. A demonstration for all interested OSD personnel was arranged wherein AR-15s and M14s were fired in comparison with the standard assault rifle of the communist world, the 7.62x39mm AK47. Within this framework the AR-15's light weight, low recoil and controllability on automatic fire appeared particularly impressive.
>
> A comprehensive OSD study of the history of service rifle caliber reduction was soon in the works. Starting with the .276 Pedersen round of the nineteen-twenties, OSD analysts worked their way through the ORO studies and BRL's small caliber, high velocity (SCHV) reports of the fifties, and concluded with the results of their own comparison of the .223 caliber AR-15 rifle with the M14 and the AK-47. A report of their findings was sent to

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[7] R. Sproull, ibid.

[8] A.O. 298 of 12/61 for AR-15 rifles, project AGILE, to Cooper-Macdonald, Inc.

[9] Stevens and Ezell, ibid., p. 100.

[10] Stevens and Ezell, ibid.

Secretary McNamara on September 27, over the signature of OSD's Comptroller, Charles Hitch. Abandoning all pretense that the AR-15 was suitable only for small-statured Vietnamese, the Hitch report stated:

> The study indicates that the AR-15 is decidedly superior in many of the factors considered. In none of them is the M14 superior. The report, therefore, concludes that in combat the AR-15 is the superior weapon. Furthermore, the available cost data indicate that it is also a cheaper weapon.
>
> Although analyzed less thoroughly, the M14 also appears somewhat inferior to the M1 rifle of World War 2, and decidedly inferior to the Soviet combat rifle, the AK-47, which in turn, was derived from the German "Sturmgewehr" of World War 2.

Because of the contradictory views about the AR-15, the White House requested and the Secretary of Defense ordered a reevaluation of the Army's rifle program, to be carried out by January 1963. The Army's Chief of Staff had, in fact, already started such an evaluation. The Army's January evaluation report was a qualified negative, recommending use of the AR-15 for airborne and special forces, but not for NATO. However, rumors of bias led the Secretary of the Army Cyrus Vance to request the Army's Inspector General (IG) to investigate. The IG reported a finding of bias.

After some further discussion with his systems analysts, who pointed out that an Army flechette-firing rifle, the Special-Purpose Individual Weapon (SPIW), was in development and might soon supersede the AR-15 and M14's, Secretary of Defense McNamara directed in January 1963 that there be no more M14 production after FY 1963, noting that there were many M14's in the inventory. The Secretary of Defense also applied M14 production funds to purchase AR-15's for the Army special forces and airborne units. The Army assumed procurement responsibility for the AR-15 soon after, and agreed to a "one-time" buy of 8,500 AR-15's, which later became 104,000, of which 19,000 were for the Air Force. A formal AR-15 project office and interservice technical committee was set up by the Army,[11] with guidance by Secretary of Defense that changes to the AR-15 were to be minimal and at least cost in order to exploit the advantages of commercial development. Also there were no RDT&E funds for the AR-15. Deputy Secretary of Defense Gilpatrick further advised the Army, "to avoid the cost, delay, and manpower difficulties of quality control, parts interchangeable and acceptance test standards programs

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[11] Apparently this was the first technical interservice committee to be concerned with rifles. They were counselled by the Secretary of Defense to consult with Eugene Stoner, developer of the A-15, about any technical changes, but apparently this was not done. Stevens and Ezell, ibid., p. 125.

of various rifle procurements."[12] However, the Army wanted a number of changes, such as manual bolt closure, bore twist, and, importantly, ammunition. The Army wanted to use more potent ball-powder ammunition, apparently in order to obtain larger lethal ranges approaching NATO requirements. The Air Force and U.S. Marine Corps disagreed with these changes; however, they were instituted, partly because the Secretary of Defense insisted on getting a single rifle for all three services, and because of the pressures of Vietnam. In 1964, the Army type-classified the AR-15 as the experimental M16 EX1[13] for issue to U.S. troops. In the spring of 1965, the M16's were in use by U.S. airborne troops deployed in Vietnam. In July, Gen. William Westmoreland requested 100,000 M16's for all American combat troops in Vietnam. However, the Commander-in-Chief, Pacific (CINCPAC) and the Joint Chiefs of Staff (JCS) disagreed with this request, giving as reasons priorities, difficulties with logistics, and the superiority of U.S. weapons in Vietnam. The intervention of a senator who visited Gen. Westmoreland in December 1965, cleared the way to satisfy this request.[14] In September 1966, new XM16E1's were issued to U.S. Army units in Vietnam. In December 1966, Secretary of the Army Resor officially informed Secretary of Defense McNamara of the results of the Army's small arms weapons systems (SAWS) program, aimed at evaluation of small arms to the 1980's -- stating that the XM16E1 was generally superior, needed a few further changes, and that the SPIW was unlikely to be useful in the foreseeable future, and certainly would not be available for Vietnam.

However, as large numbers of M16's began to be used in Vietnam, a number of serious problems began to be reported, in particular the rifle's tendency to jam under heavy use in combat. These led to visits to the field by Army and Colt experts, and also to several Congressional investigations beginning in early 1967.[15] A systematic field test was conducted by the JCS' Weapons System Evaluation Group (WSEG) with help from the Institute for Defense Analyses (IDA), to investigate the M16 problems.[16] Some of these problems were traceable to a lack of maintenance manuals and instruction, and others were eventually found to be due to excessive chamber pressure associated with the ball-type propellants imposed by the Army, which caused a more rapid firing cycle, and also to

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[12] Stevens and Ezell, ibid., p. 125.

[13] Ezell, "The Great Rifle Controversy," p. 180.

[14] Stevens and Ezell, ibid., p. 197.

[15] Hearing of the special committee on the M16 rifle programs (the Ichord hearings) Committee on Armed Services HOR, 90th Congress, 1st session, Mar-Aug. 1967.

[16] WSEG Report 164, Operational Reliability Test, M16A1, Rifle System, Feb. 1968.

corrosion associated with the propellants and the lack of interior plating of the chamber and barrel.[17] These problems were considered broadly due to the rapid rate of introduction of the rifle directly into use, without concurrent RDT&E, and the corresponding lack of proper support by industry and the Army. Partly also, some difficulties could be associated with the use of more powerful ammunition, in the desire to extend lethal range in a weapon originally designed for use at limited range. Some of these problems, e.g., maintenance manuals, were dealt with quickly; others have been overcome in a gradual "product improvement."

In early FY 1968, the M16 was made available to the South Vietnamese Army by the Secretary of Defense. In July 1968, the U.S. Military Assistance Command, Vietnam (USMACV) published an analysis of the results of arming the South Vietnamese Army army with the M16, which reconfirmed the advantages of size, weight, rate of fire, ballistics, and logistics and credited its introduction with a significant improvement of operational capability, morale, and *esprit de corps*.[18]

Many of the problems of the M16 have been gradually overcome by evolutionary improvement and change, and the M16 is now the standard rifle for the U.S. Army. The The M16 has also been sold, and is in production worldwide. Stevens and Ezell state:[19]

> As summed up at an April 1971 ARPA Small Arms Conference by Dr. W.C. Pettijohn, author of numerous studies on the analysis of small arms effectiveness:
>
> The M16 has proven itself to be a superior rifle and has been accepted as such on a worldwide basis. It also has potential for mass production in the event of an emergency. There are no weapons currently that can be considered a competitor. Government efforts to develop a successor will proceed slowly. The conference forecasts six to eight million M16 rifles being produced during the next ten year period at a cost of two to three billion {dollars].
>
> Active, direct American military involvement in the Vietnam war ended in 1973. Later Defense Intelligence Agency estimates were that among much other ordnance, the U.S. supported Army of the Republic of Vietnam

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[17] These corrosion problems had not been noticed in the AR-15, which used a different ammunition, and led to statements by the manufacturer that no cleaning was needed for the rifle. This apparently was the reason the M16 had no equipment for cleaning initially, and for statements that no training was required. However, the designer did not feel the AR-15 was in all respects an optimum product. Discussion with E.C. Ezell, 8/88.

[18] "An Evaluation of the Impact of Arming the Vietnamese Army With the M-16 Rifle." Doctrine and Analysis Division, USMACV 30 July 68.

[19] Stevens and Ezell, ibid, p. 319.

> (ARVN) and the Cambodian Army had been forced to abandon roughly 946,000 serviceable AR-15, M16, XM16E1 and M16A1 rifles to the victorious North Vietnamese Army (NVA). In the mid-1980s, when many of these weapons began to appear on the international small arms black market, the M16 became the most widely distributed 5.56mm rifle in the world.

However, problems remain in meeting NATO requirements for armor penetration and also in satisfying requirements of the U.S. Navy with the M16.[20] In fact, the U.S. adoption of the M16 as its standard rifle appears to have disregarded previous U.S. commitments to NATO.[21] Joint Army-Marine Corps efforts were started in the late 1970's under the Joint Services Small Arms Program (JSSAP) program to develop a larger caliber rifle and penetrating ammunition for use on future battlefields expected to include large numbers of armored vehicles.[22]

C. OBSERVATIONS ON SUCCESS

The AR-15, predecessor to the M16, was already for sale worldwide and had been decided on by the Air Force as a procurement item when ARPA purchased some for test in Vietnam. Thus ARPA did not undertake a technological development, but a test under field conditions which was timely and highly appropriate for the AGILE mission. The train of subsequent events, which led finally to acceptance of the M16 by the Army, can be definitely traced to the impact of the early ARPA-supported test results. However, ARPA's originally stated motivation, to quickly supply the Vietnamese troops with a weapon more suitable for their size and for the short ranges usual to jungle fighting, was not achieved. It took nearly six years for the Vietnamese army to get the M16.

The difficulty in getting Army acceptance of the AR-15 at the time was partly due to the fact that the Army had extensive commitments to the M14, which had just gotten into large-scale production, after some difficulties, and had been accepted by NATO, and partly to availability of surplus M-1 rifles in Vietnam. Partly, also, ARPA's interventions on behalf of the AR-15 aroused considerable resentment in Army circles.[23]

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[20] "The Great Rifle Controversy," Ezell, p. 250, 259, and 261.

[21] Discussion with S. Deitchman, IDA, 4/89.

[22] Testimony of B. Gen. William H. Fitch, USMC, FY 1980 DoD Authorization Hearings, Committee on Armed Services, U.S. Senate, 96th Congress, 1st Session, Part 6, p. 3073.

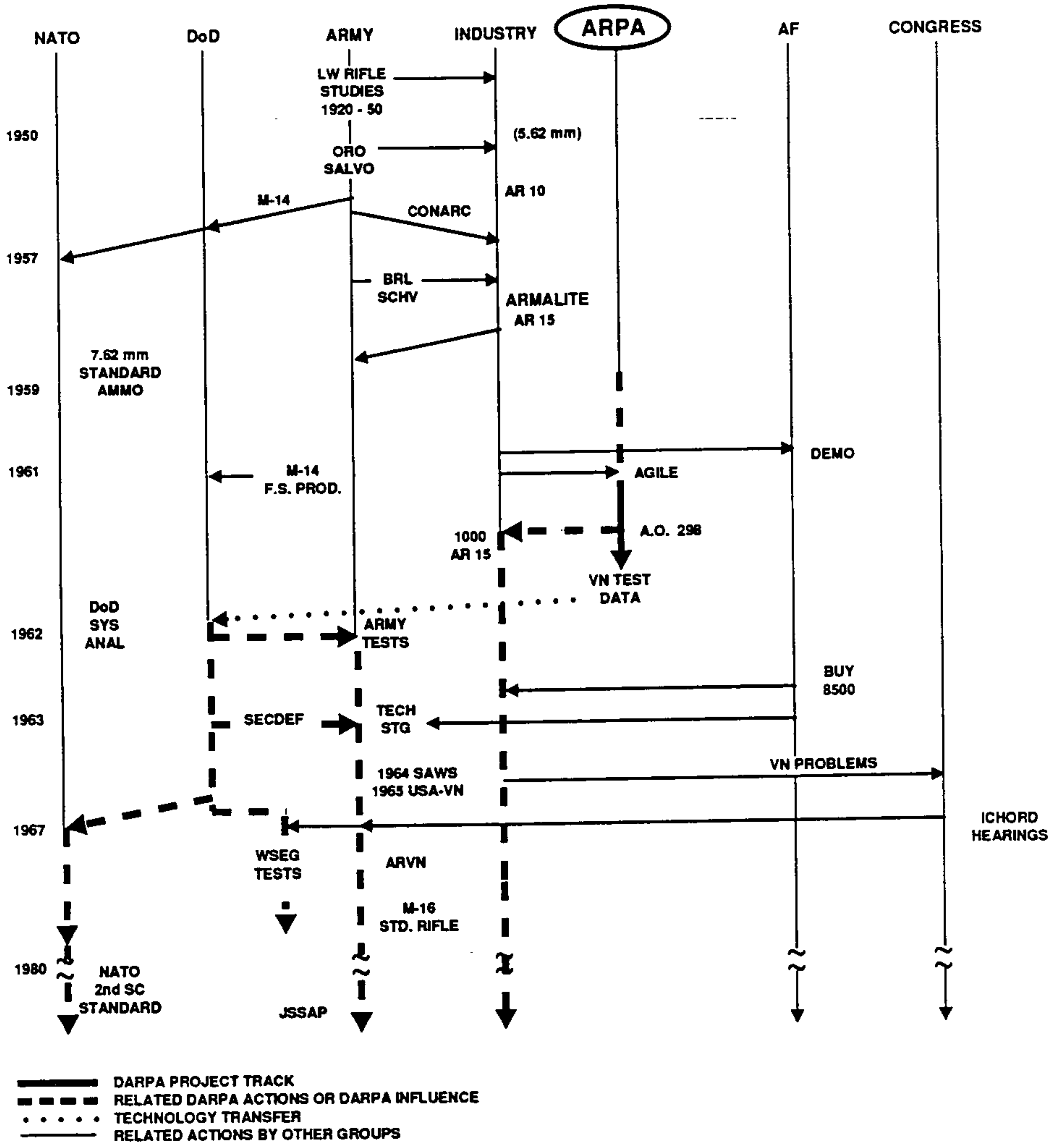
[23] R. Sproull, ibid.

The problems with the M16 that occurred in Vietnam can be traced to a mixture of DoD overconfidence in the original product, and the changes instituted by the Army without concurrent R&D and testing. The lack of R&D was due to a DoD top level decision, apparently in the belief that the AR-15 was a finished product, and that R&D would get in the way of expeditious procurement.

In spite of the fact that DoD had previously agreed to standards for lethal ranges with NATO allies, the M16, which does not meet these standards, was adopted as the principal U.S. Army rifle. Some of the troublesome changes by the Army seemed to be due to a desire to approach these NATO standards. Apparently, NATO may accept something like the M16 as a secondary assault rifle. However, expectations continue that in a NATO war longer lethal ranges and greater armor-penetrating capabilities will be needed, and R&D efforts continue to provide U.S. forces with a suitable rifle.

ARPA recorded outlay for two purchases of first 10 and later 1000 AR-15 rifles and their shipment at a cost of about $500,000. This does not include expense of the AGILE field office in Vietnam in connection with the tests. A rough estimate of dollars expended for the M16, by the U.S. and others, is between $2 and $3 billion.

AR 15 M-16



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ANNEX
REPORT ON TEST OF AR-15

Advanced Research Projects Agency
Research and Development Field Unit
31 July, 1962

Report of Task 13A, Test of ArmaLite Rifle, AR-15

Purpose

The purpose of this test was to determine if the AR-15 rifle is compatible with the small stature, body configuration and light weight of the Vietnamese Soldier and to evaluate the weapon under actual combat conditions in South Vietnam. At the request of MAAG [Military Assistance Advisory Group], Vietnam, the scope of the test was expanded to include a comparison between the AR-15 and the M2 Carbine to determine which is a more suitable replacement for other shoulder weapons in selected units of the Republic of Vietnam Armed Forces (RVNAF).

Background

The problem of selecting the most suitable basic weapon for the Vietnamese soldier is complicated by his small stature and light weight. The average soldier stands five feet tall and weighs ninety pounds. Principle US weapons presently issued to Vietnamese troops include the M1918A2; the Thompson Sub-Machine Gun, Caliber .45; and the US Carbine, Caliber .30, M1.

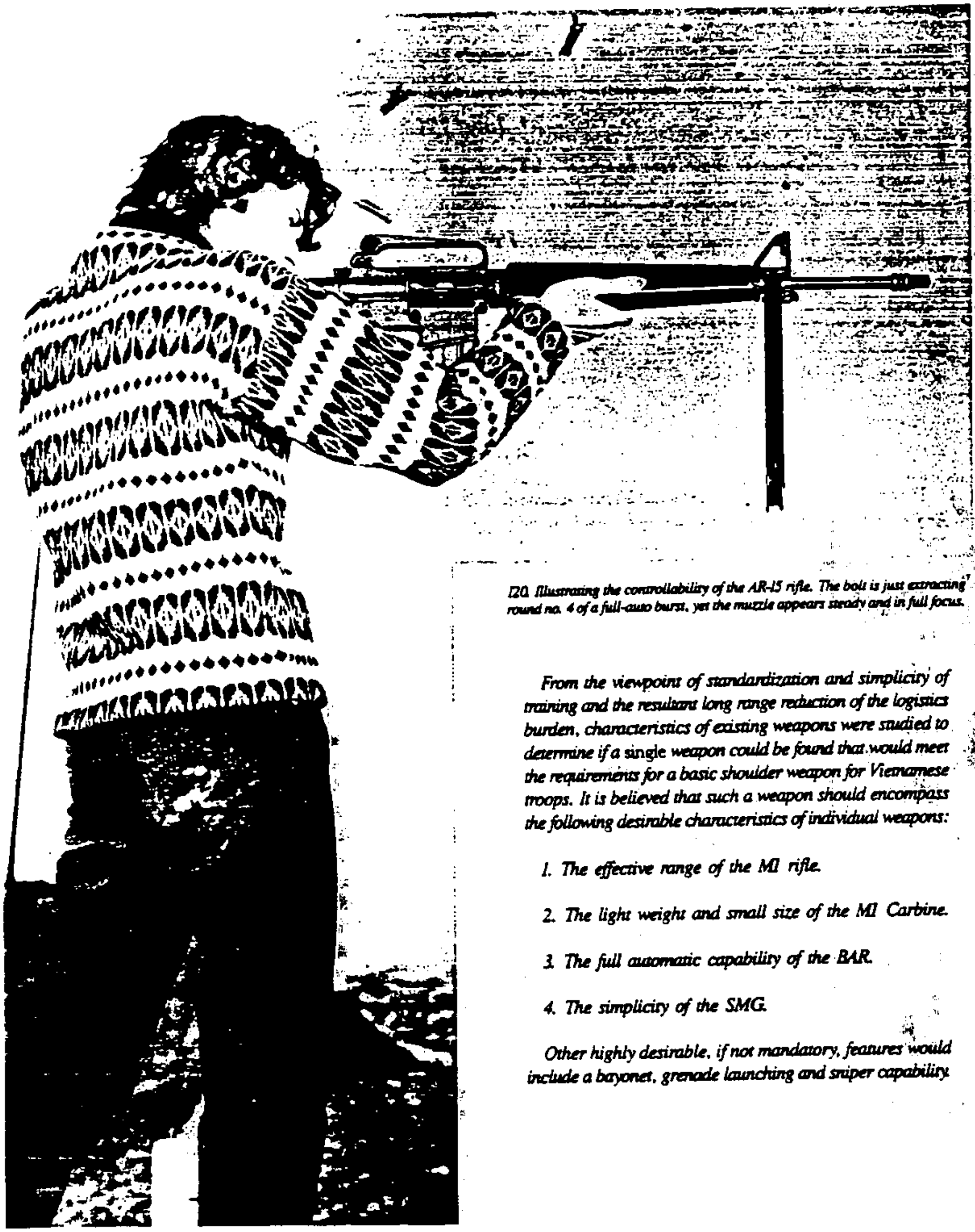
Because of its availability and the results of extensive studies and previous testing by military agencies, the Colt ArmaLite AR-15 rifle was selected in July, 1961 as the most suitable weapon for initial tests. This weapon was developed by the ArmaLite Division of Fairchild Aircraft Corporation to meet the military characteristics for a lightweight rifle utilizing the high velocity small caliber principle. It was first tested by the US Army Infantry Board in 1958. Since then, the weapon and its ammunition have undergone extensive engineering and service tests by: Aberdeen Proving Ground; the Combat Development Experimentation Center, Fort Ord, California; and the US Air Force at Lackland Air Force Base, Texas. The rifle, with several modifications resulting from these tests, is presently being manufactured by Colt's Patent [Firearms] Manufacturing Company, Hartford, Connecticut. (Prior to the completion of this report, the US Air Force adopted the AR-15 as its basic shoulder weapon, replacing the M2 Carbine, the Browning Automatic Rifle and the M3 Sub-Machine Gun).

Based upon favorable observations of the AR-15 by both US Advisors and RVNAF Commanders following limited firing demonstrations conducted in Vietnam during August 1961, weapons were requested in numbers sufficient to conduct a full-scale combat evaluation of the AR-15 by selected units of the RVNAF. In December 1961, the Secretary of Defense approved the procurement of 1,000 AR-15 rifles, necessary ammunition, spare parts and accessories for evaluation.

OSD/ARPA negotiated a contract with the firm of Cooper-Macdonald Inc., of Baltimore, Maryland, for procurement and air shipment of all materiel. The first shipment was received on 27 January 1962 and subsequent increments arrived approximately every three weeks until the contract was fulfilled on 15 May 1962. Operational evaluation and testing began on 1 February and terminated on 15 July 1962.

Discussion

The extremely mobile type of offensive warfare being stressed by US Advisors in Vietnam and the small stature and light weight of the Vietnamese soldier places a high premium on small, lightweight weapons. In addition, the violent short clashes at close ranges which are characteristic of guerrilla warfare in Vietnam makes it highly desirable to have a dependable weapon capable of producing a high rate of accurate and lethal full automatic fire.



120. Illustrating the controllability of the AR-15 rifle. The bolt is just extracting round no. 4 of a full-auto burst, yet the muzzle appears steady and in full focus.

From the viewpoint of standardization and simplicity of training and the resultant long range reduction of the logistics burden, characteristics of existing weapons were studied to determine if a single weapon could be found that would meet the requirements for a basic shoulder weapon for Vietnamese troops. It is believed that such a weapon should encompass the following desirable characteristics of individual weapons:

1. *The effective range of the M1 rifle.*
2. *The light weight and small size of the M1 Carbine.*
3. *The full automatic capability of the BAR.*
4. *The simplicity of the SMG.*

Other highly desirable, if not mandatory, features would include a bayonet, grenade launching and sniper capability.

Details of the Combat Evaluation of the AR-15

Selected Vietnamese units which had previously been engaged in considerable combat were issued AR-15 rifles and ammunition for use against the Viet Cong...[as follows:]

Unit	*AR-15 Rifles*	*Ammunition*
7th Infantry Division	*100*	*50,000 rounds*
Rangers	*100*	*50,000 rounds*
Airborne Brigade	*390*	*195,000 rounds*
VN Marines	*100*	*50,000 rounds*
VN Special Forces	*100*	*50,000 rounds*
Special Battalions	*125*	*120,000 rounds*
5th Infantry Division	*40*	*25,000 rounds*
Father Hoa	*10*	*10,000 rounds*
Total	*965*	*550,000 rounds*

Summary of Tests

To accomplish the stated purpose of this test, it was divided into two parts. One part was a combat evaluation of the AR-15 in which the weapons were issued to specially selected ARVN units for use in their operations against the Viet Cong. Along with the rifles and ammunition, Vietnamese Unit Commanders and US Military Advisors were given weapon preference and operational questionnaires and requested to complete and return them after training and combat use of the AR-15...

The other part of the test consisted of a comparison between the AR-15 rifle and the M2 Carbine. Areas in which the two weapons were compared included: physical characteristics; ease of disassembly and assembly; marksmanship ability at known distances, semi-automatic and automatic fire; marksmanship ability at unknown distances, semi-automatic and automatic fire; ruggedness and durability; adequacy of safety features; effects of open storage in a tropical environment; ability to penetrate dense brush and heavy foliage; and, the individual Vietnamese soldier's preference between the two weapons.

Analysis [of the Combat Evaluation]

Based on the numerical ratings and the comments of US Advisors and VN Unit Commanders, the AR-15 is the most desirable weapon for use in Vietnam for the following reasons:

1. *Ease of training.*
2. *Suitable physical characteristics.*
3. *It is easy to maintain.*
4. *It is more rugged and durable than present weapons.*
5. *It imposes the least logistical burden.*
6. *It is the best weapon for all-around tactical employment.*

7. Its semi-automatic firing accuracy is comparable to that of the M1 rifle, while its automatic firing accuracy is considered superior to that of the Browning Automatic Rifle.

8. Vietnamese troops, Commanders and US Advisors prefer it to any other weapon presently being used in Vietnam.

Details of Comparison Test Between the AR-15 and M2 Carbine

Personnel from a Vietnamese company that had just completed advanced individual training were used as test subjects for most of this comparison. The unit of 180 men was divided into two groups of 90 men each. Group A received one M2 Carbine per man, while Group B received an AR-15 for each man. Each group was then given a course of instruction on their respective weapon. The instruction for each was identical in time and scope of material covered. Following this, both groups underwent an identical test program which consisted of: assembly and disassembly; known distance firing, both semi-automatic and automatic fire; unknown distance firing, semi-automatic and automatic fire; bayonet course; and, infiltration course. This phase lasted for one week (44 hours). At the end of the first week, the two groups traded weapons and the course of instruction and the tests were repeated.

Analysis [of Comparison Test Results]

Test 1 - Physical Characteristics

The AR-15 and the M2 Carbine are comparable in size and weight and both are compatible with the light weight and small stature of the VN soldier. An integral grenade launcher and telescope mount and an accessory bipod are included in the weapon weight of the AR-15. These are not standard items for the M2 Carbine.

Test 2 - Comparative Ease of Disassembly and Assembly

The AR-15 is simpler and requires less time to disassemble and assemble for normal field cleaning.

The average Vietnamese soldier can be trained in the disassembly and assembly for field cleaning of the AR-15 in a shorter time than for the M2 Carbine. This was further emphasized by the fact that all test subjects had previously received 12 hours of instruction on the M1 Carbine while undergoing basic combat training.

Test 3 - Marksmanship Ability, Known Distance

The ability of the ARVN soldier to deliver accurate semi-automatic fire on targets of known range with the AR-15 and the M2 Carbine is comparable. Test participants, as a group, fired a higher percentage of qualifying scores with both the AR-15 and the M2 Carbine than they had previously fired with the M1 rifle.

The ARVN soldier's ability to deliver accurate automatic fire on targets of known range is far greater with the AR-15 rifle than with the M2 Carbine.

Test 4 - Marksmanship Ability, Unknown Distance

The ARVN soldier's ability to deliver accurate semi-automatic fire..using the AR-15 and the M2 Carbine is comparable...the..ability to deliver accurate automatic fire..is greater with the AR-15 than with the M2 Carbine.

Test 5 - Comparative Ruggedness and Durability

After the first week of firing, seven M2 Carbines were eliminated from the test. Six of these would not fire automatically because of defective disconnector springs; the other would not fire at all because of a broken disconnector pin. In contrast, all AR-15s functioned properly throughout the test period.

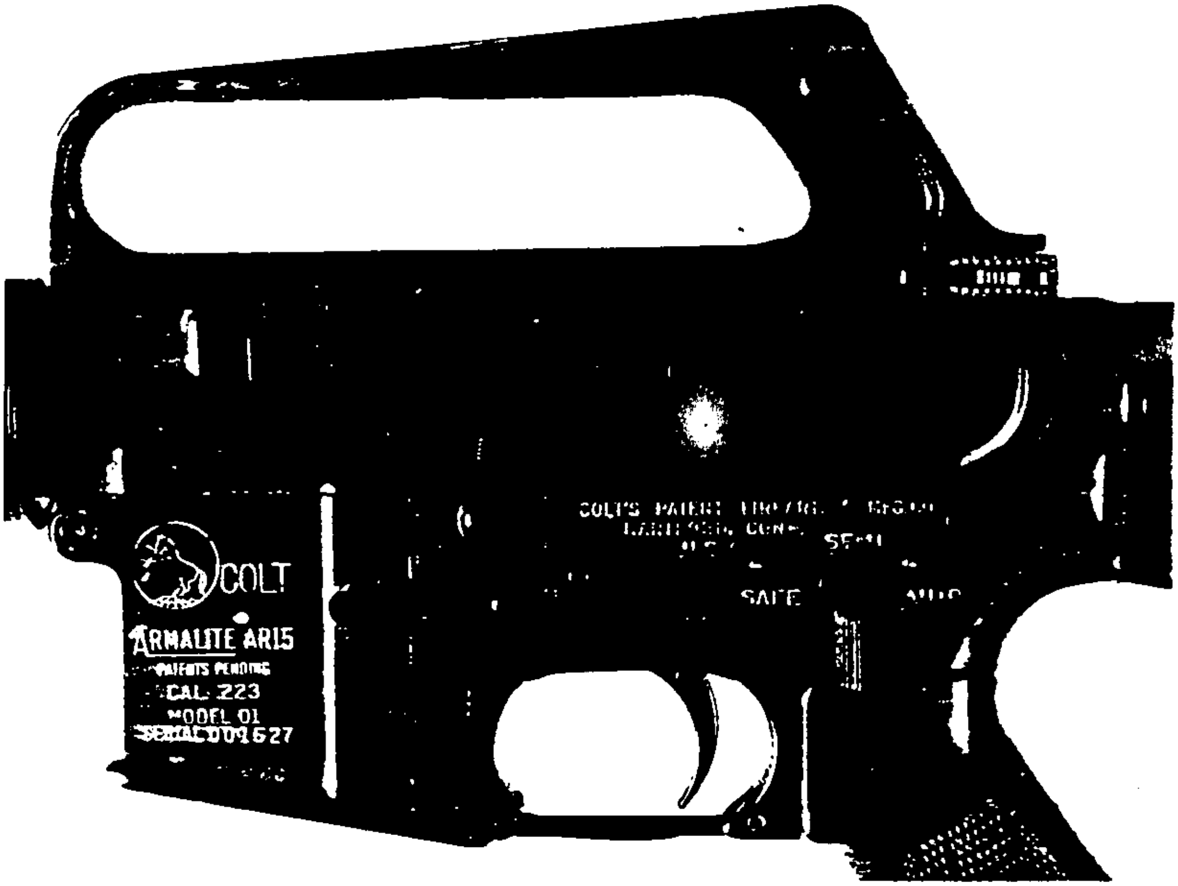
After negotiating the Bayonet Assault Course the second time, two M2 Carbines were eliminated from the test because of broken stocks. No AR-15 rifles were damaged.

The AR-15 is considered to be more rugged and durable than the M2 Carbine under conditions which require prolonged firing.

The AR-15 will stand up to rough handling normally encountered in combat situations better than the M2 Carbine.

Test 6 - Comparison of the Adequacy of Safety Features

The safety features on the AR-15 and the M2 Carbine are considered comparable with regard to function and the ARVN soldier's ability to understand them.



121. A model 01 Colt AR-15 from circa the ARPA order, serial no. 001627.
Photo credit: Eric Long, Smithsonian Institution

The location of a single selector switch which combines the functions of safety selector and rate of fire selector, on the left side of the receiver where it is easily accessible to the thumb, enables the ARVN soldier to get the first round off faster..than he can with the M2 Carbine. With the M2 Carbine, he must manipulate the safety selector with his trigger finger, then return it to the trigger to fire. With the AR-15 he can keep his finger on the trigger while manipulating the safety selector with his thumb.

Test 7 - Effects of Open Storage in a Tropical Environment

The AR-15 rifle, because it has fewer moving parts, will function more readily than the M2 Carbine after extended periods of storage in the open under tropical conditions.

Test 8 - Brush Penetration

The trajectory of the AR-15 bullet is not significantly affected when fired through dense underbrush at ranges up to 50 meters.

The AR-15 round will penetrate jungle undergrowth equally as well as the M2 Carbine round at ranges up to 50 meters.

Test 9 - Troop Preference Poll

The majority of the test subjects preferred the AR-15 rifle to the M2 Carbine in all respects covered by the poll, except for the sights. Further questioning of the subjects by the test committee personnel disclosed that this preference was due to greater familiarity with Carbine-type sights, not because of an inability to understand the AR-15 sights. This is not considered a shortcoming of the weapon but a matter of training and familiarization.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It is concluded that:

1. The AR-15 rifle is more compatible with the light weight and small stature of the Vietnamese soldier than the M1 rifle, the Browning Automatic Rifle, and the Thompson Sub-Machine Gun.

2. The AR-15 is superior to the M2 Carbine.

3. The M2 Carbine lacks the necessary dependability and versatility for consideration as the basic shoulder weapon for Vietnamese troops.

4. The AR-15 is capable of replacing any or all of the shoulder weapons currently being used by the Armed Forces of the Republic of Vietnam.

5. The AR-15 is considered by both Vietnamese Commanders and US Military Advisors who participated in the tests as the best "all around" shoulder weapon in Vietnam.

Recommendations

It is recommended that:

1. The AR-15 be considered for adoption as the basic *weapon for all RNVAF with a view toward improving effectiveness and simplifying training and weapons/logistics systems.*

2. Priority for adoption of the AR-15 be given to those units which frequently operate in jungle environment for extended periods because of the significant operational and logistical advantages accruing to their having the lightest and most effective weapon/ammunition combination available.

3. The M1 and/or M2 Carbine continue to be issued only to those individuals who, because of their duty or position, can function effectively with a weapon best suitable for a defensive role.

The Project AGILE results from the Vietnam field team, excerpted above, were summed up by ARPA back in Washington as follows:

The suitability of the AR-15 as the basic shoulder weapon for the Vietnamese has been established. For the type of conflict now occurring in Vietnam, the weapon was also found by its users and by MAAG advisors to be superior in virtually all respects to the M1 rifle, M1 and M2 Carbines, Thompson Sub-Machine Gun, and Browning Automatic Rifle.

Test data derived from recent Service evaluations of the AR-15 in the US support the technical conclusions of the report. The Central Intelligence Agency has conducted similar tests; it is understood that the results of that evaluation are essentially identical to those contained in the [above] report…

XV. CAMP SENTINEL RADAR

A. BRIEF OVERVIEW

To meet needs in Vietnam, a foliage-penetrating radar capable of automatically detecting intruders, named the Camp Sentinel Radar (CSR), was developed by the Lincoln Laboratory. CSR was field tested and put into operational use within two years, under ARPA sponsorship. The Army copied and improved the radars in a separate follow-on program. The processing technique for automatic detection formed the basis for present-day commercial acoustic intrusion alarms.

B. TECHNICAL HISTORY

In the mid 1960's, camps of U.S. military units in the non-Delta regions of Vietnam typically were in a clearing surrounded by jungle. With limited personnel it was difficult to guard against intruders who could come close enough to threaten the camps. A need was expressed for some way to automatically detect such intruders in the jungle and locate them well enough to direct fire.[1] Radar had been suggested as a possible solution, but electromagnetic propagation in the dense jungle was recognized as a problem.

Several programs had been undertaken, with ARPA and Army support, to study the penetration of jungle foliage by electromagnetic radiation, and a number of related measurements had been made in different locations.[2] A talk by a DoD representative on problems in Vietnam sparked interest at the Lincoln Laboratory on the possibilities of a foliage-penetrating radar, and their work caught the eye of ARPA staff members.[3] Lincoln had broad task support from the Air Force and ARPA for this and other exploratory work.[4] Lincoln Laboratory then was encouraged by ARPA to undertake the task of design and construction of a prototype ground-based radar system for test in Vietnam.[5]

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[1] Discussion with S. Deitchman, AGILE Director (1966-69), IDA, 10/88.

[2] E.g., AO 377, of 6/62 for Radar Foliage Penetration Research.

[3] Discussion with R. Zirkind, former ARPA program manager, 7/88.

[4] E.g., AO 498 of 7/63, for Radar Discrimination Studies.

[5] There was also a project to develop an airborne radar for similar purposes.

The problem of propagation in the jungle was difficult because of the absorption, scattering, and refraction of electromagnetic waves by the foliage, the clutter that would result from windblown leaves and tree limbs, and the small and hard-to-distinguish back-scattering characteristics of a slow-moving human target near the ground. The radar equation applicable to this situation could have several different forms, depending mainly on the absorptive and refractive conditions in the jungle, which could affect the design parameters of the radar. Using available information on attenuation in the jungle, resulting partly from previous ARPA-supported studies, plus theoretical calculations and measurements of absorption by foliage, and scattering characteristics of likely targets and of clutter, together with the condition that the radar energy be maximized at a low height corresponding to expected targets, estimates were made of polarization, wavelength, height for the radar antenna, and required transmitter power. A special analog processing scheme, a modification of one previously used by Kalmus of the Army's Harry Diamond Laboratories (HDL), was devised to deal with the difficult problem of automatic detection of a target having low doppler, without excessive false alarms, in a time-varying clutter environment. To obtain desired rapid scanning, a fixed disc-shaped antenna that scanned 360 degree electronically with solid state transmitter elements was also designed.[6] Figures 1 and 2 show a picture of two such antennas.[7]

Lincoln then constructed a first prototype experimental system which was used in extensive tests at CONUS field sites, making measurements of performance, clutter characteristics in different types of foliage, and detection of different representative targets.

In 1968, a second prototype system, Camp Sentinel II, was constructed and sent to Vietnam for test and evaluation. This second system was almost immediately put to operational use at one of the U.S. Division headquarter's camps. Electromagnetic penetration losses due to foliage were not as great as had been expected, and good automatic detection ranges were achieved. Accuracies were adequate to allow effective direction of fire on intruders. Military personnel were trained to operate the radar, which

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[6] K. Bowles, et al., in "Camp Sentinel Radar," *J. Defense Research*, Sec. B., Spring 1969, Vol. 1B No. 1, p. 66. Unclassified statements have been made based on this classified article.

[7] J.R. Dant, in "Camp Sentinel Radar III," 18th Annual Tri-Service Radar Symposium Record, Vol. 1, pp. 388 and 340.

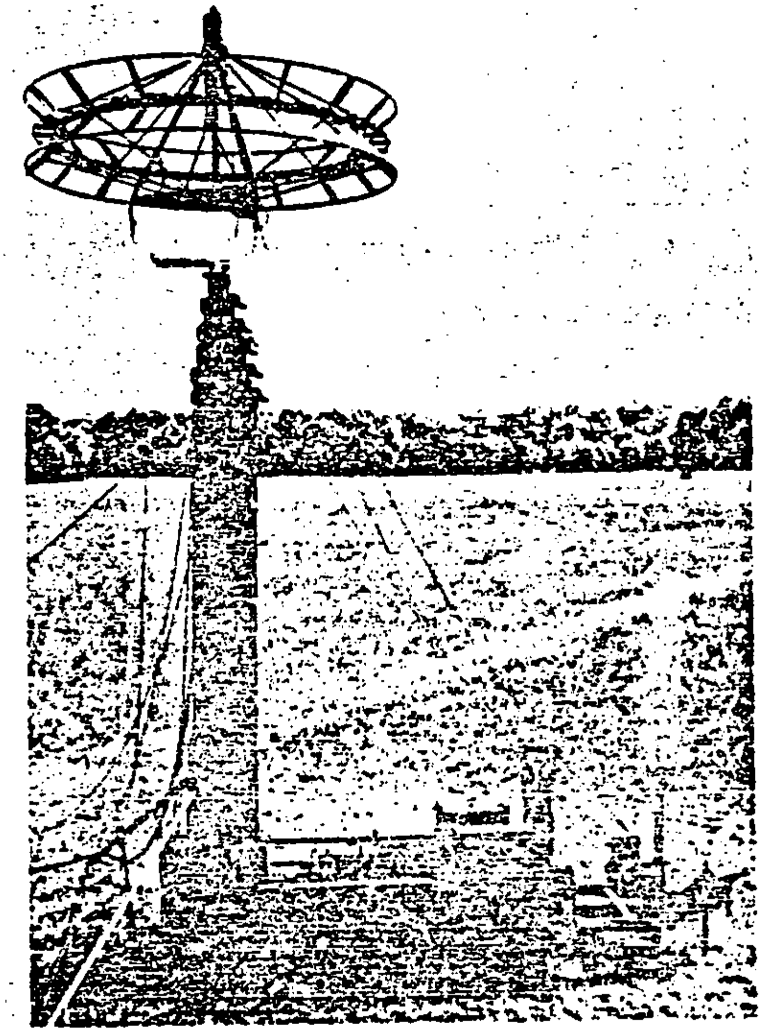

Figure 1. Antenna, 30 ft High

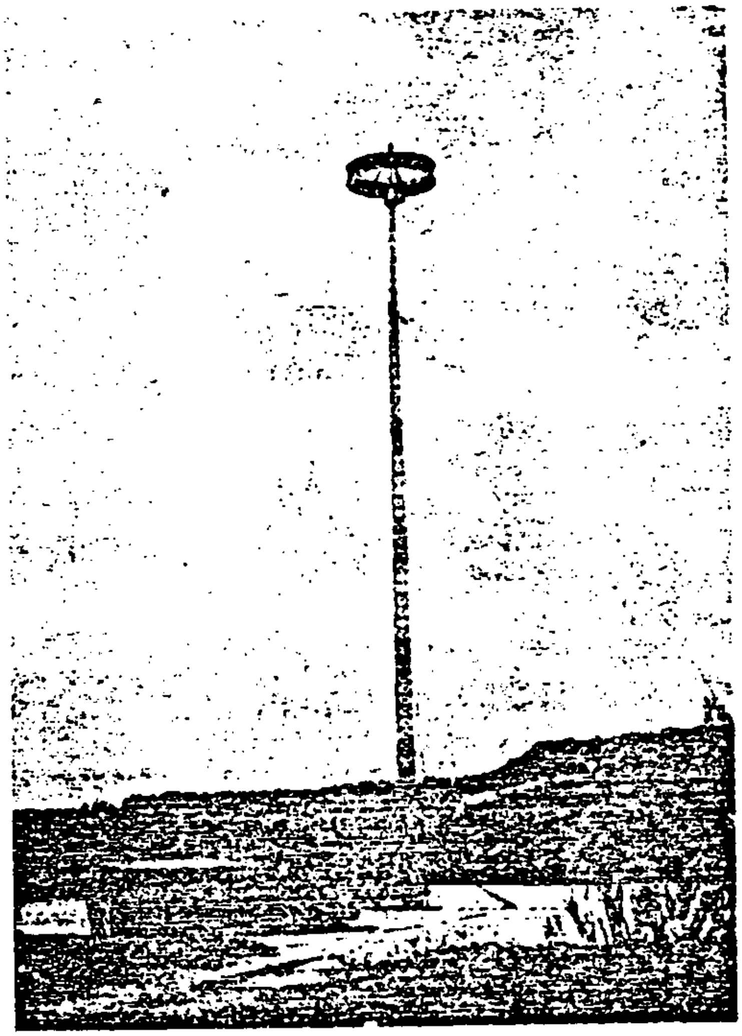

Figure 2. Antenna, 100 ft High

was moved to another site and again successfully used. Originally, plans had been to return the radar to the U.S. after its trials, for modifications on the basis of lessons learned, but because of its success the radar was kept in Vietnam until late in the war, when it was sent back to the Army's Harry Diamond Laboratories. Laboratory representatives with the Army Concept Team in Vietnam (ACTIV) had used the radar in Vietnam and had a number of suggestions for improvements. Five more Camp Sentinel III revisions, with higher power transmitters and other improvements, were eventually constructed by HDL and also sent to Vietnam. Four of these were used in the field and one for spare parts.[8] Lincoln wanted to apply a new generic digital processing technique to the Camp Sentinel Radar (CSR) in the early 1970s, but instead HDL undertook this task, using the Lincoln techniques, and incorporated them into the Camp Sentinel III radars. The resulting completely automatic anti-intrusion radar was used successfully in Vietnam. Two CSR III's were returned from Vietnam and were used at military installations, and for further R&D at HDL.

The CSR automatic detection processing system was also applied to acoustic intrusion detection by one of the Lincoln staff who left the laboratory to form a new company. This technique is apparently in use by most commercial intrusion detectors.[9]

C. OBSERVATIONS ON SUCCESS

The CSR is an example of a successful, competent Lincoln Laboratory effort, undertaken as a result of an ARPA request. CSR was developed and tested in the field successfully in two years. Some of the necessary jungle propagation work had already been done under ARPA sponsorship to solve an immediate, serious operational problem. Perhaps the most difficult system problem was the automatic clutter rejection, which was successfully solved. While all CSR system problems were not completely overcome, a successful, workable system resulted, which itself proved so useful operationally that the original "test" model was kept in Vietnam. This original version of Camp Sentinel was the basis for a larger, even more successful, Army program, which was also quickly fielded. An IPR was formally issued by the Army, but forgotten after Vietnam. The clutter rejection technique was also applied successfully in commercial acoustic intrusion detection systems.

In the opinion of some experts, Camp Sentinel, with a new design and highly effective performance in the field, was one of the most successful DoD radar projects.[10]

From project records, about $2 million was spent by the Lincoln Laboratory effort directly on the CSR. Related work on radar penetration of foliage cost about $5 million. The benefit was principally in its wartime use.

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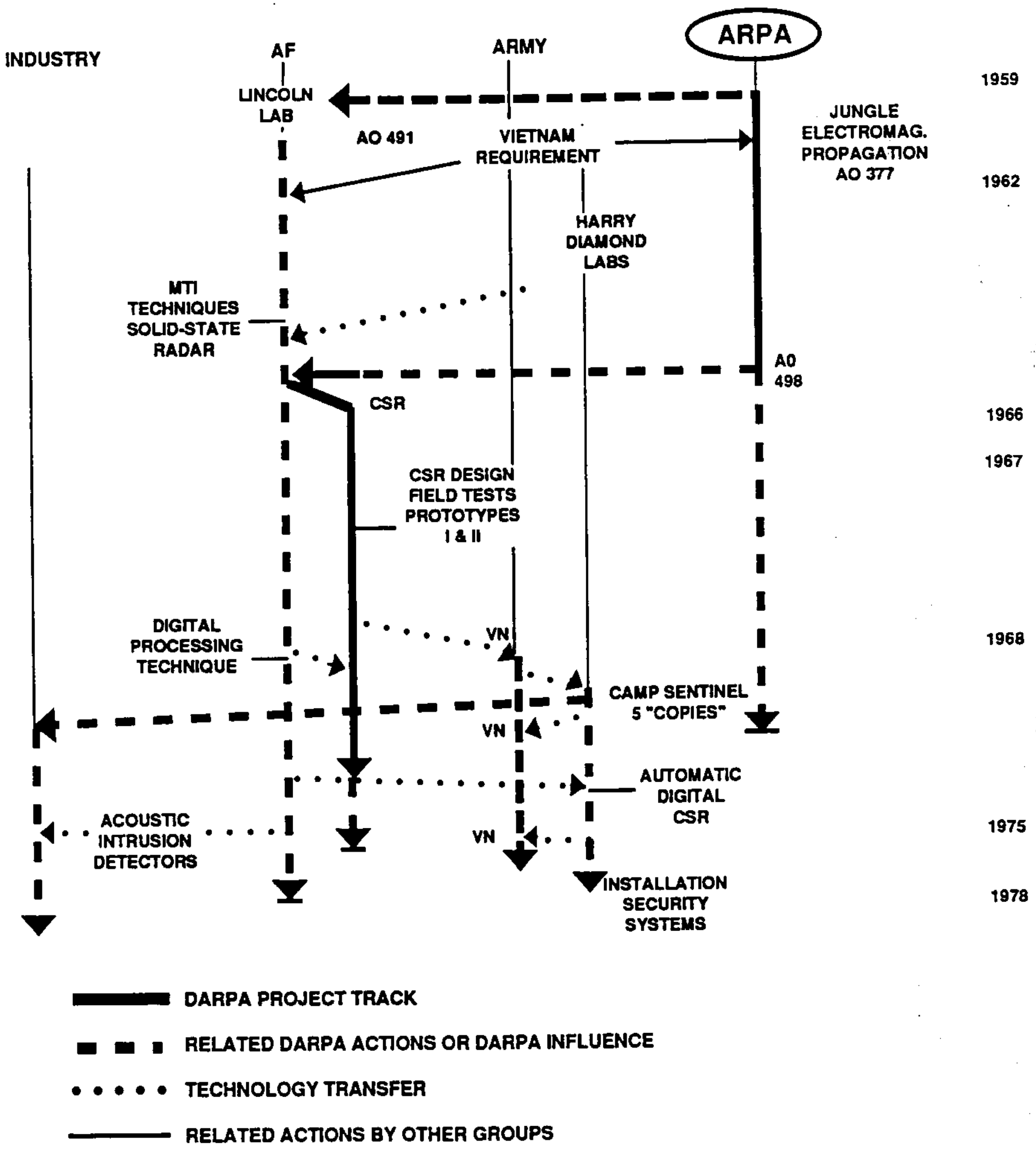
[8] Discussion with J. Dent, HDL representative in ACTIV Vietnam, 12/88.

[9] Discussion with C.E. Muehe of Lincoln Laboratory, 7/88.

[10] Discussion with R. Turner, IDA, 6/88.

CAMP SENTINEL RADAR



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XVI. THE X-26B-QT-2

A. BRIEF OVERVIEW

To meet a need in Vietnam for an acoustically stealthy night surveillance aircraft, DARPA supported development of the Lockheed X-26B, a powered modification of a well-known Schweizer sailplane. While in Vietnam, two X-26B's provided real-time surveillance as well as test information for systems improvements. This information led to the design and construction of the Army's dedicated, quiet YO-3A surveillance aircraft, which was also used successfully in Vietnam. The original X-26B's were given back to the Navy test pilot school for use in yaw-roll coupling training.

B. TECHNICAL HISTORY

In mid 1966 the Army stated a requirement for an acoustically stealthy aircraft for night surveillance in South Vietnam. Under its Vietnam assistance project AGILE, ARPA undertook to develop such an aircraft, supporting a proposal by Lockheed for the X-26B, a powered modification of a well-known sailplane, the Schweizer SGS 2-32. This sailplane was known to be rugged and roomy, and when gliding with power off would be acoustically quiet. The major modifications included an acoustically insulated and muffled Volkswagen air-cooled engine, connected to a large, low-speed, high-efficiency propeller by a long line shaft (See Fig. 1), together with an up-to-date sensor suite. Extensive use of radar-absorbing paints and other materials was also proposed to reduce radar signature.[1]

To reduce costs and save time, ARPA requisitioned two Schweizer SGS 2-32 sailplanes which had been recently bought by the Navy to give test pilots experience with yaw-roll coupling. With addition of an observer's seat and some further changes these

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[1] Jay Miller, in *The X-Planes*, Ed., Orion Books, 1987, p. 175.

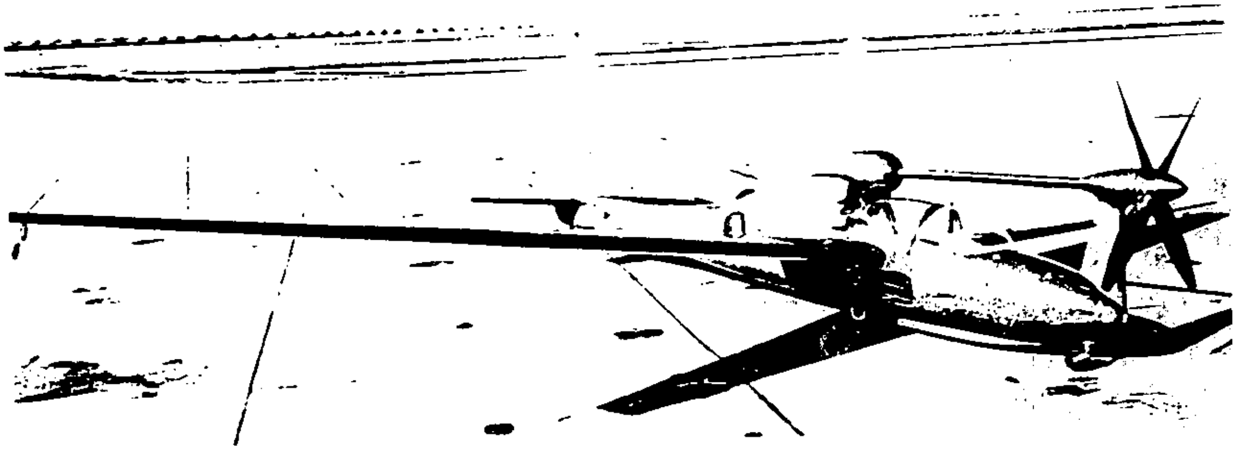

Figure 1. The Schweizer Lockheed X-26B-QT-2

aircraft were modified and designated QT-2PC's.[2] The emphasis was on acoustic quieting, and reduction of radar signature was not attempted in these aircraft. The two aircraft were sent to Vietnam in a C-141 in mid 1968 for a joint-services test under direction of the Army Concept Team in Vietnam (ACTIV). However, during the Tet offensive the QT-2PC's were pressed into service and provided valuable real-time surveillance of enemy movements at night. After completion of field tests, these aircraft were returned to Lockheed for further modification. Two more tours in Vietnam ensued, during which a combination of successful surveillance missions and tests to improve capabilities and stealthiness were conducted. The results led to design and construction of a new Lockheed surveillance aircraft, the YO-3A, which had new wing sections, new landing gear, a modified fuselage, and improved engine and drive system. The sensor technology in the YO-3A was largely determined by lessons learned using the QT-2PC's in Vietnam, and the YO-3A mission objectives were virtually identical to those of the earlier aircraft. Fully dedicated to surveillance, 14 YO-3A's were built and used successfully in Vietnam, and only one was lost in action. The rest were returned to the U.S. and used in various ways by NASA, border patrols, and the Army.

The two original QT's were returned to the Navy in 1969. The Navy had bought, by this time, two more unpowered Schweizer SQS 2-32 sailplanes (designated X-26A's), because of their unique capabilities in training pilots, without undue hazard, in the

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[2] ARPA Order 879 of 4/7/66, "Evaluation of Sailwing Aircraft," and A.O. 944 of 3/67, "QT-2 Low Noise Test Aircraft."

problems of yaw-roll coupling. However, the two powered QT's had advantages of availability over the X-26A's, since they were able to get into the air under their own power. Eventually, one of the QT's was used for spare parts; the other continued in use until 1973 at the Navy Patuxent test pilot school. It is now in the Army Aviation museum in Fort Rucker.

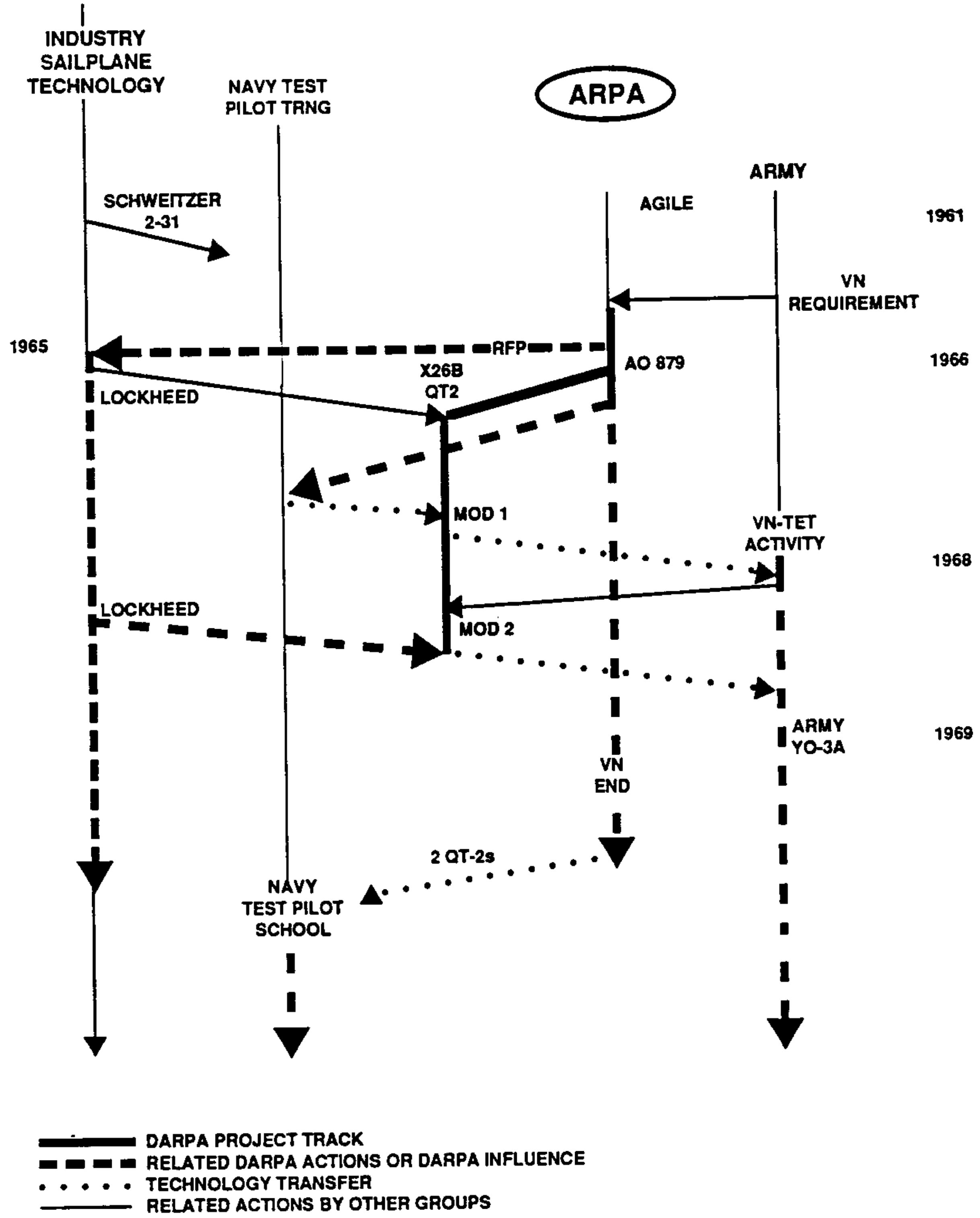
C. OBSERVATIONS ON SUCCESS

ARPA's role in the X-26B was clearly the introduction in timely fashion and at low cost, working closely with industry, of an effective new combination of available technologies almost directly into operational use. There was a stated military requirement to be met. The industry group making the proposal had a very good track record. The utility and practicality of acoustically stealthy surveillance aircraft was demonstrated and the sensor packages were tested and proved for use in other programs. An Army dedicated surveillance aircraft, the YO-3A, was designed and produced using the X-26B technology.

The X-26B-QT-2 apparently originated with a proposal from Lockheed's "skunk works." ARPA's role was to work closely with Lockheed toward meeting a stated military requirement, under Vietnam pressures. The risks were not very high and lay in the rapid and effective engineering of a new combination of technologies. An essential move to save time and cost was made by ARPA in obtaining existing sail planes from the Navy test pilot school. The result was the timely demonstration and operational use of an aeronautically stealthy aircraft, with sensor packages that were tested and proved out and used in other programs at very low cost. The original proposal included an effort to make the QT-2 electromagnetically stealthy also, but ARPA chose not to do this, probably because it was not needed for the QT-2's mission.

Using the X-26B technology, an Army dedicated surveillance aircraft, the YO-3A, was designed and produced. The QT-2's powered flight capability was also helpful to the Navy Test Pilot School and NASA when the planes were returned to the U.S. from Vietnam. The recorded ARPA outlay for the QT-2 was $250,000. The benefit was principally in its use in Vietnam.

X26B-QT-2



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XVII. POCKET VETO: BALLOON-BORNE RADAR

A. BRIEF OVERVIEW

In 1970 ARPA began project POCKET VETO, the first systematic effort to develop tethered balloon systems as sensor platforms. Originally intended to carry communication relays in Vietnam, the concept developed toward combining tethered-balloon platforms carrying radar and communications systems with RPVs for surveillance and strike missions. Although not developed in time to be used in Vietnam, POCKET VETO became a joint project with the Air Force, leading to timely deployment, under the SEEK SKYHOOK program, of tethered balloons as cost effective MTI radar platforms for Southeast CONUS air defense. POCKET VETO technology has also been used in commercial TV and communications systems in many other countries, and recently has been used by the U.S. Customs Service to begin deployment of a surveillance system for the southern U.S. border.

B. TECHNICAL HISTORY

ARPA effort to develop tethered balloons as elevated sensor platforms goes back to 1963, with several projects to obtain systems for different altitudes, some as high as the 100,000 ft altitude range.[1] Efforts to achieve high-altitude balloon platforms continued intermittently to the mid 1970s, and the technology developed formed much of the basis of the Navy's HASPA developmental program in the late 1970s.[2]

During the Vietnam war, the potential advantages of balloons to elevate sensor and communications systems were recognized by ARPA. Available balloon systems were procured by the ARPA Advanced Sensors Office (ASO), and tested for utility as carrier relays that would assist Army VHF/UHF communications in the jungle. However, these first balloons proved fragile and unstable. Also, the Air Force insisted on limiting balloon altitudes in Vietnam to 500 ft, to keep heavily used airspace clear. ASO led an attempt to

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[1] Cy. AO's 476 of 5/63 for a High Altitude Tethered Balloon System; and AO 755 and 756 of 8/65 for related research.

[2] AO 2474 of 2/73 NRL: Airborne Tethered Program.

correct the balloon instability, by aerodynamic analysis, leading to ballasting the tail sections. Much of the investigation to correct the instability was associated with the concept of using the tethered balloon radar and communications packages, together with RPV's, as combined surveillance-strike systems in Vietnam.[3] Such systems appeared very attractive, offering the possibility of very low demands on manpower as well as low cost.

ARPA approached the Lincoln Laboratory to undertake the balloon-radar project, but Lincoln refused on the grounds that the balloon would not prove stable enough as a radar platform.[4] Feeling that measured balloon stabilities were not that unfavorable, ARPA ASO proceeded to set up, in 1969, project "EGYPTIAN GOOSE." This project involved an available (GFE) Westinghouse Ka-band, aircraft-type, side-looking radar on an unstabilized, gravitationally-slung rotational mount hung below some modified barrage-balloons, left over from WW II, which ARPA purchased from the UK.[5] The radar was not fully coherent, and therefore not optimal for MTI, but it was available and could prove the concept. Tests were conducted in closed air space in Florida, some of which involved tandem balloons to reach higher altitude of about 15000 feet. However, the old barrage-type balloons proved too unstable, and the tandem balloons were difficult to launch.

Project GRANDVIEW, in the same time frame, involved the same type of balloon technology to lift a communications-relay package intended to be used in Vietnam. In this concept, RPV's such as NITE GAZELLE, would be able to communicate wide bandwidth TV surveillance information, via the GRANDVIEW balloon relays, to ground stations.[6]

The field trials with the EGYPTIAN GOOSE and GRANDVIEW systems had shown both the potential advantages of tethered balloons as intended radar and communications platforms and indicated many of the technical characteristics that would be desirable for an effective operational system.[7] In late 1969 ARPA commenced a project to develop such a system. This program, which took the name POCKET VETO,

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[3] "Standoff Sensing," by R. Cesaro and J. Goodwyn, paper at the ARPA Sensor and Combat Systems Symposium, Nat'l. Bureau of Standards, 6-8 June 1970 (Classified). Unclassified excerpts have been made from this and other classified references.

[4] Discussion with J. Goodwyn, ARPA POCKET VETO Program Manager, 8/88.

[5] AO's 1521 of 9/69 and 1604 of 3/20. There were 6 balloons left in the UK, and the Israelis wanted some also for similar projects, to enable their electromagnetic systems to look into Egypt. This was the origin of the name "Egyptian Goose," J. Goodwyn, ibid.

[6] The radar used had recently lost the competition for radars for a military aircraft system and was available as GFE, J. Goodwyn, ibid., AO 1490, 5/69 "EGYPTIAN GOOSE."

[7] "Summary of ARPA, ASO and TTO Programming," Final Report, Vol. 1, Balloons (unclassified), by J.H. Brown, M.A. Duffy and R.G. Olilla, Battelle Report, A65521, Task 44, 1977, p. 22.

encompassed work in several important technical areas including higher lift/drag coefficients, aerodynamic stability in variable winds, materials and structural design, the tether and support systems, and safety under various conditions of environmental hazard. The program also included development of a MTI radar configured to be used with the balloon systems. Several groups were involved in an extensive theoretical work, component development, and a field measurements and test program, notably: the Range Measurements Laboratory at Patrick AFB, the NASA Langley Laboratory which undertook work on aerodynamic design and test and also on balloon materials; the Air Force balloon R&D group at the Air Force Cambridge Research Laboratory on other aspects of the balloon system, including tethers; and, for a time, the Navy Material Command for hydrogen gas generators. The NASA Langley Laboratory effort involved construction of model balloon systems for measurements and a number of experiments in wind tunnels.[8] A 200,000 cu ft balloon was estimated to be required to lift the radar package. Strong fabrics originally used in airship construction were tried initially and rejected as too heavy. New materials were developed, with considerable improvements in strength/weight ratio. New lightweight power supplies were also designed, simplifying the tether requirements. The new balloons, given the collective description of "Family II" (see Fig. 1), were subjected to an unprecedented test and measurement program including tow by a helicopter at 68 knots to simulate large wind loads.

In 1972, the Air Force, pushed by Congressional concern stemming from a defecting pilot with his aircraft arriving from Cuba undetected in the Florida and Gulf area, conducted several studies of options to meet Air Defense Command (ADC) surveillance requirements in those areas. POCKET VETO, by that time, had enough data to allow a favorable comparison of its cost and IOC. Although other Air Force groups were opposed, AFADC wrote a requirements document for the mission, and in July 1973 ARPA set up a joint program with the Air Force for a tethered balloon platform to carry a surveillance MTI radar for air defense, with a plan for full transfer to the Air Force in 1975. The POCKET VETO program also involved construction of a new S-band MTI radar designed to have improved characteristics for use in the balloon platform.

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[8] AO 1682 of 8/70 Range Measurements Laboratory, "POCKET VETO." Earlier related AO's include 1666 to AFSC and 1667, both of 5/70, to NASA for "Tethered Balloon System." AO 2176 to RML and 2/77 to NASA; 2/78 to NAVMAT and 2/78 and 2/79 to AFCRL all of 2/72.

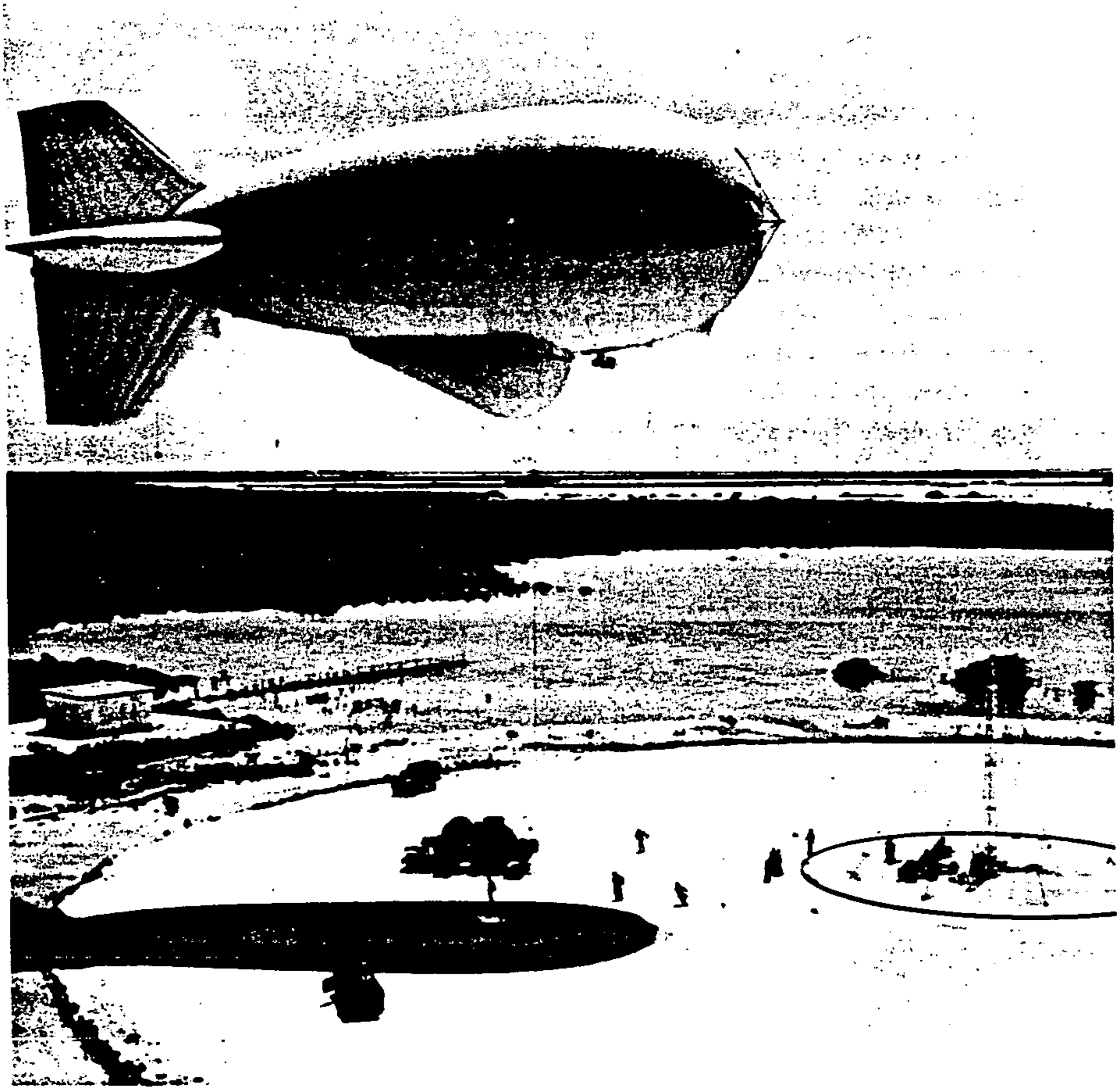

Figure 1. Family II Aerostat Launch

While POCKET VETO was being pursued ARPA, in response to an approach from the Army Security Agency (ASA), set up the joint CEFAR YONDER program.[9] CEFAR YONDER was to be the first application of the POCKET VETO balloon technology, to take place in the NATO theater, with ASA providing the payload to meet field requirements. CEFAR YONDER included effort on mobile support systems and a mobile mooring tower, together with overall ruggedization of the POCKET VETO systems. However, ASA failed to get approval for the deployment to NATO. The CEFAR-YONDER equipment was then given to the Air Force for the joint ARPA-Air Force project, now named SEEK SKYHOOK.

Formal transfer of the DARPA project to the Air Force occurred in July 1975. SEEK SKY HOOK conducted a successful one-year demonstration experiment in the Florida Keys, using a balloon to lift an improved MTI radar for air defense. The SEEK SKY HOOK system is now in operational use in the Florida area. Some further developments were undertaken by the Air Force, mainly in the directions of sensor improvements and reducing vulnerability to lightning, which has sometime caused the balloon to fall.[10]

The POCKET VETO type of system has also been exploited for commercial use by Westinghouse's TECOM division for use as a TV and communications relay in various countries. More recently these balloon radar systems, somewhat modified and updated, have begun to be used by the U.S. Customs Service for detecting illegal air traffic over the U.S. southern border (see Figure 2).[11]

POCKET VETO technology is also being studied currently for application to CONUS defense against attack by low flying aircraft or missiles.[12]

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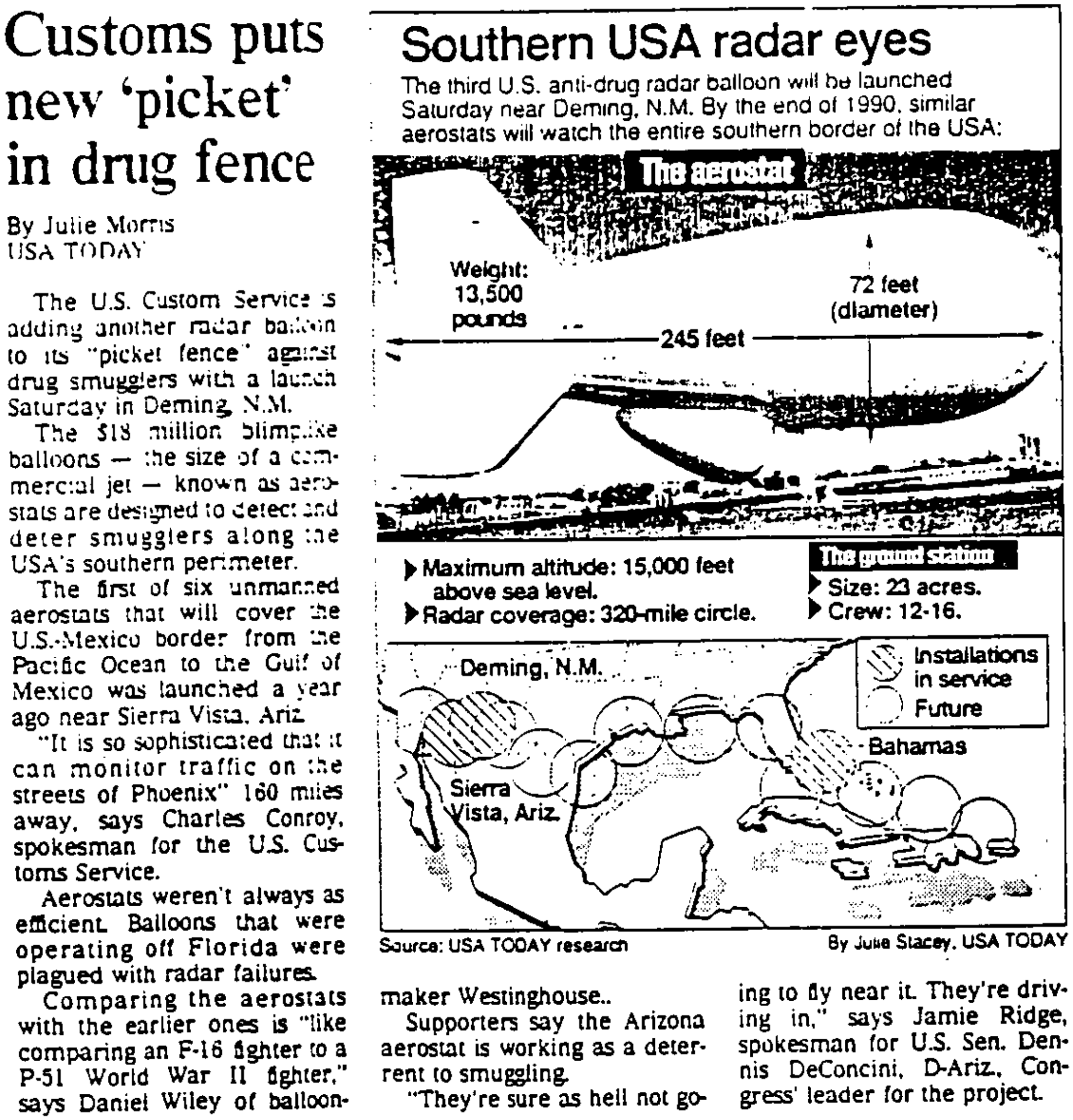
[9] AO 1876, 9/71, CEFAR YONDER.

[10] E.M. Del Papa and Mary Warner, in "A Historical Chronology of the Electronic Systems Division, 1947-1986," ESD, Hanscom AFB, Bedford, Mass, 1987, p. 39. Apparently the radars have not been damaged directly by lightning, J. Goodwyn, ibid.

[11] James Rawles, in"Keeping a Watchful Eye on The Border," in *Defense Electronics*, Aug. 1988, p. 82, and (Fig. 2) *USA Today*, Dec. 2, 1988, p. 3A.

[12] R.E. Boisvert, et al., "Tethered Aerostats as Early Warning Platforms," Lincoln Laboratory, Classified Report Aug. 1987.



Customs puts new 'picket' in drug fence

By Julie Morris
USA TODAY

The U.S. Custom Service is adding another radar balloon to its "picket fence" against drug smugglers with a launch Saturday in Deming, N.M.

The $18 million blimplike balloons — the size of a commercial jet — known as aerostats are designed to detect and deter smugglers along the USA's southern perimeter.

The first of six unmanned aerostats that will cover the U.S.-Mexico border from the Pacific Ocean to the Gulf of Mexico was launched a year ago near Sierra Vista, Ariz.

"It is so sophisticated that it can monitor traffic on the streets of Phoenix" 160 miles away, says Charles Conroy, spokesman for the U.S. Customs Service.

Aerostats weren't always as efficient. Balloons that were operating off Florida were plagued with radar failures.

Comparing the aerostats with the earlier ones is "like comparing an F-16 fighter to a P-51 World War II fighter," says Daniel Wiley of balloon-maker Westinghouse..

Supporters say the Arizona aerostat is working as a deterrent to smuggling.

"They're sure as hell not going to fly near it. They're driving in," says Jamie Ridge, spokesman for U.S. Sen. Dennis DeConcini, D-Ariz., Congress' leader for the project.

Southern USA radar eyes

The third U.S. anti-drug radar balloon will be launched Saturday near Deming, N.M. By the end of 1990, similar aerostats will watch the entire southern border of the USA:

- Maximum altitude: 15,000 feet above sea level.
- Radar coverage: 320-mile circle.

The ground station

- Size: 23 acres.
- Crew: 12-16.

Source: USA TODAY research

By Julie Stacey, USA TODAY

Figure 2. Customs Service Radar Balloons

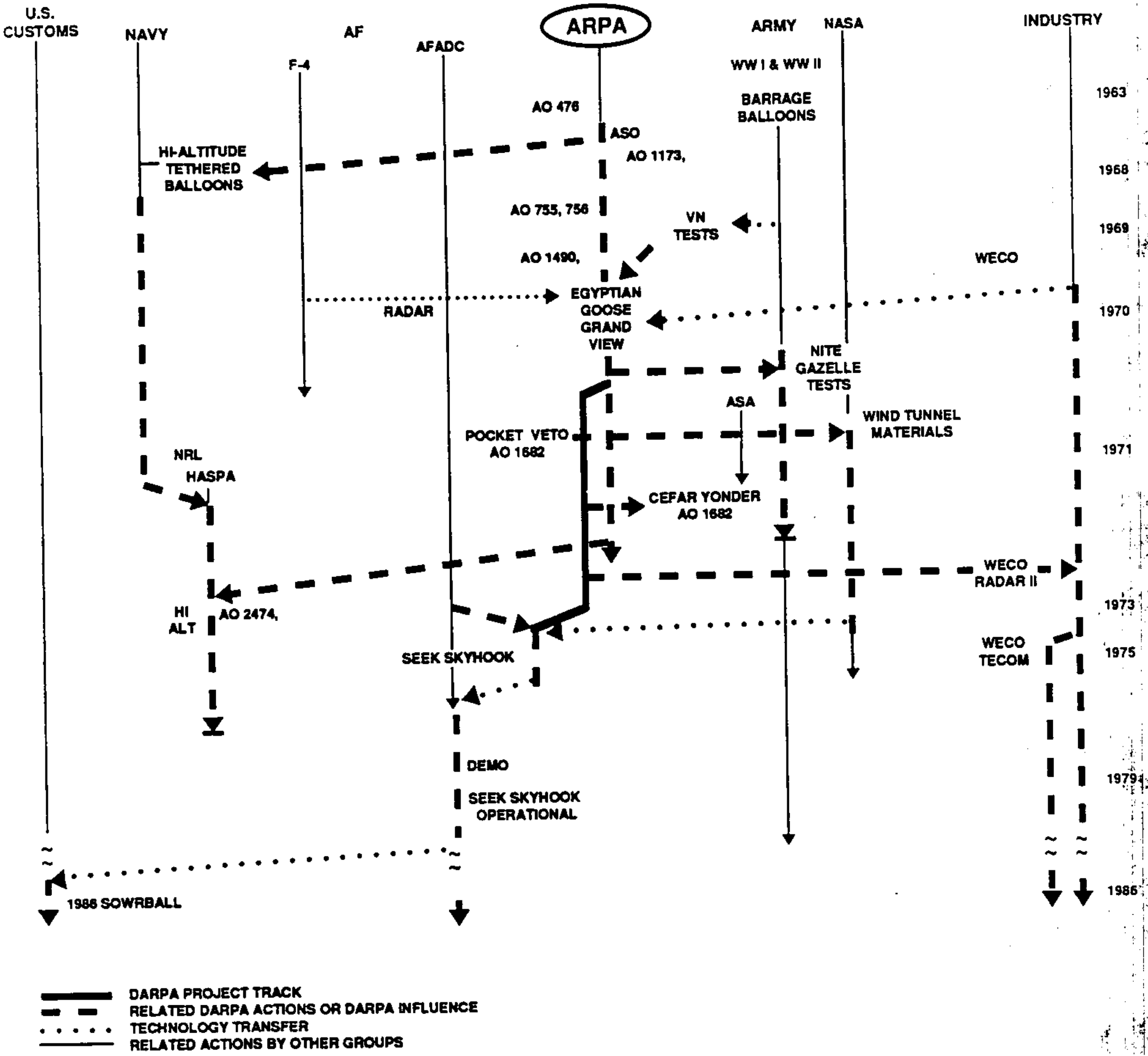
C. OBSERVATIONS ON SUCCESS

POCKET VETO was conceived initially because of the need to elevate sensors and communications links in Vietnam, in order to operate RPV surveillance and weapon systems at longer ranges. It was the first systematic attempt to develop a balloon-radar platform system that could meet operational requirements. There were many technology risks on an engineering level in POCKET VETO, primarily having to do with stability of the platform estimated by Lincoln Laboratory as too difficult to handle, and reliability of the overall system. These risks were assessed correctly by ARPA as manageable in a determined, scheduled program, and ARPA took the initiative to define and manage the program. The technology developments were successful and, while not complete, were judged useful as the basis for a military balloon system. The Vietnam motivation faded just as POCKET VETO was proved approaching completion. Unforeseen Air Force needs occurred at the same time, however, and POCKET VETO led quickly to a cost effective element in the Air Force air defense system. The direct management by ARPA and the close involvement with the Air Force in Vietnam-related tests were key factors leading to quick and effective transfer of POCKET VETO in spite of opposition on the part of some Air Force groups. POCKET VETO/SEEK SKYHOOK has been in use in SE CONUS air defense ever since.

The POCKET VETO system has also led to a successful commercial venture by Westinghouse to supply communication and TV systems abroad, and to the SOWRBALL system, now being deployed to meet current needs for U.S. border surveillance to help deal with the drug smuggling problem.

The cost of development of POCKET VETO, from project records, was about $6.0 million, plus various GFE items that were obtained by ARPA. Predecessor programs EGYPTIAN GOOSE and CEFAR YONDER appear to have cost about $3M. For comparison, for the new border surveillance system, the acquisition cost appears to be about $18 million for a single balloon and ground support system. At least six such systems are expected to be deployed.

POCKET VETO



U.S. CUSTOMS
NAVY
AF
AFADC
ARPA
ARMY
NASA
INDUSTRY
F-4
WW I & WW II
BARRAGE BALLOONS
AO 476
ASO
AO 1173,
HI-ALTITUDE TETHERED BALLOONS
AO 755, 756
VN TESTS
AO 1490,
WECO
RADAR
EGYPTIAN GOOSE GRAND VIEW
NITE GAZELLE TESTS
ASA
WIND TUNNEL MATERIALS
POCKET VETO AO 1682
NRL
HASPA
CEFAR YONDER AO 1682
WECO RADAR II
HI ALT
AO 2474,
WECO TECOM
SEEK SKYHOOK
DEMO
SEEK SKYHOOK OPERATIONAL
1986 SOWRBALL
1963
1968
1969
1970
1971
1973
1975
1979
1986
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS

E. INFORMATION PROCESSING

XVIII. ILLIAC IV

A. BRIEF OVERVIEW

The ILLIAC IV, the first array-type computer designed for large-scale parallel processing, was constructed with ARPA support in the late 1960s and early 1970s as an experimental tool and for eventual operational use on problems requiring intensive computation. ILLIAC IV posed a number of major challenges to computer technology which caused delays, cost escalation, and reduction in its own size and speed, while having at the same time a very significant impact on the general development of computer technologies. After reduction to 64 parallel processors, 1/4 of the original number, and considerable shakedown, ILLIAC IV achieved operational performance status in the mid-to-late 1970s, and was installed at NASA's Ames Research Center, under the joint DARPA-NASA Institute for Advanced Computation, remaining in use until 1981. ILLIAC IV could attain computing speeds in the hundred megaflop range, better than other machines available at the time, on several types of important problems for which there were algorithms which could be programmed in a way matched to its design.

B. TECHNICAL HISTORY

The ILLIAC IV was the fourth in a series of advanced computers developed at the University of Illinois, beginning with an agreement in 1949 between the University and the Army's Aberdeen Ballistic Research Laboratory.[1] The design concept for ILLIAC IV, due to Daniel Slotnick of the University of Illinois, involved 256 processors in an array of 4 modules of 64 processors each, under the control of a single instruction unit. A key feature of the processor structure was that each processing element could interact directly only with its nearest neighbor element or the one eight "steps" away. The SIMD (single instruction, multiple data stream) concept for parallel processing used in Illiac IV had originated with SOLOMON (a name chosen because it was to have 1000 processors) experimental computers, also designed by Slotnick and built by Westinghouse in the early 1960s with

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[1] "The Ordvac and the ILLIAC," by James E. Robertson, in *A History of Computing in The 20th Century*, Ed., N. Metropolis, et al., Academic Press, 1980, p. 34. See also D. Slotnick, "The Fastest Computer," *Scientific American*, Vol. 224, p. 76.

Air Force support.[2] This early Air Force effort also included exploration of applications and programming of parallel computers.[3]

In 1965 ARPA contacted Slotnick, who had moved to Illinois from Westinghouse, and invited him to submit a proposal for a large parallel processor.[4] Thus commenced support of his effort on the ILLIAC IV, with the explicit performance objective of design and construction of a 256-processor array computer as a experimental tool with a goal of a billion operations/sec, and with the additional objective of eventual use of the computer on various problems requiring intensive computation.[5]

The history of the ILLIAC IV project can be divided roughly into three phases: design and construction between 1965 and 1972; installation at NASA's Ames Research Center and initial R&D into its utility, 1972-1975; and operational use on major computing problems, 1975-1981.[6] ILLIAC IV was formally transferred to NASA Ames by ARPA in 1979.

Between 1966 and 1970 the project was managed by the group under Slotnick at the University of Illinois, with Burroughs Company as the overall system contractor. This period ended when ARPA decided to have the computer installed not at the University of Illinois as originally planned, but at the joint ARPA-NASA Institute for Advanced Computation at the NASA Ames Laboratory.[7]

During the initial design and construction phase a number of major problems arose which had both negative and positive aspects. Difficulties with production of chips with

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[2] "The Conception and Development of Parallel Processors -- A Personal Memory," by D.L. Slotnik, Annals of the History of Computing, Vol. 4, # 1, Jan. 1982; cf. also *Parallel Computers, Architecture, Programming and Algorithms*, by R. Hockney and C. Jesshope, Hilger, 1981, p. 16. These authors trace the roots of the Solomon computer to a 1958 paper by Unger. Apparently, Westinghouse considered but declined construction of ILLIAC IV which the AEC's Livermore Laboratory had planned to lease. ARPA provided all the support for ILLIAC IV.

[3] "Parallel Network Computer, Applications Analysis," Technical Report RADC-TDR-63-261, Aug. 1964.

[4] Slotnick, ibid.

[5] ARPA Order # 788 of 10/65,"Parallel Processing," to AFSC.

[6] The ILLIAC IV, *The First Supercomputer*, by R. Michael Hord, Computer Science Press 1980, pp. 123-132. Page 323-328 of this book gives details of the impact of the ILLIAC IV on computer technology.

[7] Cf. Slotnik, ibid., and "What Went Wrong V, Reaching for a Gigaflop " by Howard Falk, *IEEE Spectrum*, Vol. 13, Oct. 1976, p. 65. Considerations of the probability of continuing difficulties at the University of Illinois campus (indicated by the riots there in 1970) which could come when the ILLIAC IV became operational on military related problems, together with growing doubts about a

the desired number of gates using emitter coupled logic (ECL), chosen for speed of operation, caused early and drastic changes in the overall design and considerable delay.[8] On the positive side, ILLIAC IV was the first large-scale user of ECL integrated circuits, now found in many high-speed computers. Initially also, thin film memories, based on an earlier Burroughs design, were expected to be used, but the changes in design did not allow sufficient room. Fortunately, Fairchild had begun semiconductor memory development at the time and Slotnick, in spite of criticism about the risk, chose Fairchild to make the new memories. The risk in the Fairchild approach involved not only advances required in the semiconductor art, but also a number of engineering design and production problems. However, Fairchild successfully produced the memory chips, and ILLIAC IV was the first large-scale user of these. This intervention by Slotnick is credited with speeding up the pace with which semiconductor memories, widely used in present-day computers, became commercially available.[9]

Other serious problems existed with packaging, circuit design and interconnections. These posed challenges to the technology which also were eventually overcome, except for software, making ILLIAC IV also the earliest successful large-scale test bed for computer design automation, now widely used in the industry. Most of the technologies pioneered by ILLIAC IV were commercialized within five years.[10] Another novel technology in the ILLIAC IV system configuration was a laser-memory system as a tertiary memory with a capacity in the trillion-bit range, and read in and out rates in the million bits/sec range.

These early developments had positive long-run impact on the advance of computer technology, but also caused delays and cost escalation for ILLIAC IV.[11] As a result, the

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university group's ability to manage such major R&D projects, were some of the reasons stated for the move.

[8] Initially, 20 (ECL) gates were to be put on a single chip. However, these were not produced satisfactorily--leading to a change in design to one using seven gates per chip. A year later, the subcontractor was making 20 per chip for commercial use. See Falk, ibid., p. 66. Also, "terminated lines" were required, with 60,000 resistors that had to be changed after delivery. Communication from P. Schneck, 1/90.

[9] Falk, ibid., p.67.

[10] Falk, ibid., p. 68.

[11] The original cost estimate was $8 million for 256 processors. By 1970 $24 million had been spent. ARPA set up an independent cost control group in 1971, and by 1972, when installed, the cost of the completed computer was $31 million, for 64 processors. For perspective on related costs, the R&D on IBM's Stretch Computer, which also stressed the technology of the time, cost IBM about $25 million in 1956-59 dollars, twice the original estimate. See Emerson W. Pugh, "Memories That Shaped An Industry," Boston, MA., MIT Press, 1984, p. 183.

number of processors was cut a factor of 4, to a single module of 64 parallel processors instead of the 4 modules with 256 processors originally planned. The processors all "saw" the same cable lengths; extra cable was coiled for processors next to the control unit. ILLIAC IV's design also provided for a very large main memory and an information transfer rate to and from it, involving a novel, accurate synchronous control of discs, which could reach the 1.0 gigabit/sec range. Its architecture successfully employed a single instruction stream to control the multiple data streams involved in interprocessor communication, and used a microprocessor to do this, both significant innovations. This 1965-1970 period included not only the design and initial construction of the computer, but considerable effort on software to exploit the ILLIAC IV's prospective capability.[12] Some of the algorithms developed for the ILLIAC IV, e.g., "Skewed Storage," are only now being exploited extensively.[13] In 1971 Burroughs delivered the ILLIAC IV computer to the Institute for Advanced Computation (IAC) at the NASA Ames Research Center. Figure 1 is a picture of the installation, and Fig. 2 outlines its design architecture.

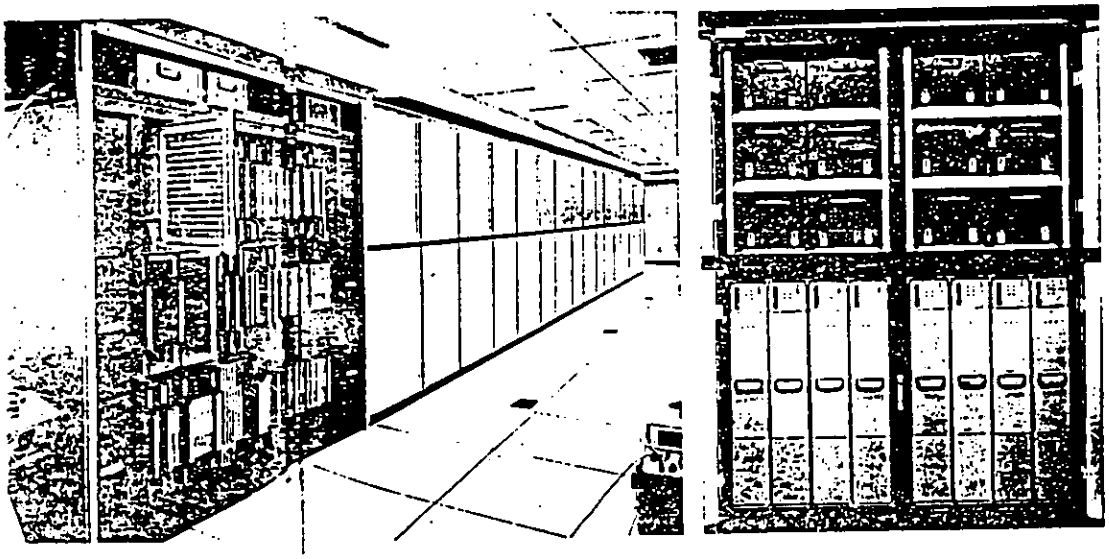

Figure 1. The Computer

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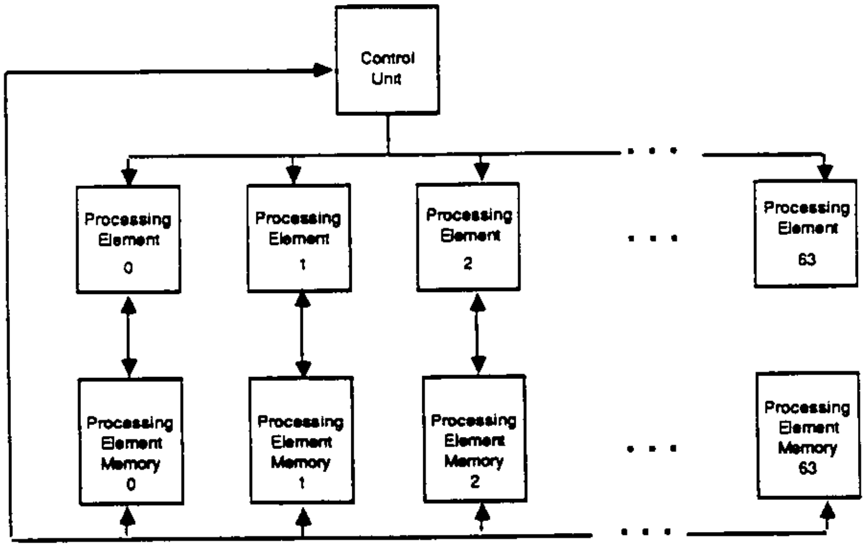
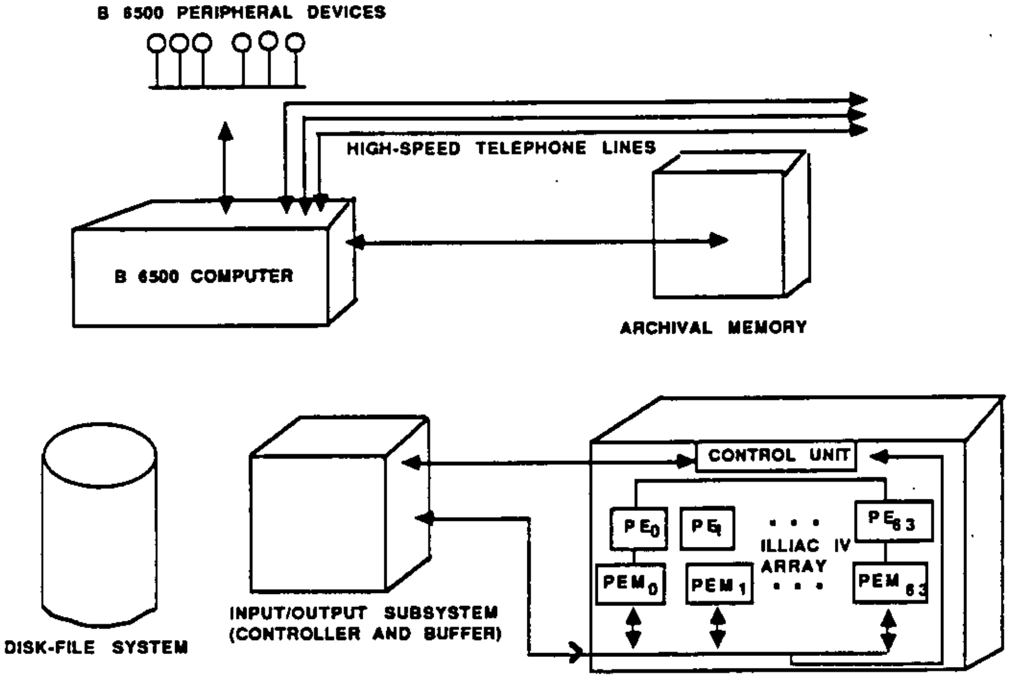
[12] Falk, ibid., p. 69. Apparently this was the first major effort at parallel programming in the U.S.

[13] Discussion with Dr. Paul Schneck, August 1988.



Parallel Organization of ILLIAC IV enables the control unit to orchestrate the operation of 64 processing elements, each with its own memory. There is a large class of mathematical problems that can be solved in all-at-once manner by independent processors, operating simultaneously, each about twice as fast as the single processor in an advanced sequential computer.



Block diagram of ILLIAC IV system shows how the ILLIAC's control unit, together with its 64 processors and primary memory units, will be connected to ancillary pieces of equipment. A secondary memory is provided by a disk-file system with a capacity of a billion bits (binary digits). A tertiary memory is provided by a new "archival" memory system, which uses a laser beam for reading and writing. Accessed through a medium-size Burroughs B 6500 computer, it will have storage for a trillion bits.

Figure 2. (from Slotnick, ibid., Fn. 1)

During the next phase, roughly 1972-75, the ILLIAC IV was operated by the IAC as a R&D project. In the period 1973-75 the first experimental "applications" began. The ILLIAC was made available eventually to a wide group of users through the Institute for Advanced Computation's connection with the ARPANET. ILLIAC IV was expected to be one of the most important nodes of ARPANET, in order to make its unique capabilities then a large fraction of the entire U.S. computing power, available to many users via the network. The ILLIAC IV trillion-bit laser memory was an important storage adjunct for outside users of the computer, avoiding the need to transfer large data volumes on ARPANET. Also 10 percent of the laser memory was to serve all ARPANET nodes requiring storage, for whatever purpose. However, there were few successes and many failures in this period due to the fact that the ILLIAC IV was not yet operating reliably, and because of the real difficulties in programming for parallel computing. One of the notable early successes was on a Monte-Carlo approach to nuclear radiation penetration, for which only one of three contractors was able to develop a workable applications program on the ILLIAC IV.[14]

In 1975, after a period of intensive effort to correct problems and establish reliability, the ILLIAC IV was declared operational. Its first use as an operational system was for the classified Fixed Mobile Experiment (FME), the first major project of the DARPA Acoustic Research Center established by DARPA's Tactical Technology Office at the Ames facility to exploit the ILLIAC IV. FME involved acoustic data transmission by satellite from remote locations, and extensive real time processing. The FME experiment demonstrated the feasibility of the concept as well as the processing capability of the ILLIAC IV. However, because of reliability problems with ILLIAC IV, FME eventually was successfully completed by the Acoustic Research Center and IAC using several PDP-10's in parallel.[15]

After the FME, ILLIAC IV became available for routine use, and DARPA directed that the IAC attempt to stimulate the use of the computer for many types of applications problems. The range of problems then addressed included, besides acoustic processing for the Acoustic Research Center, computational aerodynamics of interest to NASA including space shuttle design,[16] several types of seismic problems relating to the DARPA nuclear test detection program, atmospheric dynamics, image processing and massive linear

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[14] Hord, ibid., p. 124.

[15] Discussion with E. Smith, former Acoustic Research Center director, 7/88.

[16] *Business Week*, December 6, 1976, "Report on Super Computer," p. 42.

programming problems. New programming languages were written and a special compiler constructed.[17] ILLIAC IV was itself not a time-shared system, but many users eventually had access through ARPANET. Eventually most IAC support came from outside the original sponsors, and considering that this phase had demonstrated the desired degree of utility, DARPA turned ILLIAC IV over to NASA in 1979. However, NASA apparently did not continue to attempt to obtain a wide range of support, and shut down the ILLIAC IV in 1981, but not before a number of design studies had been made at the IAC for a follow-on computer, based partly on the ILLIAC IV experience.[18] The ILLIAC IV apparently also influenced the Burroughs' BSP computer design, planned for the commercial market. BSP was a contender for NASA's National Aeronautics Simulation Facility, the follow-on to IAC, but was withdrawn by Burroughs.[19]

In the early 1970s the ILLIAC IV experience apparently helped Burroughs to win the competition to build the PEPE parallel processor for Army's ABMDA, having capabilities also in the hundred megaflop range. PEPE was delivered in December 1976 and apparently met its technical goals almost immediately thereafter.[20]

C. OBSERVATIONS ON SUCCESS

The ILLIAC IV was a pioneer test bed for a number of important advances in computer technology, and a unique experimental project. It is widely characterized as a failure, along with the other supercomputer designs in the same period, the Texas Instruments ASC and CDC STAR. However, the ILLIAC IV was a more radical step in design, well ahead of its time, and pushed the technology on many fronts--which led to a very high risk of not achieving expectations. In the view of some experts, the failure was really of improperly formed expectations, from an experimental project.[21]

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[17] AO 2665 of April 1973 for an ILLIAC IV FORTRAN compiler. See also Hord, ibid.

[18] Hockney and Jesshope, ibid., p. 19. The IAC's PHOENIX computer design, for example, is described as several ILLIAC IV's under instruction from a central control unit.

[19] Hockney and Jesshope, ibid., p. xi, say the withdrawal was due to "production difficulties." L. Roberts indicates there might also have been uncertainty about commercial markets for the BSP. See *Expert Systems and Artificial Intelligence*, by T.C. Bartee, Howard W. Sams, 1988, p. 233.

[20] *The System Builders, The History of SDC*, by C. Baum, SDC 1981, p. 174. SDC was the prime contractor for PEPE.

[21] P. Schneck, ibid.

Regarding performance, Slotnick has been quoted as stating that:[22]

> applications have gone just about as I thought they would--no huge new computational areas have succumbed to ILLIAC, but nothing we thought would work has not worked.

The performance, of ILLIAC IV overall, eventually was regarded as better than other computers available at the time (see Fig. 3) for several important problems programmed to match its structure but far less good for other classes of problems, not so well matched. Such a wide spread, often as much as two orders of magnitude in performance, remains common to supercomputers.[23] Real-time processing, however, with its high demand on reliability, proved difficult to achieve.

The same advances in computer technology stimulated by ILLIAC IV also caused much of its delays and cost escalation. These hardware advances likely would have come along somewhat later anyway--but in this rapidly achieving area, time was and is considered important. L. Roberts felt that had older, proven hardware technology been used in ILLIAC IV there would have been, with some performance trade-offs, a quicker and less costly demonstration and evaluation of parallel processing, which was the main objective.[24] However, the difficulty of programming for parallel processing was also responsible for some of the problems.[25] Despite this difficulty, the ILLIAC IV experience apparently "convinced NASA that computational fluid dynamics was a viable alternative to the wind tunnel."[26]

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[22] Hord, ibid., p. 125, gives a sampling of applications problems run on ILLIAC IV. Besides applied problems, ILLIAC IV was used for fundamental problems in astrophysics and mathematical number theory.

[23] See S. Fernbach, Appendix A to "The Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities," National Academy of Science, 1987, pp. 59 and 71. The performance of Illiac IV, according to Hord, was quite close to what could be originally expected for the 64 processors, in the hundred megaflop range. However, according to Hockney and Jesshope, the best was in the 50M flop range. For perspective, the performance of the earlier IBM Stretch over that of the earlier IBM machine could vary a factor 100 depending on the problem and the programming. See Pugh, ibid., p. 183. Apparently a similar range of performance estimates applied to other "supercomputers" appearing in the same epoch as ILLIAC IV.

[24] L. Roberts, quoted in Falk, loc. cit.

[25] L. Roberts, ibid., and Business Week, Ref. 15, interview with Marcelline Smith of the computer group at Ames.

[26] *Beyond the Limits - Flight Enters the Computer Age*, by Paul E. Ceruzzi, MIT Press, 1989, p. 141. However, in the opinion of most aerodynamicists computational fluid dynamics is not so much an alternative to wind tunnels as it is a valuable supplement. Communication from Dr. A. Flax, IDA, 2/90.

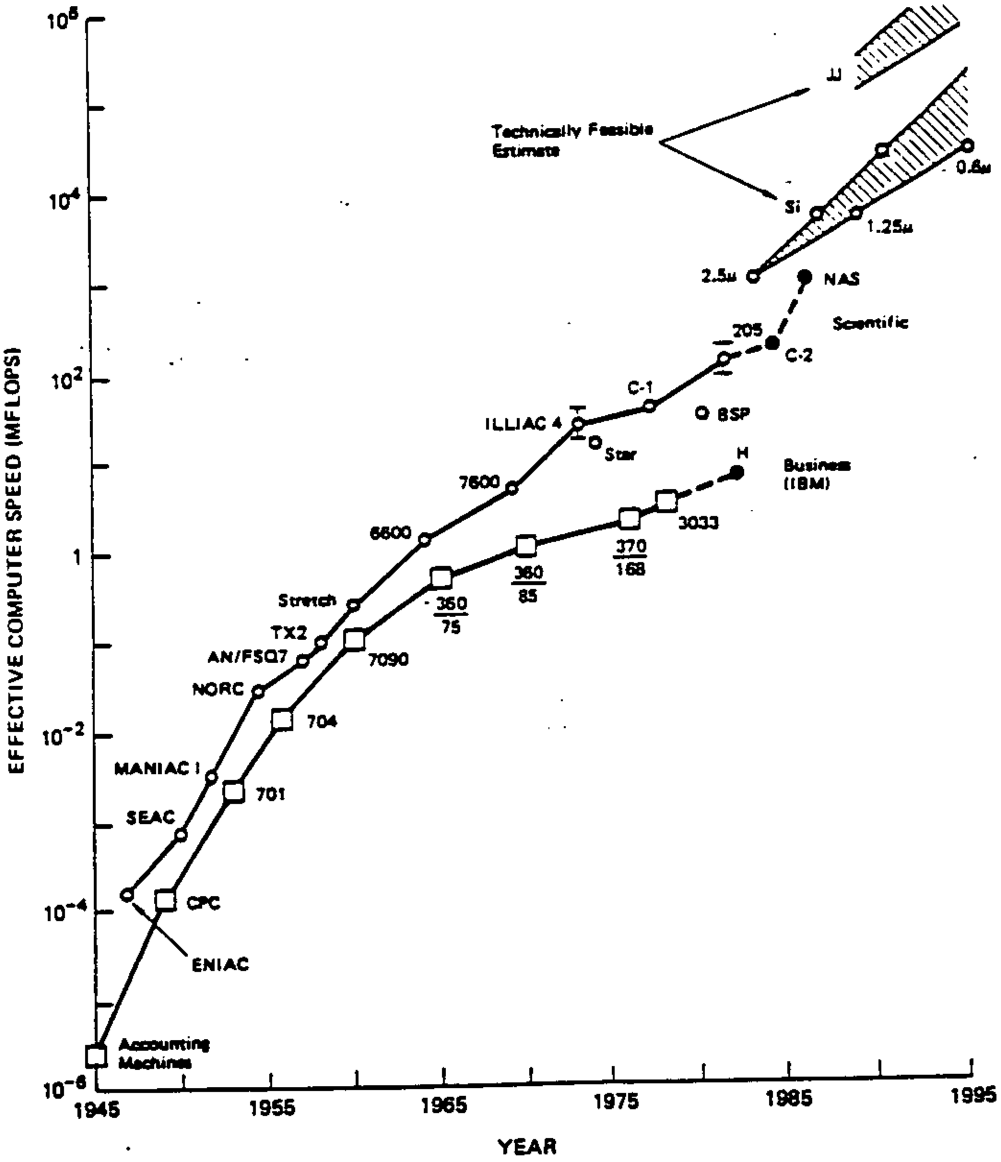

Figure 3. Development of Supercomputers - Computer Speed

Taken from Fernbach, ibid., Fn. 7.

NASA, however, eventually replaced ILLIAC IV with commercially available super computers. ILLIAC IV did not have a major impact on the next generation of supercomputers in the early 1980s. While ILLIAC IV's hardware approach was not influential on these super computer developments, it did teach some lessons regarding architecture for parallel processors, and in software.

According to those at IAC closest to the computer:[27]

> The ILLIAC IV has taught some important lessons which will have significant impact on future parallel processors. In particular, the processor interconnection scheme has been found to be wanting. It is both inflexible and difficult to program.
>
> Research in this area has focused on the optimum interconnection scheme and on the most efficient way to use a given interconnection pattern. All this has been predicated on the assumptions that the connection network must be fixed (hardwired) and that each processor can be connected to only a few other processors (because of fan-out limitations or cost considerations). These assumptions are no longer valid since there are other alternatives than interconnection schemes based on cabling, and the next generation of array computers should re-focus the attention that the ILLIAC has inadvertently misdirected.
>
> Further, the ILLIAC IV is a fixed configuration with no self-repair capability. Current research into self-repairing processors (multi-processors such as C, MMP and array processors such as PEPE) are inadequate as a base for massive computing power required by scientific computation because those prototypes in practice admit only extremely narrow bandwidth paths of information flow among processors. Future systems will have modular configurations for improved problem matching and will be able to switch ailing PEs out and good PEs into the configuration all under software control.

The challenge of software for a large parallel processor was posed for the first time by the ILLIAC IV, and the group at Illinois (Kuck, Lawrie, Sameh) pioneered in this area of research and education; and made a number of significant contributions which have come to fruition only recently.[28] One of the main lessons of ILLIAC IV, apparently being relearned, is the need to match problem (algorithm), program and machine structure to achieve the highest performance.[29]

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[27] Hord, ibid., p. 326.

[28] P. Schneck, ibid.

[29] L. Roberts, ibid. See e.g., "The Synchronous Processor," by Ira. H. Gilbert, The Lincoln Laboratory Journal, Vol. 1, No. 1, Spring 1988, p. 19.

The cost to ARPA of the ILLIAC IV itself appears, from project records, to have been about $31 million. It is widely understood that Burroughs put in $15M or more of its own funds on the ILLIAC development.[30] Nearly $28 million was also spent in shakedown and utilization of ILLIAC IV. L. Roberts, ARPA IPTO director in the early 1970s, feels that ILLIAC IV more than paid for itself in the cost savings of computer time for the problems actually worked out with it.[31] An interesting comparison can be made with IBM's experience with the STRETCH computer, in the mid 1950s, which also was a high-risk project that was expensive for its day ($25 million) and did not meet expectations, but had much influence on IBM's later system 360.[32]

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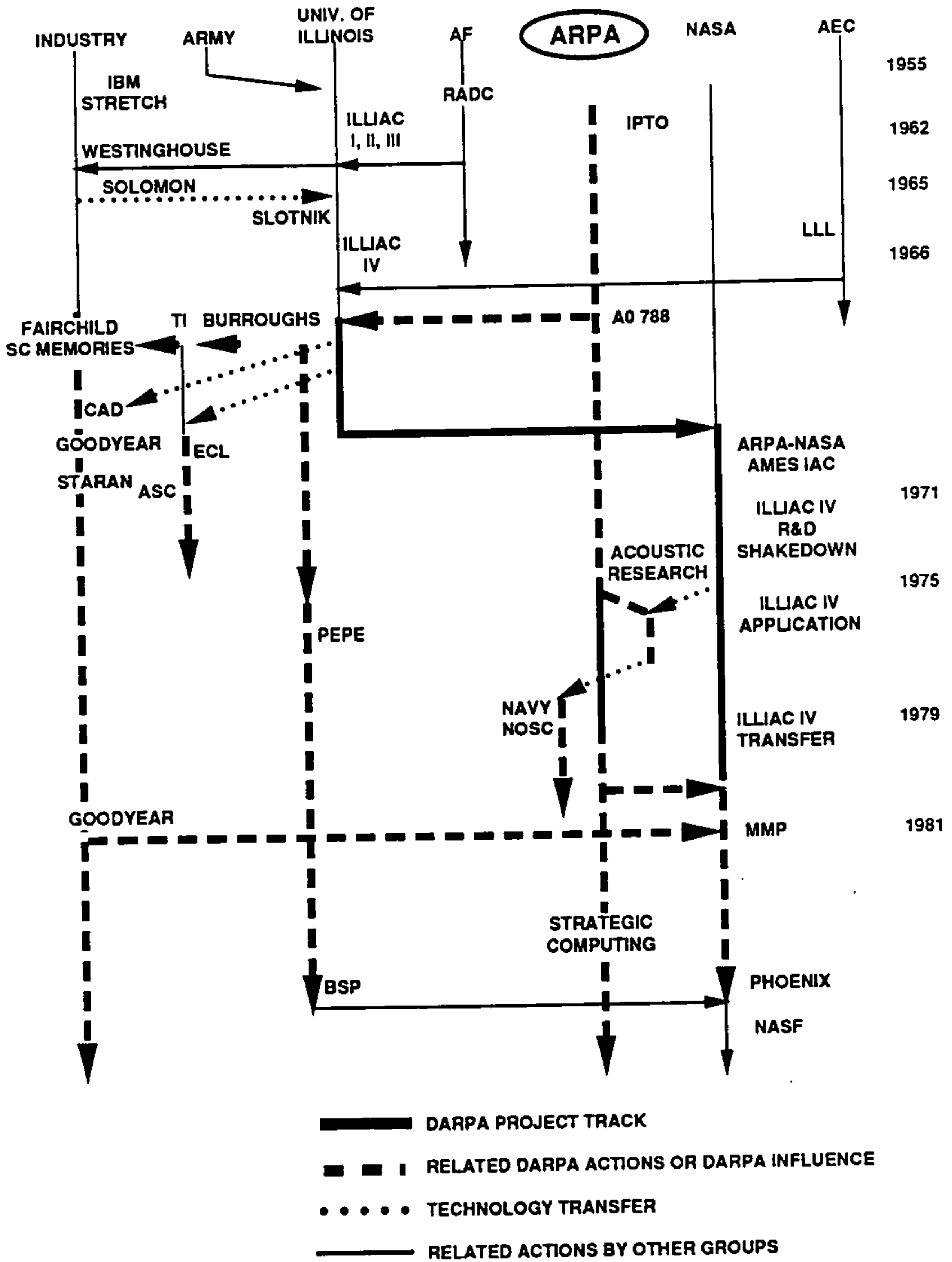
[30] Communication from Dr. P. Schneck, 1/90.

[31] L. Roberts, discussion 7/88.

[32] *IBM's Early Computers*, by Charles J. Bashe, et al., MIT Press, 1986, p. 457.

ILLIAC IV



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XIX. PROJECT MAC: COMPUTER TIME SHARING

A. BRIEF OVERVIEW

One of the first major efforts supported by ARPA's Information Processing Techniques Office (IPTO)* was project MAC[1] at the Massachusetts Institute of Technology (MIT). In the general direction of broad-based command and control research suggested by the Office of the Secretary of Defense, and based on the vision of the first IPTO Director, J.C.R. Licklider, MAC was oriented toward achieving a new level of human-computer interaction. Within this broad goal, the program included a narrower objective to make simultaneous computer access by many users (time sharing) efficient and economical. A major outcome of MAC was a large scale, successful effort to develop general purpose time sharing, subsequently affecting the design of computer systems for commercial and defense uses, generating also many widely used programs for automated engineering design, graphics and mathematical manipulation, and greatly facilitating the development of Artificial Intelligence (See Chapter XXI).

B. TECHNICAL HISTORY

1. Early Time Sharing Efforts

Time sharing of computers for special purposes was not entirely new at the time MAC began. SAGE, one of the largest command control systems, constructed in the early 1950's for air defense, involved some time-sharing features allowing multiple access on-line.[2] There were a number of commercial systems, e.g., for airline reservations and

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* The name of the office subsequently was changed to the Information Processing Technologies Office and then in 1984 to the Information Sciences and Technologies Office (ISTO).

[1] MAC stood for both "Machine Aided Cognition," reflecting the broad research aims of the program, and "Multiple Access Computers," for the actual interactive computer system seen as needed for achieving these aims. See *A Century of Electrical Engineering and Computer Science*, by M.W.V. Wilkes, et al., MIT Press 1985, p. 348. In a time-sharing mode, a computer can be accessed from multiple terminals, with several users at once, who have the illusion of "their own" computer. In batch processing, by contrast, a computer is occupied with one job at a time.

[2] C. Baum, *The System Builders - The Story of SDC*, SDC Corp., 1981, p. 24. When Air Defense, was eclipsed by the ballistic missile threat in 1958, the transistorized SAGE computer became surplus

stock market transactions, which involved some degree of interactive remote multiple access to computers.[3] There were also some early research efforts at RAND which developed time-sharing programs, and at Bolt, Beranek and Newman (BB&N), where some programs could be developed and debugged by five simultaneous users.[4] C. Strachey, of the Cambridge Computer Group in the UK, had given a general description of a time-sharing system.[5] In the late 1950's, MIT had begun to experiment with time sharing using their TX-0 and IBM 704 computers.[6] By the early 1960's, in addition to MIT, several other university centers also were developing concepts and experiments in time sharing, in particular, Carnegie Institute of Technology and Dartmouth.[7] By 1965 six commercial time sharing services had begun.[8]

In the early 1960's MIT had evolved a design for a "Compatible Time-Sharing System" (CTSS), working with IBM's Cambridge (user's) group--the first attempt at large scale, general purpose time sharing. This system evolved from an experimental system for the IBM 709 and first became available in late 1961 using a modified IBM 7090/94.[9] This was the first demonstration of feasibility of a time-sharing system allowing users to write

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and somewhat of a problem to DoD. It was moved to SDC and ARPA was asked to formulate a command-control program using it. This was the beginning of IPTO.

[3] "Computer Time-Sharing: Its Origins and Development," by T. James Glauthier, *Computers and Automation*, October, 1967, p. 23.

[4] *Time Sharing Computer Systems*, by M.V. Wilkes, Elsevier 1968, pp. 6 and 24. The JOSS time-sharing system, which was developed under ARPA sponsorship, became operational at the RAND Corporation in May, 1963. See Glauthier, ibid., p. 26.

[5] Quoted in "Time Sharing on Computers," by R.M. Fano and F.J. Corbato, *Scientific American*, Sept. 1966, p. 128.

[6] Wilkes, et al., ibid., p. 342-343.

[7] Glauthier, ibid., notes that in 1964 Dartmouth, Carnegie Institute of Technology, Stanford, and UCLA all commenced time-sharing operations. Dartmouth Time Sharing System (DTSS) development, which began in 1964 based on General Electric (GE) GE-235 hardware, became the basis of GE's MARK I commercial time sharing service. Subsequently, GE and Dartmouth collaborated on a time sharing system for GE's 635 computer, which was prototype for MARK II time sharing service. See R. Hargraves and T. Kurtz, "The Dartmouth Time Sharing Network," in N. Abrahamson and F. Kuo, *Computer-Communication Networks*, Prentice-Hall, 1973, p. 424.

[8] Glauthier, ibid.

[9] L. Belady, et al., "The IBM History of Memory Management Technology," *IBM Journal of Research and Development*, Vol. 25, No. 5, September 1981, p. 491. Also, Wilkes, et al., ibid, p. 345.

their own programs.[10] Also at this time MIT researchers were developing a time-sharing system for a PDP-1 computer donated by the Digital Equipment Corporation.[11]

2. Beginnings of MAC

In 1962, J.C.R. Licklider became the first ARPA IPTO Director. Licklider, who had led the time-sharing research effort at BB&N, had a broad vision of the benefits that would result to the military and, more generally to society, from progress in interactive computing.[12] The corresponding opportunity to undertake a major attack on time sharing using the array of capabilities at MIT was recognized by Licklider.[13] In early 1963, Project MAC was set up with participation by a wide range of MIT departments.[14]

The following was the initial research and development program of MAC:[15]

> The broad, long-term objective ... is the evolutionary development of a computer system easily and independently accessible to a large number of people and truly flexible and responsive to individual needs.... A second concomitant objective is the fuller exploitation of computers as aids to research and education, through the promotion of closer man-machine interaction....The third objective...is the long-range development of national man-power assets through education....outside of M.I.T. as well as within the confines of the campus.

The initial MAC time-sharing effort was based on a copy of the latest version of CTSS, implemented on another 7094, which was further improved and became operational by November 1963. This MAC time-sharing system could accommodate 24 users simultaneously. A key role in its development was played by J. McCarthy of the early Artificial Intelligence (AI) group at MIT, who recognized the great importance of time sharing for the development of AI.

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[10] M.V. Wilkes, et al., ibid., p. 342. CTSS was begun on a DEC PDP-1. Glauthier, ibid., p. 25.

[11] Wilkes, ibid., p. 345.

[12] J.C.R. Licklider, "The Early Years: Founding IPTO," in *Expert Systems and Artificial Intelligence*, T.C. Bartee, ed., Howard Sams, 1988, p. 219. Licklider's vision was initially published as "Man-Machine Symbiosis," in the *Institute of Radio Engineers Transactions on Human Factors in Electronics*, 1960.

[13] Wilkes, ibid., p. 347. According to Wilkes, Licklider also helped find the first project MAC leader, R.M. Fano.

[14] A.O. 433 of 2/63 "Computer Systems," for $8.45M.

[15] R. Fano, "Project MAC," Vol. 12, J. Baker, et al., eds., *Encyclopedia of Computer Science and Technology*, 1979, p. 347.

In the next two years MAC became a general laboratory in which rapid development of a wide range of computer programs and techniques took place. One of these, stemming largely from the AI group's use of CTSS for symbolic programming, was MACSYMA, which has been developed further into a commercially available package for mathematical manipulation and problem solving. Another notable development greatly aided by MAC was in the Computer-Aided Design (CAD) area, a graphic display system known as KLUDGE. This was an outgrowth of SKETCHPAD, one of the earliest computer graphics programs (developed earlier with NSF support), and the MIT mechanical engineering department's automatic engineering design effort, also supported by the Air Force. KLUDGE (see Fig. 1) in turn led to Automatic Engineering Design (AED), the first commercial computer graphics program and language.[16] SOFTECH was formed by some of the developers of AED.[17]

MAC provided a very wide range of "utility" services for compiling, problem solving, writing and debugging programs in a number of computer languages. MAC also became a large repository for data and programs, raising concerns about losing track of content and maintaining some degree of control over access. For reasons like these the time-sharing characteristics of CTSS were somewhat restricted in the first two years of MAC, while developing a file management system which had the goal of allowing sharing without damage, or excessive duplication, with an acceptable level of file security.[18] Batch processing was also provided for, in "background" or "extra" time.[19] By 1964 MAC could accommodate some thirty simultaneous users.

By this time the limitations of the 7094 for the CTSS had become increasingly apparent. It had been emphasized in the original MAC research proposal that this computer was not adequate as the basis for serious time-sharing system research. The search for a more suitable computer started in Fall 1963, and a set of requirements was specified, including:[20]

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[16] R. Flamm, *Targeting the Computer*, Brookings 1987, p. 69. See also Wilkes, et al., ibid., p. 350-351.

[17] Ibid., p. 69.

[18] R. Fano, ibid.

[19] The MIT computer center, during all this time apparently retained its computers mainly dedicated to batch processing, as well as the first version of CTSS. Wilkes, ibid.

[20] Fano, ibid., p. 348.

1. Read and write protection of user programs
2. Privileged instructions inaccessible to user programs
3. Direct addressing of at least 250,000 words
4. A multiprocessing capability with all processors playing identical roles in the system
5. An effective telecommunication unit with interfaces to high-data-rate graphic display terminals as well as conventional telephone lines
6. Mass storage units including fast drum for transferring programs in and out of core memory
7. Hardware for efficient paging and segmentation, including a suitable content addressable memory to reduce fetching overhead

Figure 1. "KLUDGE" Terminal Display

The "KLUDGE" Display System developed by MIT's Electronic Systems Laboratory has a Control Unit Display Screen, light pen and other equipment.

Source: R. Fano and F. Corbato, "Time-Sharing Computers", *Scientific American*, September 1966, p. 130.

In the words of R. Fano, MIT's Project MAC Director, "It was made abundantly clear from the beginning that project MAC was looking for more than just equipment; it was looking for a manufacturer sufficiently interested in time-sharing systems to collaborate with Project MAC in the development of significant equipment modifications and additions to meet Project MAC's needs."[21] The requirements for paging and segmentation were seen as vital, but it was recognized that no commercial computer at the time had these capabilities. With ARPA approval, these specifications became the basis for requested bids from the major computer manufacturers for a new time-sharing computer. Proposals from three manufacturers were received: Digital Equipment Corporation, General Electric Company, and IBM Corporation. GE won the competition with its "635" computer and flexible operating system (GCOS) design, and its agreement to be closely involved with MIT in the associated R&D, particularly with regard to additions and modifications to meet the last of the requirements (paging and segmentation).[22]

In 1965 the Bell Telephone Laboratories (BTL) agreed to join with MAC in the development of software (and to acquire the same computer installation), and these two were joined shortly after by GE in developing MULTICS (Multiplexed Information and Computing Service), and of the corresponding desirable changes of computer design.[23] A key feature of MULTICS, building upon the original Project MAC specifications, was that it would be mainly memory-based with a capability to segment and relocate programs and data dynamically.[24]

The loss of this competition resulted in considerable reaction by IBM, as it had been very closely involved with MIT's computer activities for many years. IBM had proposed to MIT the development of a multicomputer modification of its 360 series, incorporating some additional time-sharing features. However, these apparently lacked flexibility, specifically the feature of "dynamical relocation" of programs in and out of core memory

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[21] Ibid.

[22] Ibid. MAC also purchased a PDP-6 as a peripheral processor. See Franklin M. Fisher, et al., *IBM and the U.S. Data Processing Industry*, Praeger 1983, p. 160.

[23] Fano, ibid., and Wilkes, et al., ibid., p. 351.

[24] Fano, ibid., p. 349. J. McCarthy, who left MAC in 1962, had outlined most of these requirements in 1961. The Atlas Computer at Manchester, UK had pioneered some of the desired memory organization techniques.

specified by MAC.[25] IBM apparently had done some work on time sharing but their market analysis indicated exploitation of the other features of their 360 series would be more important commercially.[26] Shortly after losing this competition, IBM supplied a 360-based time-sharing system to the Lincoln Laboratory, which IBM regarded as experimental, and in early 1965 began to work closely with Lincoln and several other leaders in the field on a broad research effort in time sharing. The IBM R&D work by this time was considered by some of the MAC leaders as comparable in scope to their own efforts on MULTICS.[27] IBM persisted and in the 370 series in the early 1970's marketed a time sharing and "virtual memory" system, with architecture differing from MULTICS.[28]

The MULTICS effort at MIT and GE lasted about five years and proved to be considerably more difficult and costly (a factor of two) than originally expected. It was impossible to "simulate" such a new experimental system and several design iterations were found to be necessary before MULTICS could be available for general use in 1969. By 1971, MULTICS had some 10^6 words of procedure code, and served 55 simultaneous users, 22 hours a day, 7 days a week, with only one or two "crashes" in a day.[29] MULTICS incorporated a number of very advanced features: a modular structure decoupling physical storage and files organization,[30] "virtual memory" and dynamic reconfiguration--notably into operating and developmental subsystems, which could be done routinely 5 to 10 times a day. MULTICS included an automatically managed multilevel memory, and had multilayer supervision of procedures for protecting information. MULTICS used the programming language PL-1, which was available at the time, and was able to accommodate many other working languages. A very popular feature of MULTICS was that, once logged in, a user or sets of users could have their own

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[25] Fisher, ibid., p. 160-7, discusses this reaction in some detail. IBM had actually been working on the dynamic relocation capability but did not include it in their proposal to MIT. See also "The System 360, A Retrospective View," by Bob D. Evans, *Annals of the History of Computing*, Vol. 8, No. 2, 1986, p. 171.

[26] Evans, ibid., p. 175.

[27] "MULTICS-The First Seven Years," by F.J. Corbato, et al., *AFIPS Conference Proceedings*, Vol. 40, 1972, p. 572.

[28] "The Origin of the VM/370 Time-Sharing System," by R.J. Creasy, *IBM J. of Research and Development*, Vol. 25, Sept. 1981, p. 483. Evans, ibid., shows the rapid growth of IBM's market for time sharing and networking computer systems, greater than IBM had expected.

[29] Corbato, ibid., p. 571.

[30] Ibid., p. 573.

apparently "closed" subsystem. The structure is indicated in Figs. 2 and 3. By 1972 MULTICS had become a useful and flexible general purpose computer utility and while still evolving to some extent, was judged mature and turned over to the MIT Information Processing Center.[31]

Honeywell, which had bought out GE, supplied the modified 635 computer, now called a 636, to MAC for MULTICS, and by the time of its transfer to the MIT Information Processing Center was to further supply a "6080," internally nearly identical to the 635. The 6080 type, together with software derived from MULTICS, was then being sold commercially by Honeywell. Over eighty of these computers were eventually bought by military groups, e.g., Air Force (RADC and Air Force Data Centers) and by the World-wide Military Command and Control System (WWMCCS) in DoD and its field stations.[32] Later, efforts continued in several places on multilevel security aspects of MULTICS, and on other applications including image processing and Computer Aided Instruction (CAI).[33] However, "retrofit" MULTICS security modifications offered by Honeywell were not bought by WWMCCS and DCA, because of cost and certification problems.[34]

By 1969 the major goals of MAC were felt to have been achieved.[35] MAC became one of the main nodes of the ARPANET in 1970, and continued for several years as a research project on such topics as robotics and automatic programming. The AI group working with MAC had grown and in 1971 became a separate laboratory. In 1975 MAC ended as a multidisciplinary project and further research activities were continued at MIT under the Laboratory for Computer Sciences. In 1987 MULTICS was shut down at MIT.

3. Other Developments in Time Sharing Systems

In 1969 the BTL group involved with MULTICS returned to their parent laboratory. Shortly afterwards key members of this group, reacting to their MULTICS

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[31] Ibid., p. 580.

[32] See testimony of G. Dineen, Hearing before Defense Subcommittee of the Committee on Appropriations, H.O.R., 96th Congress, 1st Session, p. 248 ff, 1979.

[33] "Evaluation of TICS," a MULTICS Subsystem for Development and Use of OAI Course with MITRE, ESD 75-76, 1975. Also J. McCarthy had gone to Stanford from MIT and in 1963 designed a time-sharing system for experiments conducted there by P. Suppes. Discussion with D. Fletcher, IDA, 2/89.

[34] Discussion with Dr. I. Bialek. JCS, 3/89. See also, "MULTICS Security Kernel Validations, Vol. 1" by Ames, ed., MITRE, ESD TR-78/48 July 1978. MULTICS was considered the first control system designed from the beginning with security in mind; one of its motifs was to protect MIT users from mischief and plagiarism.

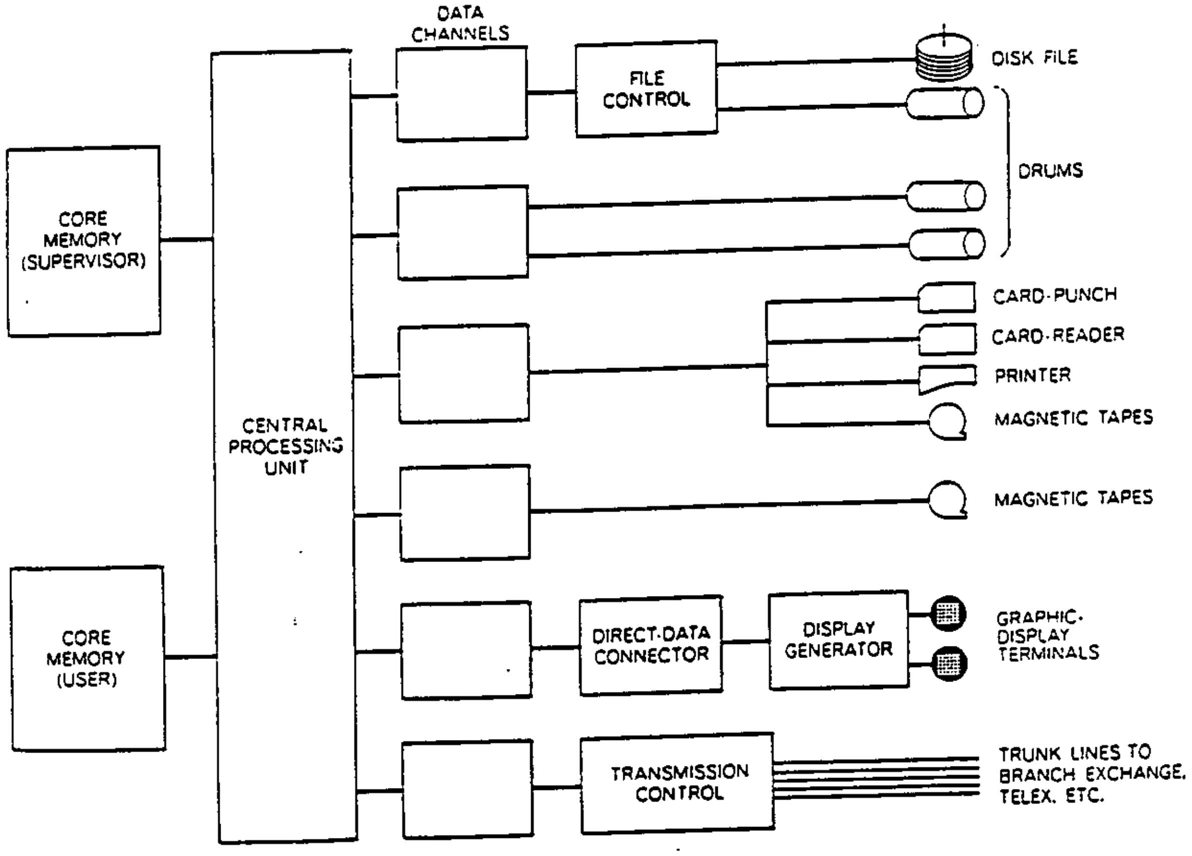

Figure 2. Simplified Schematic Diagram of Principal Elements of the MIT Time-Sharing Computer Installation

Source: R. Fano and F. Corbato, "Time-Sharing Computers", *Scientific American*, September 1966, p. 135.

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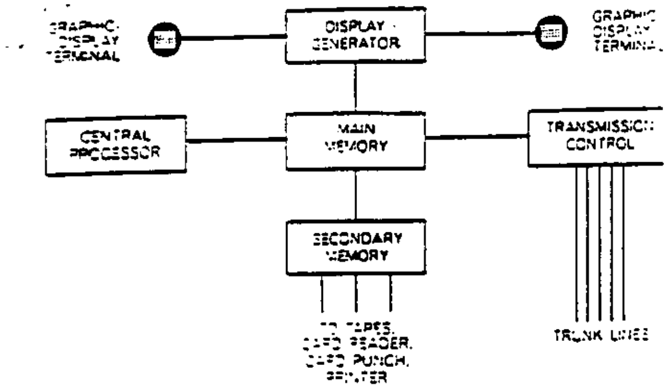
[35] See Fano, ibid., p. 352, and discussion with Dr. I. Bialek, 3/89.



SUPERVISOR has the effect of reducing the equipment layout diagrammed on the preceding page to the functional arrangement illustrated here. The main (core) memory, rather than the central processing unit, is in effect the central unit with which other units communicate; the various mass-storage devices are in effect a single secondary memory

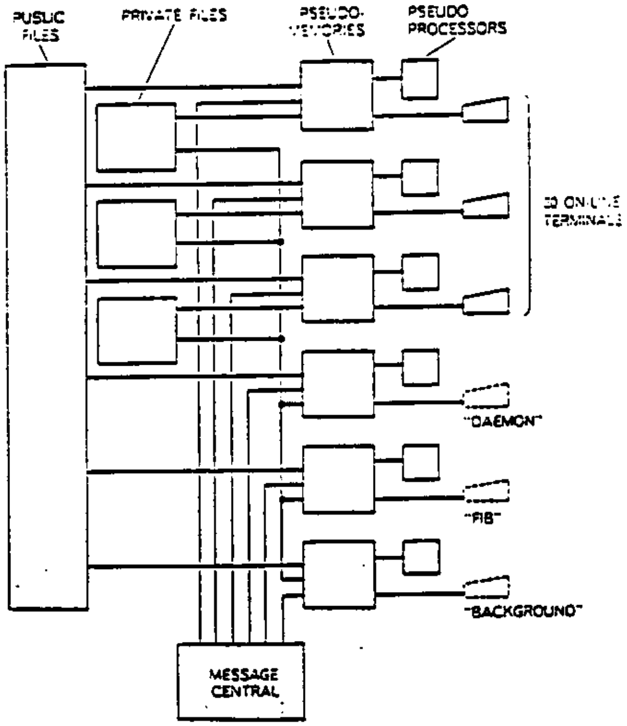


Figure 3. "Users View" of the System Is Quite Different

Each of the 30 On-Line Users has available for all practical purposes, his own processor and memory. Each memory has in effect a capacity of 32,768 words and has access to public files as well as the user's own files.

Source: R. Fano and F. Corbato, "Time-Sharing Computers", *Scientific American*, September 1966, p. 136.

experience, invented UNIX, a simpler system allowing the type of flexible, cooperative remote computer usage that seemed more appropriate for professionals at BTL.[36] After some successful experience internally at BTL, UNIX has become available commercially and is in widespread use largely in a DARPA-supported modification by the University of California, Berkeley.[37]

Another major early time-sharing R&D effort supported by ARPA was at Systems Development Corporation (SDC).[38] The Q32 computer initially designed as a transistorized upgrade to the SAGE system was given to SDC to be used for the ARPA command-control R&D program. SDC had been a key participant in several command-control system designs, notably those of the Air Force "L" systems. However, the SDC work was redirected to emphasize time sharing by Licklider when he became first IPTO director in late 1962. This redirection included a demand for a working time-sharing system, based on the Q-32, in six months. This was accomplished by the experienced programming team at SDC and the resulting time-sharing system (TSS) design won the AFIPS prize the following year. This SDC Q-32 TSS was linked by teletype with MIT's CTSS and demonstrated at MAC's initial summer study, in 1963.

The SDC TSS, together with advanced display systems and a more flexible language, evolved into a new time-shared data management system, TDMS, leading in turn to ADEPT, which accepted nearly natural-language computer commands and which could be operated initially on the time-sharing IBM 360/67's and later on other computers. ADEPT incorporated special provisions for security, and beginning in 1968 was used for some time at the National Command Center (NCC) and the Air Force Command Center. SAC also used ADEPT for its status reporting system, for which it later took back the Q-32 computer from SDC to SAC HQ at Omaha.[39] ADEPT also was the basis for the TIPI tactical information processing system, designed for the Air Force in 1968 and entering procurement in 1971.[40] The TDMS, in turn, while suffering some early business-application oriented setbacks, led to further applications such as MEDLARS and the

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[36] The name "UNIX" was to be contrasted to MULTICS--to emphasize the cooperative, as opposed to proprietary features of program generations associated with MULTICS.

[37] "A Short History of UNIX," *Electronics*, March 14, 1981, p. 126, and "Evolution of the UNIX Operating System," ibid., July 28, 1983, p. 115.

[38] Baum, ibid., p. 91.

[39] Baum, ibid., p. 119. ADEPT was eventually abandoned by the NCC, however, due to slowness in turnaround. Discussion with N. Jorstad, IDA, 2/89.

[40] Ibid., pp. 123 and 171.

associated medical information retrieved system MEDLINE, and later to SDC's own commercial information retrieval service.[41]

TOPS 20, the DEC Company's Commercial Time Sharing Systems, was also impacted by DARPA supporting the TENEX operating system.[42]

C. OBSERVATIONS ON SUCCESS

MAC was an ARPA initiative, part of the broad vision of the first IPTO director, Licklider, who focussed on general purpose "time-sharing" as the next major development to make computers more useful. There were internal obstacles in that the ARPA director, Robert Sproull, was not enthusiastic at first, feeling that computer development should be left to companies like IBM. After a visit to several laboratories with Licklider, however, Sproull became convinced that IBM was mainly interested in large-scale commercial batch processing applications, and not the technology needed for time sharing and command control problems and that ARPA should do something to develop this technology.[43]

Rather than attack the command control application head-on Licklider felt that a research effort to develop the broad capabilities needed in the long run would prove more useful.[44] MIT was an ideal academic environment for MAC, already having a large number of participants stimulated by the earlier CTSS development, such as the strong groups active in engineering graphics and AI and recognizing that a big step beyond CTSS was needed. Not only was this next development, project MAC sponsored by ARPA at MIT, ARPA also played an important role in sponsoring several other time-sharing systems in the first years. "In fact, of the first twelve systems developed, ARPA participated in the sponsorship of six of them."[45] The early contributions from the AI group at MIT were very significant; time sharing was realized (before MAC) by J. McCarthy of that group to be an essential tool for rapid progress in AI. Time sharing was also understood to be very important for Computer Aided Instruction.

Perhaps the main national impetus towards time-sharing development had been accomplished by 1965, with commercial systems springing up at several places and

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[41] Ibid., p. 183.

[42] Flamm, ibid., p. 58.

[43] Discussion with Dr. R. Sproull, 3/88.

[44] R. Sproull, ibid.

[45] Glauthier, ibid., p. 25.

commercial services beginning to be sold about that time. While some of these seem to have grown independently of ARPA and MAC, it also seems clear that nothing like the rate of progress in the area would have existed without the ARPA support for MAC. The next step beyond time sharing, computer networking, also a part of Licklider's early vision, soon began to develop, stimulated by the success of MAC and other time-sharing efforts, while MAC was still going on.

The MULTICS initiative seems to have been MIT's, as a natural "second generation time-sharing" effort. As a cooperative software-hardware effort it was one of the very few of this kind. MULTICS led to development of some hardware features of the Honeywell 6000 computer series, and directly to the associated software. MIT has a tradition of effective "technology transfer" to industry, illustrated in this case by working together first with IBM for the CTSS, and later with GE and Honeywell . Their time-sharing capabilities and the desirable features of the GCOS operating system were key reasons why the GE computers were selected by MAC.[46] The Honeywell 6000-series computers seem to have been a fairly successful commercial product, and were widely used by DoD.

MIT's selection of GE for MULTICS seems to have caused IBM to move much more rapidly toward time sharing than otherwise, and thus had considerable commercial impact. While MULTICS and the 6000 series were delayed due to underestimation of difficulties in achieving time sharing capabilities with acceptable level of flexibility and security, much the same seems to have happened in the later IBM time sharing effort. A positive result of MULTICS delays and problems was in the reaction of the BTL participants, who went home and invented the simpler UNIX system, partly as a reaction to MULTICS' characteristics for protection of information, desirable in the university and military environments, but which somewhat inhibited cooperative work by professionals at BTL.

By the early 1970's time sharing had become the dominant mode of computer operation in military, business, and academic centers. About the same time as IBM's introduction of its VM-based systems, DEC's mainframe computers adopted time sharing as an integral aspect of their systems. Subsequent developments in microelectronics technology, both in memories and logic devices created the personal computer (PC) and specialized work stations as alternatives to time-shared mainframes. While the rapid spread

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[46] GE's operating system, GE COS, was considered the best at the time and influenced IBM's development considerably. Discussion with W. Mulroney, IDA, 2/89.

of PCs and work stations has, to some degree, overshadowed the time-shared mainframe, the advent of supercomputers has further stimulated time sharing locally and remotely via networking. The interplay of these technologies continues as technical and economic factors drive solutions to computer systems.

The MULTICS-based approach toward multilevel security was followed up in R&D by the Air Force, but not picked up by the DoD, apparently due to concerns primarily regarding certification and related cost .[47]

ARPA expenditures for MAC are estimated from MIT records as about $25M for the 1963-70 period.[48] The WWMCCS had spent, by 1979, about $700M on Honeywell 6000-type computers, peripherals and software.[49] By the mid 1970's nearly every mainframe computer sold had time-sharing capabilities.

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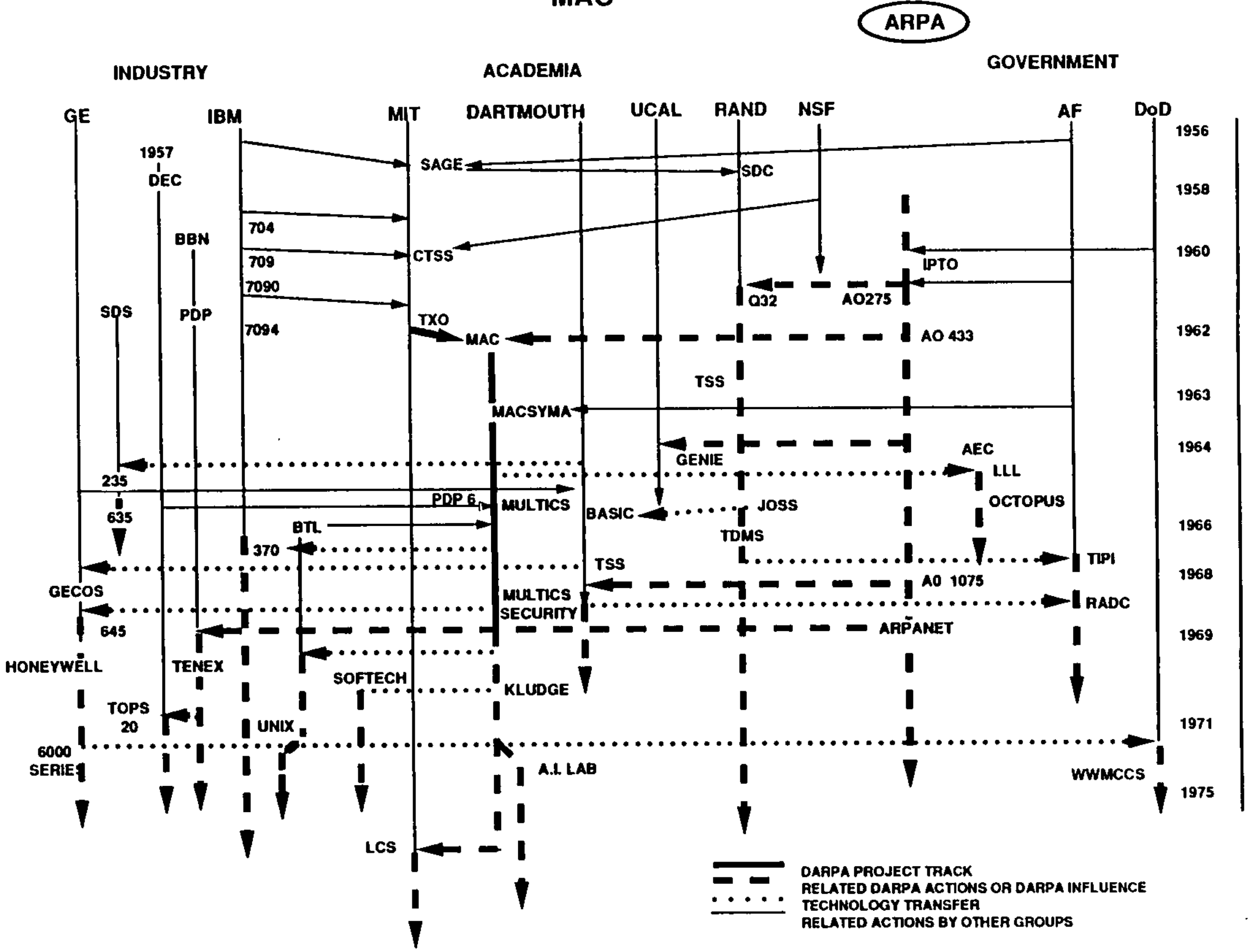
[47] N. Jorstad, ibid.

[48] Report on Sponsored Research, MIT Archives.

[49] Hearing Department of Defense Appropriations for 1980, 96th Congress, 1st Session Part 6, Testimony of Dr. Dickens, p. 248.

MAC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MULTICS
BASIC
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OCTOPUS
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SECURITY
RADC
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ARPANET
HONEYWELL
TENEX
SOFTECH
KLUDGE
TOPS
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UNIX
6000
SERIES
A.I. LAB
WWMCCS
LCS
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS

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XX. ARPANET

A. BRIEF OVERVIEW

ARPA effort on packet-switching technology to achieve efficient, low cost intercomputer communications was initiated by Lawrence G. Roberts in 1967, linking selected IPTO[1] contractors. In 1969 ARPANET, the first wide area general purpose packet switching computer-communications network, was set up, linking different types of computers over leased communications lines. Evolving as an experimental network, ARPANET operated for several years with scientific measurements and analysis results openly published, and was soon extended to include experiments with packet speech, and with radio and satellite communications links. From the early 1970's ARPANET technology has been used to an increasing degree in successive generations of DoD's data networks. ARPANET also led directly to TELENET, the first U.S. commercial public packet switching communications service, and its technology has been the basis of most of the many worldwide commercial and common-carrier data networks. As these networks grew and required interconnections, ARPANET software research and experience has provided much of the basis for network intercommunication protocols. With the increasing need for wider bandwidth networks, ARPANET will be replaced by a Defense Research Network, incorporating a new generation of packet-switching technology.

B. TECHNICAL HISTORY

ARPANET's history can be divided into several phases: (1) a gestation and planning phase from mid 1960's to about 1969; (2) an early development and experimentation phase, from about 1969 to 1972, culminating in a significant public demonstration in 1972; (3) an initial implementation phase, from about 1972 to 1975, and (4) a DoD-wide implementation and commercialization phase from 1975 onward. Significantly, the "Defense Data Network" (DDN) for interactive communications is based directly on ARPANET technology. Research on the extension of ARPANET packet switching technology into other media and applications also has been conducted from the

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[1] ARPA's Information Processing Technology Office.

early-1970s. With the prospect of a national research network requiring much wider bandwidths, current plans are that the ARPANET will be replaced by a "defense research network" more tuned to new capabilities.

1. Origins

J.C.R. Licklider, the first ARPA IPTO director, had a vision and a broad program for developing man-computer interaction technology.[2] After time sharing had been demonstrated and its impact began to be widespread in the mid 1960's, the next logical step in this program was the linking of computers and terminals by communications networks, so that computer capabilities, programs and file resources could be accessed readily and shared remotely. The mainstream of ARPANET development involved individuals and institutions in the computer research communities which were supported by the growing ARPA IPTO program. However, related early work was done by others, including several private networks and laboratories.

Notable early contributions had been made by P. Baran and collaborators at RAND. Baran's work in the early 1960's outlined a distributed, survivable digital communications system for the Air Force, in which a data stream would be broken near the point of initiation into addressed sub-units of less than two hundred bits, which would then be routed by "intelligent" nodes over multiple paths which could include satellites as well as telephone communication lines. Baran's group also ran a simplified computer simulation of such a network, using six nodes, which demonstrated its workability and survivability and indicated that the nodes did not need to store many message segments in order to be effective.[3] Baran's work also showed that such a distributed system would be more economical than conventional communication for "bursty" data exchanged by a sufficiently large number of computers.[4] A 1962 thesis by L. Kleinrock, then at Lincoln Laboratory, came to a similar conclusion. The Air Force did not follow up Baran's work, apparently because of skepticism from the communications community, which felt that data hang-ups

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[2] "Man Computer Symbiosis," by J.C.R. Licklider, *IRE Trans. Human Factors in Electronics*, Vol. 1, 1960, p. 4.

[3] "On Distributed Communications Networks," by P. Baran, *IEEE Trans. on Communication Systems*, March 1964. Apparently Baran's work at Rand dated back at least to 1960, cf. A. Wohlstetter and R. Brody, "Continuing Control as a Requirement for Deterring," in A. Carter, et al., eds., *Managing Nuclear Operations*, The Brookings Institution, Washington, D.C., 1987, p. 175.

[4] L. Roberts,"The Evolution of Packet Switching," in R. Rosner, ed., *Satellites, Packets, and Distributed Telecommunications: A Compendium of Source Materials*, Lifetime Learning Publications, 1984, p.111.

would be common and buffer storage requirements large.[5] Baran's work, apparently, was not well known to members of the DARPA community when they began their plans for computer communications networks.

In 1965, D. Davies of the UK's National Physics Laboratory (NPL) gave a seminar at MIT's ARPA-sponsored project MAC (see Chapter XIX) in which he outlined several ideas about what he later named a "packet switching" network. Returning to the UK, Davies proposed such a system to the British Post Office, which expressed interest but responded slowly. Davies also set up a minimal prototype packet-switching network at NPL.

One of those at Davies' MIT seminar was Lawrence Roberts of Lincoln Laboratory, who had by that time been involved in experiments (also supported by ARPA) carried out at Computer Corporation of America (CCA), linking the Lincoln time-sharing TX computer with the SDC's Q32.[6] This experiment indicated problems because of the slow switching times of the telephone dialing system and the noise of telephone lines designed for the relatively long and "forgiving" nature of voice communications. Roberts recounts that earlier, on the basis of discussions with Licklider and others at a meeting in 1964, he had concluded that time sharing was launched and that the next important step was to design computer-communication links from the computer point of view.[7] Alternatives to special intercomputer communications systems, such as developing a "universal language" for all computers, or demanding all computers be designed to be compatible with communications, seemed impractical.

At about the same time there had also been a number of inter-computer links, as an outgrowth of time-sharing at other laboratories, in industry, and academic institutions, notably the OCTOPUS system at the Lawrence Livermore Laboratory linking large computers[8], experiments at Bell Telephone Laboratory (BTL) on load-levelling by linking similar computers, and in the SITA airline reservation system. OCTOPUS apparently used a technique similar to packet switching, but did not give the technique a name.[9] The

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[5] L. Roberts, unpublished address, 1985.

[6] "Toward a Cooperative Network of Time-Shared Computers," by T. Marill and L. Roberts, *Proc. First Joint Computer Congress*, 1966, p. 425. An earlier time-sharing link of these computers had been demonstrated in project MAC's first summer study.

[7] L. Roberts, ibid.

[8] D. Pehrson, "Interfacing and Data Concentration," Chapter 6 in *Computer-Communication Networks*, N. Abrahamson and F. Kuo, eds. Prentice-Hall, 1973, describes the Octopus system.

[9] Discussion with J. Fletcher, LLL, 5/89.

NERCOMP system, set up by Dartmouth University as an outgrowth of the Dartmouth Time Sharing System, by the late-1960s linked a number of smaller academic institutes throughout New England.[10] While relatively slow and unsophisticated, this was perhaps the first time-sharing network to be operated on a pay-for-itself basis.[11]

Roberts came to ARPA in late 1966 and commenced developing plans for networking to link computers. R. Taylor, head of IPTO at that time, had a background and ideas similar to Licklider's about the benefits from developing man-computer interactions on a broad front. He was anxious to involve the 15-20 computer researchers supported by ARPA in planning the initial ARPA network, soon to be called ARPANET. An informal working group made up of most of these researchers helped assess and plan different possibilities for communication links between their research computers, which were of many different types and used generally different operating systems and communications control programs.[12]

This group soon concluded that a distributed, multinode network was needed, which could be linked by leased telephone lines with faster switching and wider bandwidth than the common carrier switched voice network. A key suggestion was made by W. Clark that small intermediate computers, between the "host" computers resident at each users' location (or node) and the communication lines, could remove some of the burden of programming each different host computer to interface with the communication lines.[13] Communications in the ARPA network was then envisaged as taking place among these small computers, later called "interface message processors," or IMPS, in a distributed communications network, and between IMPS and host computers. A "hot potato" routing scheme, discussed by Baran (about whose work Roberts apparently was now aware), for handling message segments or "packets" was adopted initially for the new ARPA network.

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[10] R. Hargraves, Jr. and T. Hurtz, "The Dartmouth Time Sharing Network," Chapter 11 in *Computer - Communication Networks*, N. Abrahamson and F. Kuo, eds. Prentice-Hall, 1973.

[11] "In at the Beginnings" by P.M. Morse, MIT 1977, p. 355. ARPA apparently provided some assistance to Dartmouth for this system, A.O. 1075 of 8/67.

[12] See "Expanding AI Research and Founding ARPANET," by L. Roberts, in *Expert Systems on Artificial Intelligence*, T. Bartee, ed., Sams, 1988. Roberts mentions that McCarthy and Minsky of MIT's AI group initially opposed the idea of others sharing their computer resources.

[13] *Tools for Thought*, by H. Rheingold, Simon & Schuster, 1985, p. 216. A similar suggestion had also been made by Davies.

IMP routing schemes and algorithms were changed and improved several times in the ARPANET project, becoming progressively more complex and "intelligent."[14]

Roberts and his co-workers outlined their rather detailed plans for ARPANET at a computer conference late in 1967. A very similar UK NPL plan was presented at the same conference, but based on a higher (1.5 Mbit/sec) communication line speed. Discussions at the conference influenced ARPANET to use 56 kbit/sec line speed for the "backbone" system, a higher transmission line speed than previously planned.[15] The objectives of the ARPA program stated at this meeting were to develop and test computer-communication techniques, and to obtain benefits and economies of resources sharing for as many as possible of the then 30-odd ARPA contractors in the IPTO program.[16] It was envisioned that short data sets of the type generated in terminal-computer interactions would have to be handled by the combined computer and transmission line network with an overall transaction time less than the desired human interaction time of about one second. Very low error rates were also desired because of the high accuracy required for data transmissions between computers, and for this purpose an error-checking code was added to each packet.[17] Further network bandwidth requirements came from the desire to have remote interactive graphics capability. For this purpose, desired end-to-end bandwidths had to exceed 20 kilobits/sec. The initial number of users was selected as 15, large enough to involve many researchers to help design data formats or protocols together with the operating procedures for the network, have interactions between many different kinds of computers, and have enough traffic to be able to make meaningful statistical measurements and analysis.

2. Early Development and Experimentation

A detailed specification along the lines presented by Roberts in 1967 was set forth in an ARPA RFP in 1968. Many major computer manufacturers chose not to bid, apparently because they did not then make minicomputers of the type required for IMPs.[18]

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[14] *Computer Networks*, by Andrew S. Tanenbaum, Prentice Hall 1988, p. 289.

[15] "The Evolution of Packet-Switching," by L. Roberts, *Proc. IEEE*, Vol. 66, 1978, p. 1308. The ARPANET speed is a fraction of the line speed, depending on characteristics of messages and congestion.

[16] Roberts later estimated that the savings to the IPTO program was a factor three over what would have been required had each contractor been supplied equivalent computers of their own. Roberts, 1985.

[17] "The ARPA Network," by Lawrence G. Roberts and Barry D. Wessler, Ch. 13 in *Computer-Communication Networks*, N. Abramson and F. Kuo, eds., Prentice-Hall, 1973, p. 485.

[18] L. Roberts, ibid., 1985.

Bolt, Beranek and Newman (BB&N) won the contract to design the software for the "interface message processors" (IMPs).[19] The IMP's were initially based on a modified Honeywell 516 computer; later, more capable IMPs used BBN designed computers. The first few IMPS were built and installed within a year.[20] DECCO, a contracting unit of DCA in communication services, was given initial responsibility for leasing 56 kbit/sec lines, because of favorable government rates. Progress was facilitated by AT&T setting up a special unit for dealing with problems of interfacing with the ARPA network for this purpose.[21] ARPA also contracted with the Network Analysis Corporation (NAC) for assistance in designing the "topology" of the network.[22]

A "Network Working Group" of key contractors and ARPA managers was set up to help design the initial system, especially the software "protocols" needed for standardized forms of communication among IMPS, between an IMP and a host, and between hosts. In less than a year BB&N had a 4-"node" initial ARPA network, soon named ARPANET, set up and running. While inter-IMP communications were going well, the intercomputer links took longer to achieve satisfactory operation. A very important feature was that ARPANET was operated from the beginning as a scientific experiment, making measurements of important quantitative features and publishing results.[23] For this purpose one of the key nodes from the beginning was at UCLA under L. Kleinrock, with the responsibility of gathering data and making analyses. Soon after ARPANET started, a "network control" was set up whereby BB&N could remotely monitor performance of any IMP and identify and "fix" software problems. This remote control of software proved important for economic and efficient network operations, and for other applications.

In 1969, a number of other private computer communication systems began to be operated, including the SITA system for international airline reservations, which used

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[19] A.O. 1260 of 6/68 for "Interface Message Processors."

[20] "History of ARPANET - the First 10 Years," BB&N, p. 24. Software for the IMPs was at first regarded as proprietary by BB&N, but DARPA ruled that this had to be open along with other data. See "Computers in the Public Interest: The Promise and Reality of ARPANET," By D.S. Bushnell and Victoria B. Elder, George Mason University, Fairfax, VA, 1987.

[21] BB&N, ibid.

[22] AO # 1380 of 1/69 for "Computer Network Modelling and Measurements."

[23] Apparently, the French Cyclades packet-switching system, in operation a bit later, also published much of its performance data and associated analysis.

packet-switching together with voice, and TYMNET for TYMSHARE, one of the large time-sharing service companies. These networks involved routing and switching principles somewhat different from those used in ARPANET.[24] Retrospectively, Roberts points out that all these developments were probably due to the fact that 1969 was the year when the cost of computing fell below the cost of communications for computer-communications.[25]

The distributed ARPANET that evolved attempted to achieve the general objectives of minimizing costs and maximizing the probability of successful and adequate message transmission. In this early growth phase problems of designing such a network began to be recognized. One important issue was the optimizing of network topology for these objectives.[26] The topology problem was not fully solved, but eventually approached by successive adjustments to an approximate solution. Other problems were routing and flow control, taking into account the levels of traffic, capacities of links, and cost. Kleinrock states that while a number of these problems were and are still unsolved, the network operates quite successfully due to the high degree of adaptability of the system and its operators. [27]

Use of the IMPs allowed a degree of standardization of message formats or "protocols" over the long communications lines, while reducing the software requirements on the host computer operating systems. It was soon found that IMPs should be designed to support several hosts in a time-sharing node. Host to host communications via the IMPs proved more difficult than expected, and further "interfacing" between host computers and the network through additional small computers proved necessary in some cases.

In addition, a need arose among groups without computers of their own to access computers through terminals. In 1971, responding to this need, a "Terminal Interface Processor," or TIP was designed which allowed direct access to IMPs and so to the entire

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[24] SITA was characterized by BB&N, ibid., as surprisingly sophisticated for its time but not well known to the DARPA computer community. See also "TYMNET I: An Alternative to Packet-Switching Technology," by J. Rinde, p. 594 in *Satellites, Packets and Distributed Telecommunications*, Roy D. Rosner, Ed. Lifetime Learning Publication 1981, p. 594.

[25] L. Roberts, *Proc. IEEE*, ibid., 1307. This is the cost given the previous investment in the communications lines and line-related facilitites used and based on the current "tariffs" set by the FCC.

[26] "Principles and Results in Packet Communications," by L. Kleinrock, *Proc. IEEE*, Vol. 66, Nov. 1978,

[27] Ibid. Recently, more "intelligent" IMPS can control routing to more closely approximate these objectives.

network. Costs of IMP's in the early 1980's were around $50K and TIPs, which gradually also absorbed IMP functions, about $100K.[28]

3. Demonstration, Transfer, and Initial Applications

By 1972, having gained considerable experience with ARPANET, ARPA decided to stage a public demonstration of its capabilities. It took nearly a year and considerable shakedown effort to arrange for this, but at the Washington International Computer Conference in November, 1972, the demonstration, orchestrated by R. Kahn (then of BB&N), was very successful. This demonstration linked, via ARPANET, some 25 terminals at the conference location with a variety of computer resources. In 1973 ARPANET was made available to DoD and its contractors, who became a fast-growing clientele.

After this successful demonstration of the ARPANET technology, an approach was made by ARPA to AT&T to take over operation of ARPANET as a public network, with a view that such a "utility" could serve commercial, research and military users. However, AT&T, which also was opening circuit switched services for data transmission at the time, declined.[29] Similar discussions were held with other common carriers, but a GAO report raised the issue whether ARPANET, a government-funded system, should not be first offered to government agencies.[30] After the GAO report, ARPA commissioned wide-ranging studies of the utility of ARPANET which laid the basis for high level discussions in DoD, leading eventually to negotiations with DCA.[31]

The mission of DCA was to provide communications for the military and it was at first reluctant to operate a research network such as ARPANET which also involved non-military users, and which had at the time no provisions for security. However, within DCA no one in authority voiced major objections to taking over responsibility for ARPANET.[32] There were, also, several other factors affecting DCA's actions regarding

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[28] *What Can be Automated?*, MIT Press, 1980, p. 383.

[29] In 1976 AT&T used packet switching extensively in its CCIS between its switching nodes, to control communications, and later also offered a form of packet switching services to customers. See e.g., "Evolution of the Intelligent Telecommunications Network," by John S. Mayo, *Science*, Vol. 215, 1982, p. 831. A display of telecommunications "breakthroughs" in this article, however, does not include packet-switching.

[30] Discussion with R. Kahn and V. Cerf, 5/89. In fact, ARPANET technology had been picked up quickly by NSA.

[31] P. Baran, who had done the earliest studies of packet switching, participated in these studies.

[32] Discussion with E. Hoverston, 5/89.

ARPANET: (1) there was a growing number of military nodes of ARPANET; (2) ARPA, in order to be able to share classified data over the network undertook to develop, with NSA, a "private line interface" (PLI) device allowing end-to-end ARPANET encryption;[33] and (3) internal studies by DCA of the next generation defense data communication system indicated the desirability of using packet-switching technology. An agreement that DCA would take over operating responsibilities of ARPANET was effective in mid 1975, and allowed DARPA to continue its research programs on the network as a "DoD sponsor."

ARPANET grew rapidly in number of "nodes," and in traffic volume in the first few years. Figures 1 and 2 show the ARPANET network at early (1970) and later (1985) stages. Early estimates had been that the traffic growth would be exponential and that network capacity would soon be saturated. It soon turned out that the growth flattened out and that the host computers were saturated before the network.[34] In the mid 1980's, however, network congestion was common.[35] Also, early estimates were that message length distribution would be bimodal, with many short messages and a smaller number of large messages.[36] Eventually, short "electronic mail" messages dominated.

BB&N, with the ARPANET experience under its belt, was encouraged by DARPA to set up a public packet-switched data network under the new FCC rules.[37] BB&N set up a subsidiary, TELENET, to do so, and Roberts left DARPA and joined TELENET soon afterwards. Apparently, however, it took nearly two years to raise enough venture capital and to get FCC approval to launch the new network. TELENET started operation in 1975.[38] In a few years TELENET grew to serve about 200 nodes in different cities. TELENET incorporated "Virtual Circuits" and ARPANET "datagram" technology.[39]

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[33] AO 2755 "Net Encryption" of 11/74 and A.O. 3092 of 8/75.

[34] BB&N, ibid., p. III-72. This was apparently due to a rapid adaptation by the users. BB&N, ibid., p. III-74.

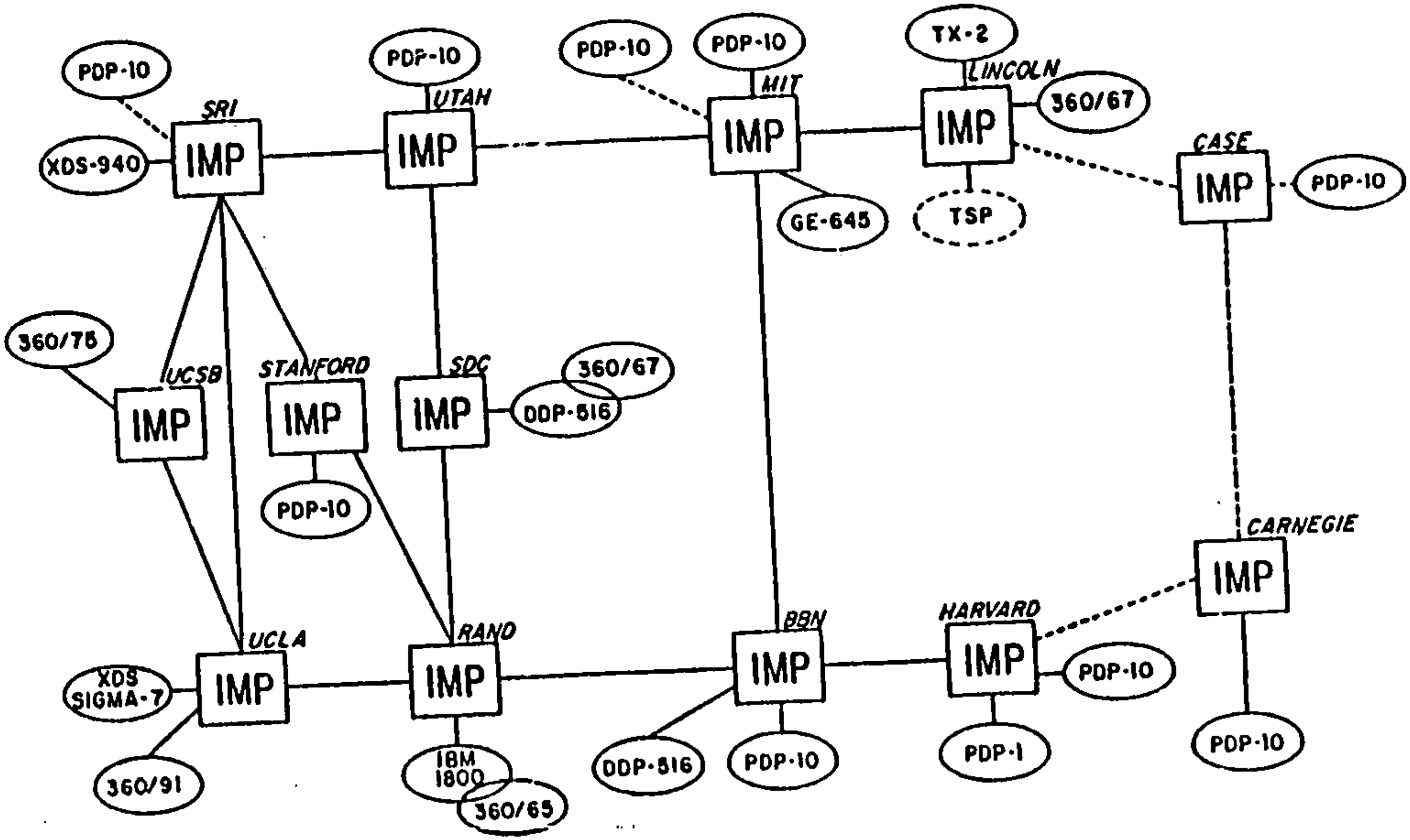
[35] *Toward a National Research Network*, National Academy of Sciences, 1988, p. 11.

[36] Kleinrock, ibid., p. 1320.

[37] D. Bushnell and V. Elder, ibid.

[38] "Electronic Post for Switching Data," *New Scientist*, 15 May 1976, p. 351, and "Three Decades of Contributions in Science and Technology," BB&N, 1988, p. 10.

[39] Virtual circuit technology with flow control apparently was pioneered by the French RCP packet-switching system. See Roberts, *Proc IEEE*, ibid., p. 1309.



ARPA NET, DECEMBER 1970

Figure 1. An illustration of the proliferation of networks used by researchers worldwide. (Modified from IEEE Spectrum, Vol. 25, No. 2, February 1988, pg. 56.)

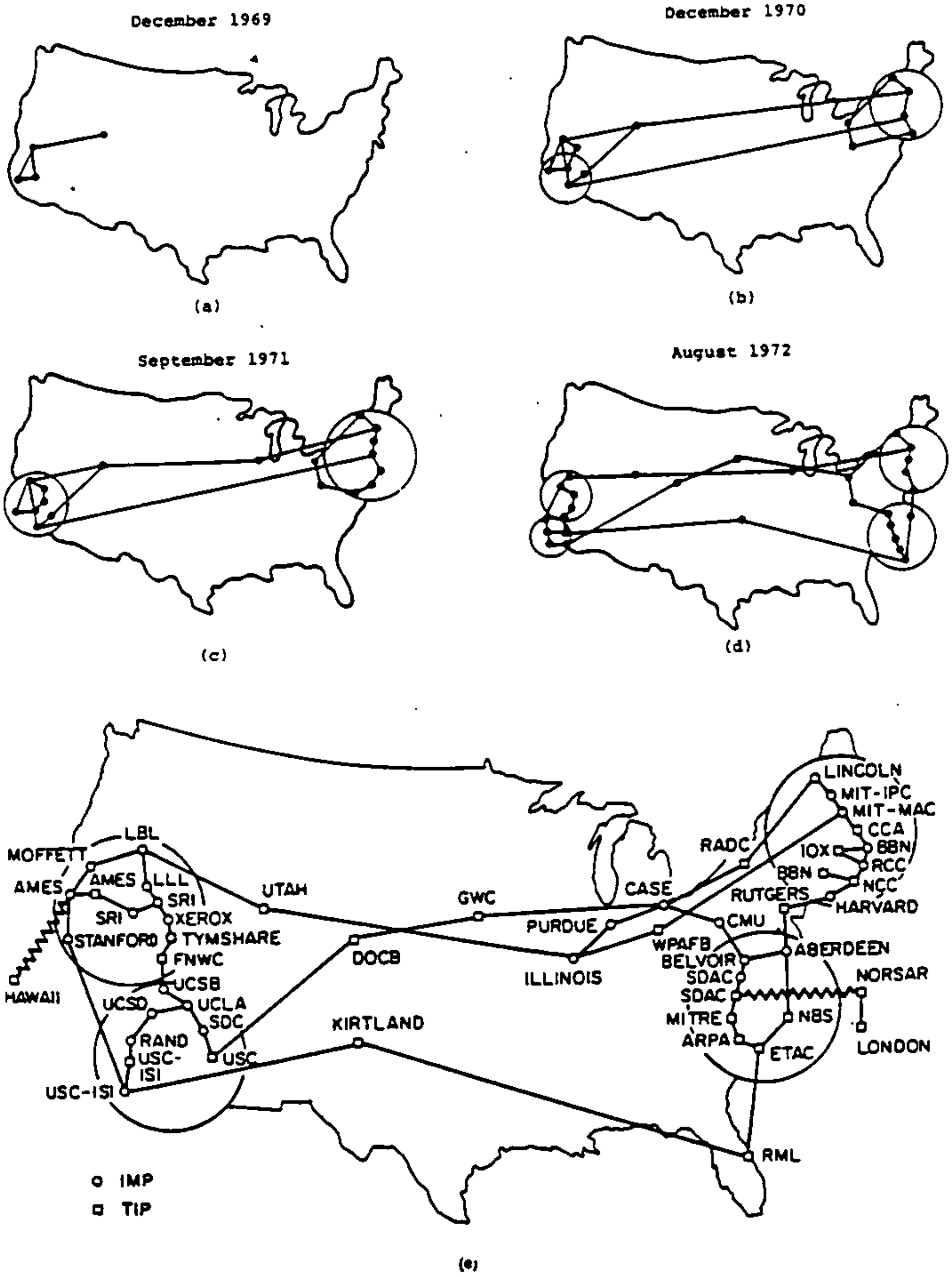


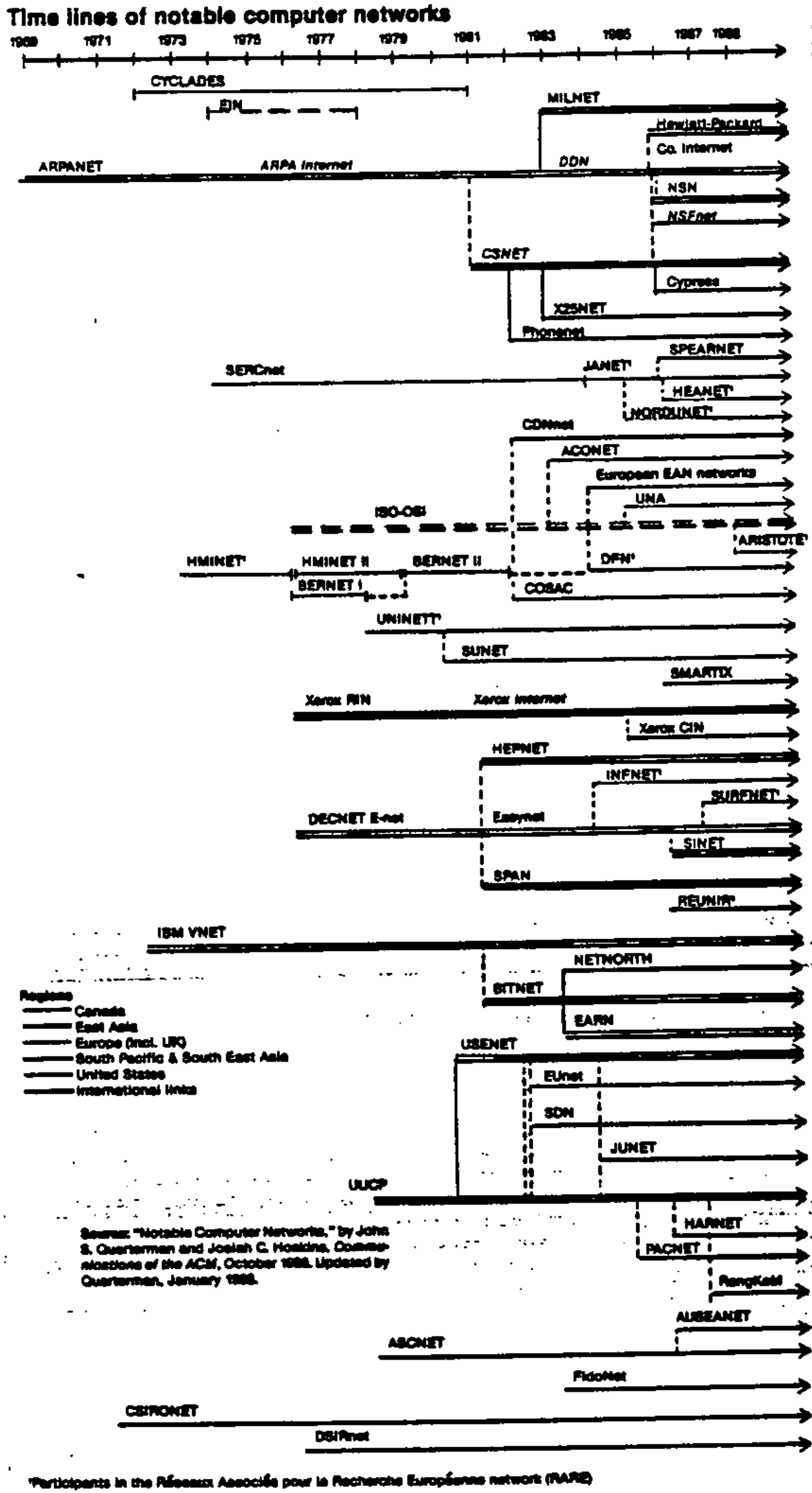
Figure 2. Evolution of the ARPA Network, (a) December 1969, (b) December 1970, (c) September 1971, (d) August 1972, (e) November 1974 (from Howard Frank, "ARPA Network," *Proc. IEEE*, Vol. 66, No. 11, November 1978)

Figure 3 shows the worldwide proliferation of network activity from 1972 to 1975. This can be credited to several factors: (1) the impact of the economics of computing and of communication, worldwide; (2) in the U.S., the FCC decision to permit value-added carriers to compete with the established carriers; (3) that the technology did not require any major technological breakthrough; and, perhaps most importantly, (4) the impact of the existing operating ARPANET and the published scientific information about it.

4. Expanded Defense Application

From the early 1970s into this decade ARPANET packet switching technology has been the basis for the development of defense-wide systems for data communications. While several application efforts started in the early 1970s, the development of this defense-wide capability began with the military nodes of ARPANET which were already heavy users of ARPANET through the 1970s. Starting in 1971 interactive networking efforts in both the command and control (WIN) and intelligence (COINS) arena began as experimental extensions of ARPANET packet switching technology. In both of these efforts individuals who had been directly involved in the development and use of ARPANET carried these concepts into their specific highly classified user environments. Through the 1970s, these experimental prototype networks grew into and were accepted as operational systems within the confines of the security limitations of these classified arenas. Attempts were made starting in 1972 to introduce some packet switching into a planned replacement of the AUTODIN system for DoD message and data communications. This effort, AUTODIN II, was judged to be unsuccessful, and in 1982 a decision was made to implement an alternative approach for interactive data communications, the Defense Data Network (DDN) based explicitly on ARPANET incorporating the MILNET and the WIN networks. These developments, described below in more detail, proceeded in parallel, but not in isolation. There was early recognition of the desirability of interlinking the independent network developments, but also an appreciation of the difficulties of doing so given the differing levels of security this would entail. While considerable progress has been made, the internetting of the DoD ARPANET-based packet switching networks still is not complete.

The transfer of operational responsibility to DCA in 1975 highlighted a dichotomy in the character of ARPANET as a dual purpose system--both a research network and an



Source: "Notable Computer Networks," by John S. Quarterman and Josiah C. Hoskins, Communications of the ACM, October 1986. Updated by Quarterman, January 1988.

*Participants in the Réseaux Associés pour la Recherche Européenne network (RARE)

ACONET: Akademisches Computer Netz
ARISTOTE: Association de Réseaux Informatiques en Système Totalement Ouvert et Très Elaboré
ARPANET: Advanced Research Projects Agency Network
ASCNET: Australian Computer Science Network
AUSEANET: Austroasian Network
BERNET I, II: Berlin Network
BITNET: Because It's Time Network
COSAC: Communications sans Connections
CSIRONET: Commonwealth Scientific & Industrial Research Organization Network
CSNET: Computer Science Network
DDN: Defense Data Network
DECNET E-net: DEC Engineering Network
DFN: Deutsche Forschungsnetz
DSIRnet: Government network in New Zealand
EARN: European Academic Research Network
EIN: European Informatics Network
EUnet: European Unix Network
HARNET: Hong Kong Academic & Research Network
HEANET: Higher Education Authority Network
HEPNET: High Energy Physics Network
HMINET I, II: Hahn-Meitner Institut
IBM VNET: Virtual Network
INFNET: Istituto Nazionale Fisica Nucleare
ISO-OSI: International Organization for Standardization–Open Systems Interconnect
JANET: Joint Academic Network
JUNET: Japanese Unix Network
MILNET: Military Network
NORDUNET: Nordic University Network
NSFnet: National Science Foundation Network
NSN: NASA Science Network
PACNET: Pacific Network
RangKoM: Rangkaian Komputer Malaysia
REUNIR: Réseaux des Universités et de la Recherche
SDN: System Development Network
SERCnet: Science Engineering Research Council Network
SINET: Schlumberger Information Network
SPAN: Space Physics Analysis Network
SPEARNET: South Pacific Education and Research Network
SUNET: Swedish University Network
SURFNET: Dutch university network
UNA: Universitäts-Netz Austria
UNINETT: Nordic university network
USENET: Users' Network
UUCP: Unix to Unix Copy
Xerox CIN: Corporate Internet
Xerox RIN: Research Internet

Note: CDNnet, CYCLADES, EAN, NETNORTH, and SMARTIX are not acronyms.

The past five years have seen the number of networks soar dramatically. Many initially used transmission protocols and technology developed by one or more older networks; these are indicated by the vertical dashed lines connecting networks. (More recently, some networks have begun to use other protocols, particularly ISO-OSI and Arpanet standards.) Solid vertical lines between networks indicate systems under closely related administrations. Dashed horizontal lines indicate protocols or demonstration systems, rather than operational networks. Networks in italics are internets—several networks tied together that use the same transmission protocols.

Figure 3. An Illustration of the Proliferation of Networks Used by Researchers Worldwide. (Modified from IEEE Spectrum, Vol. 25, No. 2, February 1988, pg. 56)

unclassified defense network for military users. With increasing use by military users for "operational," as opposed to research applications, this dichotomy raised organizational concerns within DCA.[40]

> ...ARPANET has had a dual character. On the one hand, it has existed as an operational network serving a wide variety of users. On the other hand, it has served as an experimental testbed for research on packet switching. ...ARPANET is ...an operational DoD facility, used solely for government-related business. The operational users require reliable, consistent network service ... and... attention paid to security and privacy.

With the creation of DDN in 1982, these military nodes were split off from ARPANET as MILNET.

WIN

The Worldwide Military Command and Control System (WWMCCS), under the auspices of the Joint Technical Support Agency, purchased an ARPANET-type system from BB&N for the Prototype WWMCCS Intercomputer Network (PWIN). This was "an experimental program from 1971 to 1977 to determine the operational benefit of networking and to identify the characteristics needed to support military operations."[41] WWMCCS, whose communications were being provided by DCA, had been procuring H6000 series computers for DoD's major Unified and Specified Command Centers. This provided the equipment compatibility for the development of intercomputer communications within WWMCCS, a capability that was seen as essential.

The tests of PWIN proved sufficiently successful, despite some problems, that it became the basis for the much larger "WIN" system. Six initial WIN sites in 1977 increased to 20 sites by 1981. However, problems in the technical and procedural aspects of systems performance led, in 1980, to a major program to upgrade hardware, software and reliability.[42] This upgrade was completed in 1983.[43] As will be discussed below, in 1982 the DDN, initially called the "WIN/ARPANET replica," was built upon this base.[44]

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[40] T. Harris, et al., "Development of the MILNET," CH1828-3/82, IEEE, 1982, p. 78.

[41] *Modernization of the WWMCCS Information System (WIS)*, Assistant Secretary of Defense, (Communications, Command, Control, and Intelligence), 19 January 1981, p.7.

[42] Ibid., p.7 and p. 39.

[43] Defense Science Board, *Defense Data Network*, Office of the Under Secretary of Defense for Research and Engineering, 1985, p. 3.

[44] *Hearings before Defense Sub-Committee of Committee on Appropriations*, HOR, 96th Congress, 1st Session, Part 6, 1979, p. 253.

COINS

In 1965, the National Security Agency (NSA) began the Community On-line Intelligence System (COINS), an "experiment in exchange of intelligence information throughout the intelligence community." COINS was initially a store-and-forward network which became operational in 1973.[45] From 1973 to 1977 COINS was upgraded from a store-and-forward to a packet switched system based on ARPANET technology. The packet switched network, COINS II, was declared operational in 1977.[46] The following were seen as the features and advantages of the new ARPANET-based COINS:[47]

- The star network switch has been replaced by a distributed, packet-switched communications system modelled after ARPANET. There is no longer a single point of failure.
- The protocol set has been enlarged to include interactive operation.
- Host systems are attached to the network via front-end processors, which execute the network protocols. The hosts are thus freed from a substantial (and increasing) network overhead burden.
- The network can be accessed from terminal concentrators which are not directly associated with any network host. Given proper authorization and a secure environment, any terminal can access COINS from any location.

The COINS initial store-and-forward configuration was established at the Defense Intelligence Agency's (DIA) Arlington Hall facility and linked to NSA. In 1973, through 1977, additional intelligence community hosts were added to the packet-switched system and in 1978 the first terminal concentrator permitting access to the network from points not associated with a host computer became operational.[48] By 1980, while the system was generally operational, it was constrained by accessibility problems due to the age of some of the computers, lack of necessary interactive protocols between some of the network components, and the mixture of non-standard front-end processors. A key limitation was the lack of a multi-level security capability, restricting access to the SI/TK level. "Most of

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[45] *COINS Long Range Plan, Part II COINS Network Architecture for the Long Range Plan*, COINS Project Management Office, NSA, Ft. Meade, Maryland, 23 March 1981, pp. 1-2.

[46] Ibid.

[47] Ibid., p. 5.

[48] Ibid.

the potential intelligence community users [were] thus excluded from COINS."[49] Although the access problems due to both technology and security limitations were still needing resolution, it was envisioned that COINS would interconnect via "gateways" to several other networks either in existence or then in the planning stage: ARPANET, PLATFORM, IDHSC, AUTODIN II, and IAIPS.[50] Importantly, these interconnectivity plans were being made under the assumption that the new DoD-wide data communications system then under development, AUTODIN II, would become operational. The failure of that development and the difficulty of achieving acceptable multi-level security gateway links between COINS and other DoD intelligence networks have delayed the envisioned inter-network connections.

AUTODIN II

In 1972 the first plans for the new DoD AUTODIN II telecommunications system began to be laid.[51] This was partly in response to requests originating from the new Assistant Secretary of Defense for Telecommunications, Dr. Rechtin (the ARPA director during the early phases of ARPANET), who had "tasked the Director, Defense Communications Agency (DCA) to make recommendations concerning the provision of a family of Defense Communication System (DCS) switched services to fulfill computer communications requirements for the DoD."[52] In addition the Joint Chiefs of Staff, in July 1972, tasked the Director, DCA to prepare a plan to satisfy WWMCCS ADP communications requirements. DCA studies of users' requirements were then ongoing for a new system to replace AUTODIN I. Essentially a teletype message switching system with store-and-forward capabilities, AUTODIN I was recognized to be slow and unable to handle interactive computer traffic, for which there was increasing demand in the DoD.

The computers at military installations which were to be linked by DCA were of several different types, often with their own software. Large dollar and training economies appeared possible if they could be linked together via a network in which, like ARPANET, these computers could communicate with one another and be able to share software and

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[49] Ibid., p. 8-9.

[50] Ibid., p. 11.

[51] "The Autodin II Network," by Col. A. Stathopoulos and H.F. Cally, EASCON-77, IEEE, 1977, p. 8-1A.

[52] Ibid.

other resources.[53] A panel, including some from the ARPANET community, was called in for assistance by DCA and recommended IMP-type interfaces and ARPANET-like protocols for the network and the "backbone" long haul communications circuits.

Despite the recommendations of the advisory panel to use ARPANET technology and protocols, the AUTODIN system detailed in the System Performance Specification showed substantial differences between the characteristics of AUTODIN II and ARPANET.[54] A key difference was that AUTODIN II employed only a very few (initially four and planned eight) central nodes into which data would be directed and rerouted, requiring very large message storage capabilities in each central node. Moreover, each center required many personnel cleared to the SI/TK level and TEMPEST secure, guarded facilities. This architectural aspect of AUTODIN II substantially reduced the effectiveness of the packet switching capabilities of the internode communications. The recommendation of DCA was based on the fact that there was already a large inventory of older AUTODIN I equipment, and switching over to an ARPANET based packet switching system was seen as a very costly approach, given this installed base.

Moreover, the technique for assessing the security classification of messages used an approach that was cumbersome and manpower intensive, yet DCA was not satisfied that its security requirements could be met adequately by packet switching. The individual nodes were very large operations, with large data storage systems and had sizeable manpower requirements to enforce security since the data within a portion of each node had to be in the clear for routing purposes. Multilevel security for AUTODIN II was based on a software "security kernel" approach, which proved to be difficult to implement and certify as sufficiently trustworthy for data above the secret level.

AUTODIN II construction commenced in 1977 and proceeded at a very slow pace, even with only 4 nodes in the initial phase. The difficulties encountered in implementing this system led to a major review that led to AUTODIN II being superseded by an alternative approach, the DDN:[55]

> As a two year program for initial implementation stretched to four and a half, a growing number of problems and uncertainties about AUTODIN II were encountered. In July 1980, an OSD review group was established to

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[53] "History of the ARPANET," BBN, ibid., p. II-4.

[54] Stathopoulos, ibid., p. 8-1C.

[55] *Report of Defense Science Board Task Force on AUTODIN II*, Office of the Under Secretary of Defense for Research and Engineering, December 1982, p. 3.

> review the system...(which) ... considered the cost, security, performance, and survivability of AUTODIN II....[T]he group also explored available options if AUTODIN II failed. Principal among the alternatives considered was an expansion of the WWMCCS Information Network and ARPANET systems.

DDN

There were growing concerns about and criticism of AUTODIN II because of the generally slow pace of progress, the lack of potential to meet growing needs, and most importantly, costs.[56] Survivability of the system, which was estimated to be low for the AUTODIN II nodes, was also a concern. Because of the necessity for a digital DoD network to provide interactive service, the Assistant Secretary of Defense for C^3I ($ASDC^3I$) tasked the Institute for Defense Analyses (IDA) to develop an alternate (or "back up") design in case the AUTODIN II system problems proved insurmountable.[57]

The design produced by IDA had two separate networks, (1) an unclassified network (called MILNET) and (2) a classified (C^3I) network which included service for WIN, DoDIIS (then IDIIS), and SACDIN. The design used ARPANET and its packet-switching technology. C30s, the updated IMPs, were used in the switches. TCP/IP and X.25 or 1822 were proposed as lower network protocols. A key point in the design was the use of private line interface (PLI) devices (or their successors, IPLIs and BLACKER) to provide end-to-end encryption to separate classified users.[58] The collocation of WIN and DODIIS sites and the short runs to switches provided economy and the many switches provided survivability.

The proposed network design was circulated and many potential users stated strong preference for this design versus the AUTODIN II design. The $ASDC^3I$ then tasked the Defense Science Board (DSB) to review the AUTODIN problem and the proposed solution.[59] The DSB Task Force recommended the termination of AUTODIN II and its

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[56] *Hearings before Defense Subcommittee of Committee on Appropriations*, HOR, 97th Congress, 2nd Session, p. 91 ff.

[57] The following is derived from discussions in 8/89 with T. Bartee of IDA, who developed the DDN architecture.

[58] A.O. 3173 of 12/75 had provided for development of PLI's.

[59] *Report of Defense Science Board Task Force on AUTODIN II*, Office of the Under Secretary of Defense for Research and Engineering, December 1982.

replacement by the Defense Data Network. This recommendation was enacted by Secretary of Defense Carlucci on April 2, 1982.[60]

At the same time, ASDC^{3}I also tasked DCA to determine the optimum design for DoD. DCA formed three task forces--(1) a group to update and improve the AUTODIN II design and explore future possibilities and costs; (2) a group to further develop the details of the design proposed by IDA and predict future developments and a more detailed cost estimate; and, (3) a team to decide between the two designs.

The result was a choice of the ARPANET technology plus NSA/DARPA security features. AUTODIN II was cancelled and the IPLI and BLACKER projects were initiated. A DDN office was formed at DCA under Col. Heidner, who had headed the winning design team.

The planned evolution of the DoD network from the 1982 Defense Science Board Report, shown in Figure 4, "consists of the evolution and expansion of existing and newly established networks based on ARPANET technology and their ultimate consolidation into an integrated network suitable for use at multiple levels of security."[61] DDN was planned to be a more survivable system with a much larger number of distributed nodes and links. The use of ARPANET technology permitted easy expansion of the network. By this time the experience with operating ARPANET and the open scientific data published about it had also built confidence in the technology.

Because the BLACKER and IPLI were in development, the DDN was originally designed in separate pieces, including MILNET, ARPANET, WIN, DODIIS, "Secret Net," etc.[62] This was as planned, however. Merging the classified sections has been delayed because of BLACKER delays and NSA's decision to continue only BLACKER and not the IPLI program. Apparently the problems of achieving adequate multilevel security, without the high expense of a large number of IPLI's, has proved more difficult

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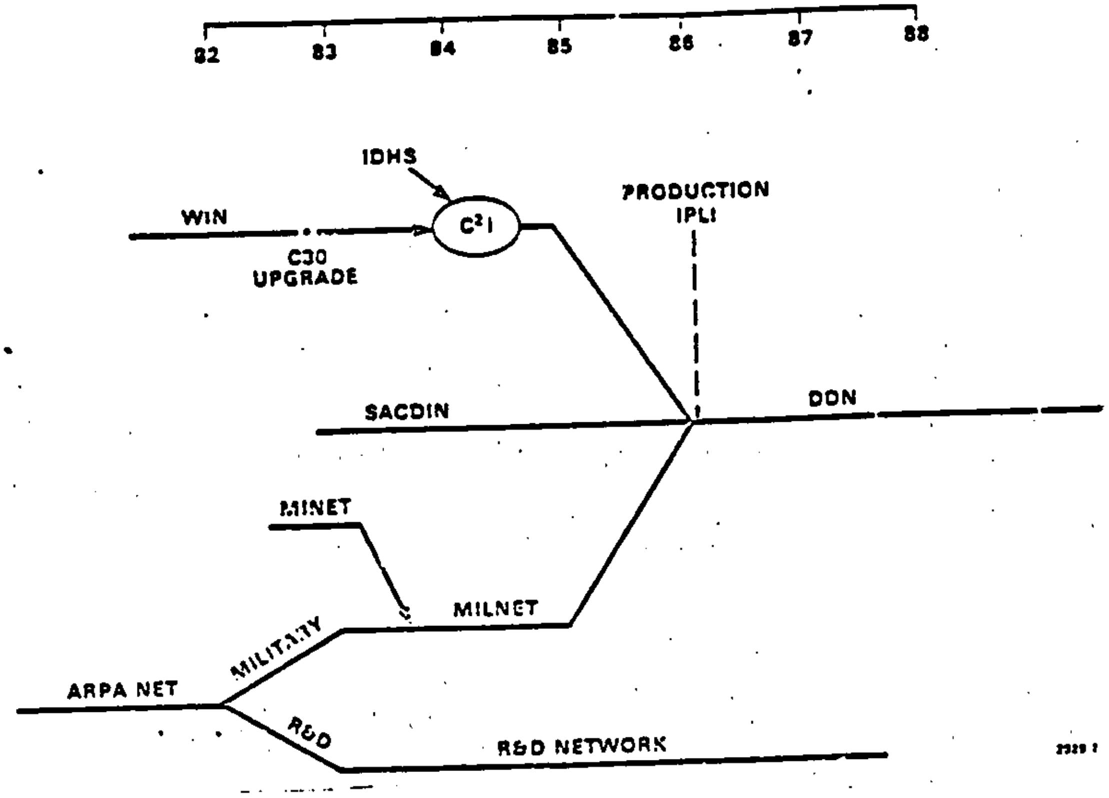
[60] The cancellation was not sudden but had been planned for some time. It took place one day after the formal contract completion date, to minimize overall costs. Discussion with V.Cerf and R. Kahn 5/89.

[61] *Final Report Defense Science Board Task Force on Defense Data Network*, Office of the Under Secretary of Defense for Research and Engineering, 30 August 1985, p.2.

[62] Testimony of D. Latham, Deputy Assistant Secretary of Defense (Communications, Command, Control and Intelligence), Hearings of the Subcommittee on the Department of Defense of the Committee on Appropriations, Defense Appropriations for 1984, House of Representatives, First Session, 98th Congress, May 11, 1983, p. 343.

than anticipated.[63] At present, plans to merge the classified networks have been established and BLACKER testing has begun on operational networks. Worries about computer "viruses" make interconnection of the classified and unclassified network dangerous.

As "[a] first step in the evolution of the DDN," MILNET was established, separating out the operational military nodes from the ARPANET.[64] MILNET handles unclassified but sensitive operational traffic using commercial grade cryptographic systems, and until recently had a link to ARPANET through a physically separate "gateway."



Source: *Final Report, Defense Science Board Task Force on Defense Data Network,* Office of the Under Secretary of Defense for Research and Engineering, 30 August, 1985.

Figure 4. DDN Network Design

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[63] *Defense Science Board Task Force on the Defense Data Networks*, ibid., and discussion with Dr. T. Quinn, OSD, 12/87. A number of other problems with the WIN as of 1981 were noted in the DoD report on modernization of the WWMCCS information systems, 19 Jan. 1981, p. 7. Apparently BLACKER has just recently passed laboratory tests. Discussion with Dr. T. Quinn, 12/87 and 6/89.

[64] Ibid. p.77.

MILNET was split off from the rest of ARPANET initially by the TCP/IP software protocol, developed by DARPA, and effective in 1984, when this protocol was accepted by DCA. Secure gateways also linked MILNET and its European counterpart, Movements Information Network (MINET), to classified DCA networks.[65] The MILNET/MINET network has grown to approximately 250 nodes reaching "most DoD facilities around the world, stretching from Turkey in the east around to Guam and Korea in the west."

5. Other ARPANET Research

As the ARPANET demonstration and applications in telecommunications networking showed the promise of packet switch technology, DARPA pursued additional areas of its possible application. These included "Packet Radio," "Packet Voice," and "Packet Satellite." In addition, the ARPANET itself became an important contributor to successful conduct of other DARPA programs, in particular, the AI research program and MOSIS, a program to facilitate integrated circuit fabrication research.

Packet Radio

Experiments were conducted in the early 1970's to link computer users by "packet radio," beginning with the "ALOHA" system linking educational institutions in the Hawaiian Islands.[66] The concept of linking computers by packet switching communications using radio broadcast rather than conventional lines appeared to offer many advantages, particularly for Army mobile systems in the field. Some packet radio demonstrations were later conducted with the Strategic Air Command (SAC). Special broad band, countermeasure resistant radios were developed for field test at Fort Bragg, but proved expensive. Problems with multipath transmission and interference were investigated. Related R&D has continued jointly with the Army to date. Problems of "collision" of messages from many transmitters, characteristic of the radio packet environment, were dealt with by arrangements such as "slotted Aloha," due to L. Roberts of DARPA. Packet contention problems in local area networks have been handled also by techniques related to those used in ALOHA.[67]

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[65] D. Perry, et al., "The ARPANET and the DARPA Internet," *Library Hi TECH*, Vol. 6, No. 2, 1988, p. 56.

[66] R. Kahn who joined DARPA in 1973 led this packet radio development effort. "Advance in Packet Radio Technology," by R.E. Kahn, et al., *Proc. IEEE*, Vol. 66, 1978, p. 1468, also "The Aloha System," by Abramson, et al., in *Computer-Communication Networks*, Abramson and Kuo, eds., ibid.

[67] "An Introduction to Local Area Networks," by D. Cline et al., *Proc. IEEE*, Vol. 66, 1978, p. 1497.

High costs of the packet radios developed for Army field use were addressed by a special joint DARPA-Army effort. However, the Army decided recently to save time, some expense, and its TRI-TAC programs by "jumping" the R&D process, and as a "non-development initiative" purchased in 1985, for field trials of "mobile subscriber equipment" (MSE), a version of the "RITA" field radio system which had been developed by the French in the mid to late 1970's. The U.S. Army version of RITA is apparently a circuit switched system, with a central control node.[68] An upgrade to incorporate packet-switching is expected in the 1990's.[69] Also, the Air Force is installing an electromagnetic pulse hardened packet-switched radio system, the groundwave emergency network (GWEN), for missile warning centers, command centers and strategic force bases.[70]

A spinoff of DARPA's efforts in packet radio was made to speed up the solution of some logistic problems of the 82nd Airborne Division. Very rapid adjustments of space, weight and lift capabilities are faced when loading this division for different missions when, as typically occurs, changes have to be made because of aircraft and equipment availability. The AALPS computer-based system for loading the division was developed by SRI with support from the DARPA packet radio program. With a computer terminal on the airfield, a mainframe computer which can run AALPS could be accessed by radio. Adjustments could then be made on the airfield, in near real time, according to dynamically changing availability of aircraft. After a number of trials including one experiment using a group of sergeants making manual calculations as competition, AALPS was adopted by the 82nd Division and is now part of their regular procedure for rapid deployment.[71]

Packet Voice

In the early 1970's experiments began using ARPANET packet switching (digitized) voice and combined data and voice communications, using both lines and packet radios.[72] Packet digitized voice has advantages for encryption and efficiency in military communications, but loses much of an individual's speaking (and so identification)

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[68] Discussion with Col. W. Stevens, IDA, 3/89. RITA apparently can have a packet switching capability as did its competitor, the UK's Ptarmigan, but this feature is not now being exploited by the Army system. See A. Wohlstetter and R. Brody, "Continuing Control...", Ref. 3., pp. 176-177.

[69] *Jane's Military Communications*, 1989, p. 810.

[70] A. Wohlstetter and R. Brody, "Continuing Control as a Requirement for Deterring," ibid., p. 177.

[71] Discussion with V. Cerf, 5/89.

[72] "Experience With Speech Communications in Packet Networks," by Clifford J. Weinstein and Joseph W. Forgie, *IEEE Journal*, on selected areas in communications, Vol. SAC-1 No. 6, See 1983, p. 963.

characteristics. Delay times for presently available bandwidth circuits also proved troublesome. Apparently, satisfactory voice and data communications, with many users, will require wider band circuits and faster switches than initially used by ARPANET.[73] Work along these lines, over wideband, higher speed links, has intensified recently and has involved active participation of the "common carriers," such as AT&T.

Packet Satellite

ARPANET wideband satellite packet switching links were set up with Hawaii, Norway and London.[74] Satellite packet switching investigations led to a commercial service offered for a while by Western Union, but now shut down. Satellite packet communications apparently have found use primarily in applications which are less sensitive to transmission delays.[75] SIMNET, a graphic simulation system which uses satellite packet switching for training widely separated Army tank crews, has had growing success.[76]

Local Area Networks

"Local area" networks (LANs), with limited geographic distribution and greater bandwidths than ARPANET, began in the mid 1960's. One of the earliest was the Lawrence Livermore Laboratory's OCTOPUS system, mentioned above, which was based initially on concepts published by project MAC.[77] LLL developed their own dynamic switching software (with some limited packet switching capabilities) to link their several different types of large computers directly to each other and to terminals.[78]

In the early 1970's Xerox constructed Ethernet, partly based on ARPA's packet-switching technology developed for packet radio.[79] Ethernet soon became a commercial success. Local area network systems, based primarily on ARPANET technology, also developed rapidly in DoD agencies. The growth of LANs and other networks within DoD

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[73] L. Roberts, unpublished, 1985.

[74] NORSAR was the terminal in Norway for data transmission to the seismic research center of DARPA's NMO.

[75] Discussion with Dr. V. Cerf, 5/88. See also "ARPANET Hitches a Satellite Ride," by S. Blumenthal, *Communications Systems Worldwide*, Sept. 1985.

[76] Discussion with J. Orlansky, IDA, 3/88.

[77] Discussion with J. Fletcher, LLL, 5/89.

[78] Pherson, ibid., p. 229.

brought a need to formulate protocols which had provision for security. DARPA led the successful effort to define the TCP/IP protocols for multilevel security.

ARPANET as a Research Tool: AI and MOSIS

In providing interactive computer communications among researchers, ARPANET contributed to several ARPA computer-based development efforts. One successful effort to exploit ARPANET was the intensive use of "electronic mail" and a form of teleconferencing to develop the AI language, Common LISP. Still another successful ARPANET exploitation has been made in MOSIS, a system to expedite fabrication of integrated circuits. A central facility for MOSIS is provided by the University of Southern California's Information Sciences Institute.

As described by Newell and Sproull, MOSIS allows integrated circuit designs to be transmitted to a fabrication facility:[80]

> ...as an electronic mail message describing in a text form the geometry of the several masks that control integrated-circuit fabrication.... MOSIS uses the network to allow a great many designers to share access to fabrication. Moreover, the system is able to combine several separate designs onto one chip (a so-called multiproject chip) in order to reduce fabrication cost. Centralizing fabrication services in this way simplifies interactions with vendors and frees the chip designer from a great many troublesome details. An important advantage is the avoidance of dealing with a human bureaucracy (the alternative organization technology for managing the same process), which tends to become unresponsive, error prone, and hard to control.... [The network] becomes an integral part of a larger computational enterprise. The design sent by [electronic] mail to MOSIS is not prepared by hand, but is produced by computer-aided design tools for preparing mask geometry and for checking the design.

ARPANET'S Impact on Internetwork Communications

The value of the DARPA effort to develop protocols for internetwork communications was recognized by the international community, and DARPA again played a prominent role in the remarkably rapid development of international standards for computer-network and network-network communications, such as the CCITT X.25, very

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[79] R. Taylor, ex-head of DARPA's IPTO, went to Xerox and started PARC, where ETHERNET was built. See *Tools for Thought*, by H. Rheingold, Simon & Schuster, 1985, p. 205 ff.

[80] "Computer Networks, Prospects for Scientists," by Allan Howell and Robin F. Sproull, *Science*, Vol. 215, Feb. 1982, p. 849.

similar to the ARPANET TCP/IP protocol. Other related developments, such as "virtual links" with individual flow control, originating with the French RCP network, also played an important role in setting standards.[81] More recent development in standards have led to the International Standards Organization's "Open System Interconnections" protocols, gradually being adopted worldwide, which differs from the TCP/IP of ARPANET, but has as yet much less working experience. Many, if not most, commercial network systems are now based on TCP/IP.[82]

Within the research community demand for network capabilities has increased markedly, due to developments such as the convenience of "electronic mail," and the desire to facilitate access to supercomputers.[83] The availability of "free" electronic mail on ARPANET had a major impact on the style and efficiency of research by its users. Another motif comes from the desire for simultaneous processing, e.g., for geophysical research or seismic monitoring, of worldwide observations. NSF, in the mid 1980's, set up an agreement with DARPA initially to allow expansion of the number of nodes in ARPANET, to include NSF-supported research groups, and later linking ARPANET to other nets such as CSNET.[84] Network traffic levels apparently have increased to the point of frequent congestion and less reliable internet performance.

With increasing demand for remote usage of supercomputers, the need for greater bandwidth and higher speed transmission links has led to plans for a new wideband network, with corresponding switching speed capabilities. ARPANET, according to recent reports, will be replaced by a new "Defense Research Net," with the new range of capabilities, also to be run by DCA.[85] These new capabilities bring with them also a new generation of problems related to the design of the interface processors, switching software, network designs, and economics.

In 1982, L. Roberts and L. Kleinrock were awarded Ericsson prizes, the Electrical Engineers' version of the Nobel Prize, by the government of Sweden, in recognition of their contributions to the technology of packet-switching.

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[81] Roberts, unpublished, 1985.

[82] V. Cerf, ibid.

[83] *Information Technology and The Conduct of Research*, National Academy of Science (NAS), 1989, Washington, D.C., contains a survey and recommendations for the future.

[84] B. Schultz, "The Evolution of ARPANET," *Datamation*, Vol. 34, No. 15, 1 Aug. 1988, p. 71, and Newall and Sproull, ibid., p. 583. Also, *Information Technology and The Conduct of Research*, NAS, ibid., 1989.

[85] Schultz, ibid., p. 74.

C. OBSERVATIONS ON SUCCESS

ARPANET was an ARPA initiative, a major result of the "grand scheme" of J.C.R. Licklider, the first IPTO director, and carried through by his successors, R. Taylor and L. Roberts. There was software development involved but apparently no technological "breakthrough" required for effective implementation of the packet-switching basis for ARPANET.[86] Roberts describes the impact of ARPANET as "in part a massive and evolutionary change in computer technology, and in part a modest and revolutionary change in telecommunication technology."[87] These changes came from the computer community and were resisted initially by most of the communications community.

ARPANET, like the previous time sharing efforts on which it was based, was not envisaged as a specifically military development, although it was clearly understood that the DoD would be a major user of the technology. This was in accord with high level viewpoints at the time that the U.S. lead in the computer area would be enhanced and its national benefit best obtained by a broad R&D effort not tied to specific military projects.

Perhaps the greatest contribution of ARPANET was the fact that it was operated as an scientific experiment with participation by a highly competent group of contractors, whose results and analysis were openly published. This facilitated a broad transfer of technology and understanding and provided for establishment of confidence in a way that would not have occurred if industrial developments had taken the normal course, slower and more "hidden" because of inevitable proprietorship.

Timing was a major factor in several respects. In 1972, at the time ARPANET was first demonstrated, DCA was in process of studying the next steps to take with AUTODIN, its first attempt at data and message automation. Computer communication was a major factor in the study. It took from 1972 to 1977 to get AUTODIN II under contract and by the time it reached Initial Operating Capability (IOC) it had demonstrated many problems of cost, schedule, growth potential and vulnerability. It was shut down in 1982, as soon as legalities and economies would allow, and was replaced by DDN, a network based directly on ARPANET technology. Despite the delays, ARPANET technology probably sped up the modernization of DoD communications by several years.[88]

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[86] Roberts, ibid.

[87] Roberts, 1985, ibid.

[88] Discussion with L. Roberts 5/88.

ARPANET flourished as an unclassified network. When discussions began about DCA taking over responsibility for ARPANET, network security became a major issue, resulting in a DARPA program leading to the widely used TCP/IP protocol. However, the recent experience of the intelligence community and DDN with multi-level security indicates the difficulty of achieving an economic and satisfactorily secure defense network.

ARPANET's development was well timed technically, economically, politically, and in regard to military needs. The economics of packet versus circuit switching keyed to the rapid fall in computer hardware costs, and the FCC decisions in the U.S., had great effect upon the timing of commercial development. These features of packet switching technology also greatly affected DoD decisions regarding telecommunications. The initial commercial success of packet switching has now grown to the billion dollar range.

The ARPANET evolution was paced, of course, by the external technology developments relating to chips and integrated circuits embodied in microprocessors and memories. In the same period as the corresponding increase of ARPANET capability, there occurred an increase of local computing power at progressively decreasing costs, through the development of personal computers and work stations. This development effectively reduced one of the major early motifs cited for ARPANET: to make larger computer capabilities available more widely and with the economy advantage of doing so with a small number of large mainframes. In this sense, ARPANET's use for more efficient use of computer resources does not seem to have been as successful as its use for electronic mail. However, this objective has returned to prominence with the advent of supercomputers. But to accommodate these computers, the packet-switching technology has to be updated to accommodate the greater bandwidths and switching speed required.

The development of local area networks in recent years can be regarded as an outgrowth of time sharing and packet-switching. Technology transfer to Ethernet, one of the earliest LANs, was facilitated by key people moving from the DARPA environment and DARPA supported projects such as MAC to Xerox.

"Packet Radio" has been picked up commercially to a limited extent and has an enthusiastic following in amateur radio. While DARPA R&D on field packet radio has continued, the Army decided to buy initially a circuit-switching MSE system based on the French RITA system for its near-future battlefield communications. Apparently, the Army's reasons were mainly economical and political. A packet-switching capability for the Army MSE System is expected to be available in the 1990's.

"Packet Satellites," except for "batch" type communication or limited categories not bothered by the transmission delay, have not been widely used so far. However, the less time-sensitive remote-interactive requirements of computer-aided Army simulation training systems, such as SIMNET, can accept the satellite transmission delay. SIMNET is now beginning to take hold for training exercises involving Army groups at geographically distributed groups throughout the world.

Very effective and efficient transfer of ARPANET technology took place by relocation of key people and involvement of key contractors. As mentioned above, strong early impetus toward DoD use of ARPANET technology for its data communication came from the new DoD Assistant Secretary for Telecommunications, E. Rechtin, who had been ARPA director in the ARPANET gestation period. L. Roberts, who got ARPANET going, went to BB&N to head TELENET. R. Taylor, from DARPA, went to PARC and got Ethernet going. And BB&N, the key ARPANET contractor, became involved with, first, the WWMCCS "PWIN" experimental system, and later with setting up DDN.

The greatest impact of the ARPANET program has been its broad, indirect impact on the greater efficiency of R&D, industrial, and military processes requiring computer communications. Initially "free" to ARPANET users, this service is now more subject to economic incentives in the various networks. Some of the non-military areas which have intensively used packet switching technology include medical research and psychology. It is remarkable that the facilitation of psychological research was the motif that spurred Licklider toward the earliest ARPA efforts in time-sharing and ARPANET.

ARPA outlays for ARPANET, from project records, were about $25M to 1975, when the transfer to DCA took place. Including radio and satellite packet switching, and network-related research, total outlays are about $150M to date.[89]

The commercial packet-switching market is currently estimated at about $1/2B.[90] DCA's first expense for packet-switching for their WIN/ARPANET replica was estimated, in 1983, at about $430M.[91] The GWEN packet switching network costs to date are estimated as about $1/2B.[92]

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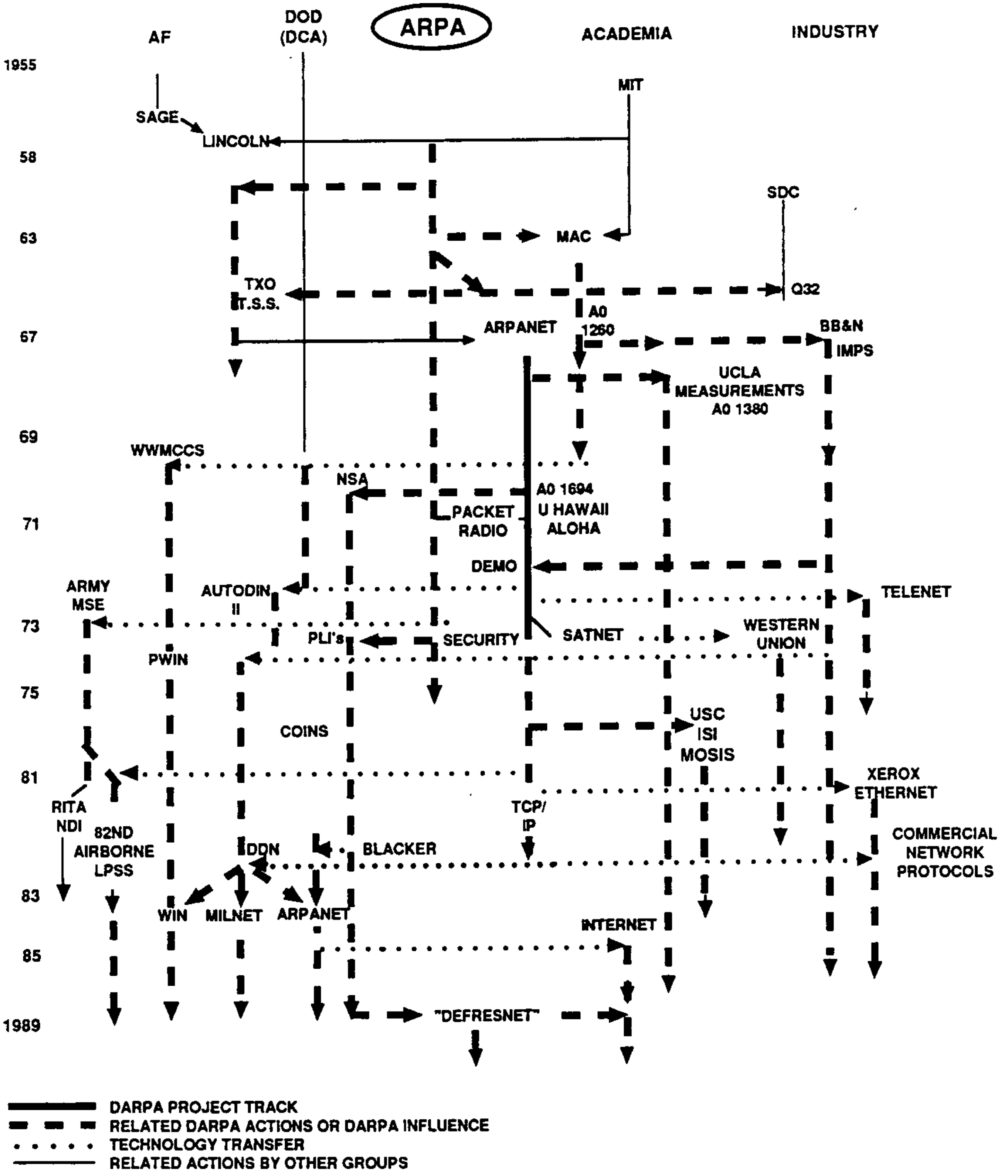
[89] About $40M of this went for packet and satellite radio R&D.

[90] Discussion with L. Roberts, 11/89.

[91] DoD Appropriations Hearing for 1984, HASC, 98th Congress, first session, part 5, p. 420.

[92] HASC Authorization Hearings, FY 1986, Part 2, pp. 127 and 137.

ARPANET



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XXI. ARTIFICIAL INTELLIGENCE

A. BRIEF OVERVIEW

The growth of Artificial Intelligence (AI) in the U.S. can be credited greatly to ARPA support, which built upon earlier efforts by the Services and Academia. ARPA support of the development of computer time-sharing in project MAC in the early 1960's was largely motivated by the need to develop the computer tools essential for AI. Through the mid 1970's, building on this base, DARPA* was the primary supporter of AI research. DARPA also promoted large focussed AI application efforts, such as automatic speech recognition and image understanding. A number of AI applications began to appear in the late 1970's, including some for military systems, largely based on technology and technologists supported by DARPA. In 1983, AI technology was incorporated as a key component of DARPA's Strategic Computing Program.

B. TECHNICAL HISTORY

The name "Artificial Intelligence" was given by John McCarthy to describe the main topic of the first U.S. meeting in the area, supported by the Services and National Science Foundation (NSF) in the mid 1950's.[1] However, a key paper at that meeting, describing a successful heuristic computer-based "theorem prover" given by Herbert Simon of Carnegie Technical Institute (now Carnegie-Mellon University), did not use the term "artificial intelligence." AI is usually defined as the technology of making computers do things that would be regarded as intelligent. There is a great deal of overlap with sophisticated automation, with the distinction being that automation pertains to doing things that are more

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* The Advanced Research Projects Agency (ARPA) became the Defense Advanced Research Projects Agency (DARPA) in 1972.

[1] Discussions about intelligent computers go back to the times of Gottfried Leibniz and Lady Ada Lovelace. In the 1930's and 1940's Turing's work, and later von Neumann's led to further interest in "intelligent" behavior of computers.

or less routine.[2] Thus some types of mines long used by the military had activation systems sometimes described as "intelligent."

One of the first large efforts of this kind in the late 1950's was undertaken a by the Air Force in the related area of automatic language translation. However, such translation was found to be quite difficult and a National Academy of Sciences committee reviewing the problem discouraged further efforts.[3] In this same time period, there were also some related developments by industry in automated design of engines, and in the business area for investment choices.[4]

Some research was supported by the Services in the early 1950s on approaches to intelligent sensors and systems based on the study of neurophysical processes, and of the operations of the brain. One of the resulting devices, the "Perceptron," was capable of emulating some of these processes but to a very limited degree because of the limitations of technology. But the growing availability of computers at the time offered another avenue to AI, based more on the logical capabilities of computers, which were not then designed with brain-like structures to augment human capabilities. It was this latter approach that was followed by Simon, McCarthy and others in the major development of AI.

Mathematical logic was one of the first areas in which researchers turned to computers to augment human capabilities. In the late 1950s, H. Wong of Harvard was able to prove several hundred of the propositions in mathematical logic in Whitehead and Russell's *Principia Mathematica*, using only machine programming, without having the types of heuristic approaches or structured reasoning tools now associated with AI. The limitations and cumbersome nature of such an approach for solving deductive logic problems with a computer led to efforts to develop a computer language for processing lists of symbols.

Around this same time, McCarthy, then at the Massachusetts Institute of Technology (MIT), was grappling with the problem

> ...could you have a program that would solve a variety of problems, and furthermore take advice in order to improve its performance? So he proposed some ideas for a program called the Advice Taker, a program that would have common sense - that is, it would deduce from what it was told,

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[2] *Artificial Intelligence*, by H. Simon, Davis Lecture, Naval War College, National Academy of Sciences publication, 1985.

[3] Ibid.

[4] Ibid.

> and what it already knew, the immediate consequences of any actions it might take. [5]

In order to pursue this problem, McCarthy began working on the programming language LISP, which built upon and made more general the concepts of the list-processing languages of Newell, Shaw, and Simon.[6] LISP since has been developed into a basic tool for AI. While McCarthy's earliest work on LISP was not supported by ARPA, much of its later development and implementations were.

Beginning in the mid 1960's, ARPA began to support the development of AI. The initial ARPA support was indirect: Project MAC at MIT to develop computer time-sharing at MIT had as one of its main motifs interactive program writing and debugging needed for rapid development of AI.[7] The development of MACSYMA, a system to aid mathematicians with symbolic computation, by Joel Moses of the MIT AI group, was much expanded under project MAC.[8] Now a commercial product for a range of mathematical symbolic processes, MACSYMA derived, in turn, partly from a symbolic mathematics effort at the MITRE Corporation supported by the Air Force.[9]

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[5] P. McCorduck, *Machines Who Think*, W.H. Freeman, 1979, p. 215-216

[6] Ibid., cf. A. Newell, J. Shaw, and H. Simon, "Empirical Exploration of the Logic Theory Machine: A Case Study in Heuristics," *Proc. 1957 Western Computer Conference*, 1957.

[7] This emphasis was largely due to the insight of McCarthy who perceived the great importance of time-sharing for AI development. J. McCarthy memo to P. Morse, quoted in *A Century of Electrical Engineering and Computer Science at MIT*, by K. Wildes, MIT Press, 1985, p. 243. See also McCorduck, ibid., p. 217, who quotes McCarthy that his first funding for time-sharing was a grant from the National Science Foundation. One involved participant observes, "Time-sharing is not Artificial Intelligence, but Artificial Intelligence demanded it". P. Winston, *The AI Business*, MIT Press 1985, p. 5.

[8] P. Winston, ibid., "Project MAC-25th Anniversary," MIT, Laboratory for Computer Sciences, 1988, foldout; MACSYMA was an early challenge to the "generalist" concept for AI development, embodied in Newell's General Problem Solver (GPS), and was considered by some of MIT's AI leading theoreticians at the time not to be AI. The argument was over MACSYMA's reliance on expert, specific knowledge, see P. McCorduck, ibid., p. 229.

[9] Discussion with E. Lafferty, 5/89 .

In the mid 1960's ARPA became a key supporter of AI in the U.S.[10] Support was given by ARPA to the Heuristic Programming Project of Stanford's Edward Feigenbaum, a former student of Simon's at Carnegie-Mellon University (CMU). As opposed to the broad, general "laws of thinking" that underlay initial AI conceptualizations of Newell's General Problem Solver, or McCarthy's Advice Taker concept, the approach of Feigenbaum was to develop "expert systems" focussing on real, not "toy" problems and designed to capture and utilize expertise in a narrow domain.[11]

The "real problem" that was the initial focus of Feigenbaum's work was the analysis of the structure of organic molecules. Later called DENDRAL, this project was supported, in the late 1960's and early 1970's, by ARPA. A concern of ARPA was that the project was heavily oriented toward chemistry and that this aspect should be supported by others.[12] The National Institutes of Health (NIH) and the National Aeronautics and Space Administration (NASA) became funders of the research for automatic interpretation of mass spectrograms and nuclear magnetic resonance spectra to identify chemical compounds.[13] After NASA support in the AI area dwindled, DENDRAL was supported primarily by NIH, and became a widely used laboratory and commercial product in the late 1970's. DENDRAL is widely considered to have been the first major successful AI expert system application. Development of DENDRAL took place over many years and involved extensive cooperation of AI researchers and investigators specializing in other fields.[14]

AI was first explicitly called out in 1968 or 1969 as a separate research area in the ARPA IPTO research budget.[15] ARPA support was given both to fundamental areas, such

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[10] In the early 1960's there were a number of studies and meetings on AI in the UK. Largely due to this activity, much of which was centered at the University of Edinburgh, the UK was regarded as leading the field at this time. However, in the early 1970's a high-level UK committee, under Sir James Lighthill, turned down AI for a large grant. The UK, at the time, was selecting promising areas to be funded under the title, "National Development Initiatives". This largely discouraged the UK AI group, some of whom subsequently came to the U.S. See E. Feigenbaum and P. McCorduck, *The Fifth Generation*, 175-176. Also see M. Minsky,"The Problems and the Promise," in P. Winston and K. Prendergast, eds., *The AI Business*, MIT Press, 1984, p. 246. Recently, however, the UK's "Alvey" program in information sciences has included a sizeable component of AI. *Information Technology R&D*, OTA, U.S. Government Printing Office, 1985.

[11] E. Feigenbaum and P. McCorduck, *The Fifth Generation*, Addisson-Wesley, 1983, p. 65. AO 457 of 3/63 Heuristic Programming.

[12] C. Green, "AI During IPTO's Middle Years," in T. Bartee, ed., *Expert Systems and Artificial Intelligence*, Howard Sams, 1988, ibid., p. 238.

[13] *The Seeds of Artificial Intelligence*, National Institutes of Health, PO-2071, 1980, pp. 18-19.

[14] Ibid., p. 25.

[15] "Expanding AI Research and Founding ARPANET," by L. Roberts, in Bartee, ibid., p. 229. AO 1058 of 7/67 for "Intelligent Automata."

as knowledge representation, problem solving, and natural language structure, and to applications in areas such as expert systems, automatic programming, robotics and computer vision.[16] This AI research was carried out mainly at MIT, Stanford, Stanford Research Institute (SRI), Bolt Beranek and Newman (BB&N), and later Carnegie-Mellon University (CMU), which have remained major AI centers to date. However, C. Green, who was in charge of this early AI work at ARPA, felt that there was more money than good ideas at the time.[17]

In the early 1970s the early developments of ARPANET already expanded the range of possibilities for interactive computing.[18] At this time another NIH-supported AI effort was started at Rutgers focussed on problem solving.[19] This and other NIH AI-related medical research resource development programs quickly took advantage of ARPANET wherever possible, together with other networks, to speed up exchange of research information.[20]

The Xerox Palo Alto Research Center (PARC) was set up near Stanford in the early 1970's by R. Taylor, who had been director of ARPA's IPTO. One of the earliest efforts supported there by ARPA was the development of a widely used version of LISP, "Inter LISP." Other LISP "dialects" began to proliferate, and were eventually coordinated in the late 1970's by meetings and ARPANET teleconferences promoted by DARPA.[21]

In the early 1970s there were proposals to construct a new computer especially configured to execute LISP. ARPA, apparently, did not support these efforts explicitly, partly because of the IPTO experience with ILLIAC IV.[22] There were also concerns at the time about government support of computer building outside of industry, with "cheap labor" of graduate students.[23] MIT persisted, however, and in 1980 LISP machines had been constructed and used in MIT's Laboratory for Computer Science (LCS), and Xerox's PARC, which had built its own, and were offered for sale by companies formed by ex-

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[16] "The Early Years, Founding IPTO, by JCR Licklider, in Bartee, ibid., p. 220.

[17] "A.I. During IPTO's Middle Years," by G. Green, in Bartee, ibid., p. 237.

[18] Interestingly, ARPANET was not greeted enthusiastically by all members of the AI community, cf. Roberts, ibid.

[19] S. Amarel, "Problem Solving," Chapter 4 in T. Bartee, ed., *Expert Systems*, ibid.

[20] *Seeds of Artificial Intelligence*, ibid., p. 69. See also "Computer Networks - Prospects for Scientists," by Allen G. Newell and Robert F. Sproull, *Science*, Vol. 215, 1982, p. 851.

[21] Footnote by R. Engelmore in Bartee ibid., p. 244.

[22] Roberts, ibid., p. 232-3.

[23] Discussion with M. Denicoff, 6/89.

MIT researchers. Many of these LISP computers were subsequently purchased by AI researchers with ARPA support, and by other government laboratory groups.[24] The computers involved in a typical current AI laboratory (NRL) are shown in Fig 1. Recently, however, LISP execution on the CRAY (general purpose) supercomputer, in a test supported by DARPA, has been demonstrated to be faster than specialized LISP machines.[25]

1. Applications

In the early 1970's ARPA's first major concentrated AI applications project was begun as part of an interdisciplinary effort toward the Speech Understanding Research Project (SUR). This was the first large effort on computer speech, and it was undertaken despite a National Academy of Science Committee's (Pierce Committee) negative recommendation. At the same time there were also some encouraging developments, such as a device to automatically generate phonemes from speech.[26] A very strong motivation for this program was the great advantages that were envisioned of being able to communicate with computers with speech.

The ARPA SUR program was initially planned to have two 5-year phases, with the first having the goal of a 1000-word vocabulary, uttered by a limited number of speakers in a relatively quiet room.[27] Some AI researchers, however, regarded such quantitative goal-setting as premature at that early stage of AI research. The SUR project funded several competitive approaches and there was also a broad supporting research program. The following summarizes the results of the first phase of this program:[28]

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[24] Initially, the LISP machines were specialized mainframe computers. Later, with the increase of power of smaller machines, LISP could be executed with interactive graphics on personal computers, and more recently, on a single chip.

[25] *IEEE Spectrum*, 1989.

[26] Roberts ibid., p.234. AO 1943 of 8/71.

[27] Green, ibid., recounts that Roberts, IPTO head at the time, said he wanted 10^4 words, and if not that, as much as could be done. However, a committee of peers was set up by ARPA, and decided 10^3 words was a reasonable goal.

[28] R.S. Englemore, et al., "Hearsay - II," in R. Englemore and T. Morgan, eds., *Blackboard Systems*, Addison-Wesley, 1988, p. 25. L. Erman, et al., "The Hearsay-II Speech Understanding System: Integrating Knowledge to Resolve Uncertainty," in R. Englemore and T. Morgan, *Blackboard Systems*, ibid., pp. 60 - 75, compares the competing systems.

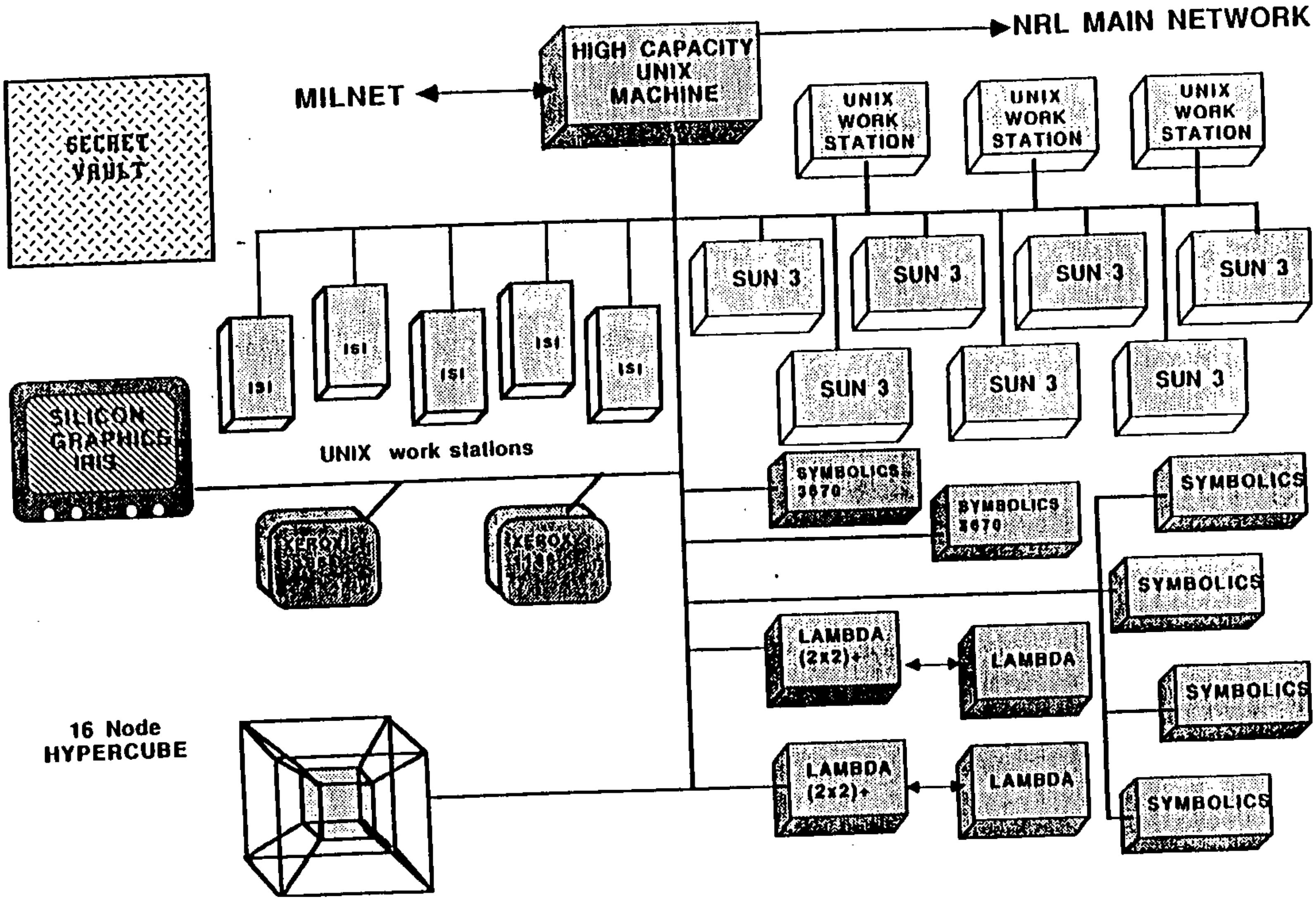

Figure 1. NRL's NCAR AI Computing Facility

> Three organizations finally demonstrated systems at the conclusion of the project in 1976. These were Carnegie-Mellon University (CMU) that actually demonstrated two systems; Bolt, Beranek and Newman (BBN), and System Development Corporation with Stanford Research Institute (SDC/SRI)....The system that came the closest to satisfying the original project goals was the CMU HARPY system. The relatively high performance...was largely achieved through 'hard-wiring' information...into the system's knowledge base. Although HARPY made some interesting contributions, its dependence on extensive pre-knowledge limited the applicability of the approach to other signal-understanding tasks.

The second phase of SUR, however, was not carried out. Some feel this was because the first phase did not produce a sufficiently impressive product.[29] However, performance was recognized to have been limited, in part, by the speed of the available computers, and some improvements would await a new generation of computers, several years away. During the SUR project there were a number of proposals to construct LISP computers, motivated by the expected advantages for speech recognition, but as mentioned above, these were not supported by ARPA. In order to get an objective assessment and not lose track of SUR research achievements, a small effort was supported by ARPA and ONR to review and document the SUR effort.[30]

Besides leading to a number of specific research contributions to the field, summarized in Fig. 2, the SUR effort developed methods that have had wider application. One such spinoff is the "blackboard" technique, which was a feature of a second SUR system developed by CMU, Hearsay-II. This is an approach "for coping with problems characterized by the need to deal with uncertain data, make use of uncertain knowledge, and apply a nondeterministic solution strategy."[31] Applications of this technique include image recognition, signal understanding, protein-crystallographic analysis, and data fusion.[32] The blackboard techniques developed under Hearsay-II were adopted as the framework for the ARPA-sponsored HASP program on ocean surveillance signal understanding.[33]

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[29] Licklider, ibid., p. 226.

[30] "Review of the ARPA SUR Project" ONR report by Wayne Lea and June Shoup, Speech Communication Research Laboratory, January 1979, and "AI Development and the Office of Naval Research," by M. Denicoff, in Bartee, ibid., p. 280.

[31] R. Englemore and T. Morgan, *Blackboard Systems*, Addison-Wesley, 1988, p. ix.

[32] Ibid. See also *Computer/Vision*, by D.H. Ballard and C. Brown, Prentice Hall, 1986, p. 505.

[33] H. P. Nii, et al., "Signal-to-Symbol Transformation: HASP/SIAP Case Study,", in R. Englemore and T. Morgan, ibid., pp. 1235-1236.

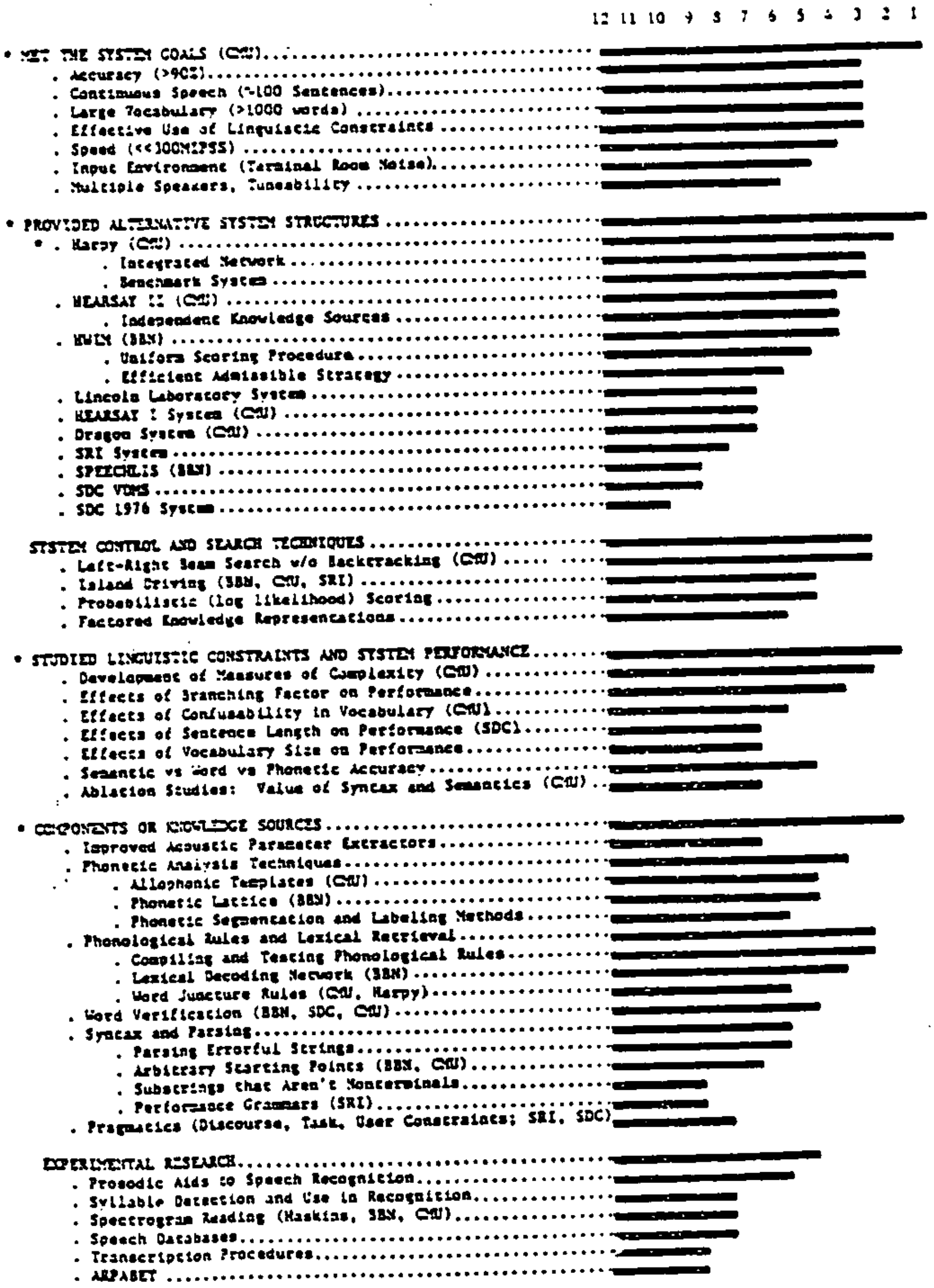

Figure 2. Review of Project SUR Research Developments

Source: W. Lea at J. Shoup, "Review of the ARPA SUR Project," ONR Report, January 1979.

The HASP program began in 1972 as an effort to use AI techniques to automatically recognize signals from seismograms from underground explosions or in sonagrams used in ASW.[34] HASP was to use the ILLIAC IV, the most powerful computer at the time which was being exploited for seismic underwater acoustic research. HASP and its successor program, SIAP, showed some success, but the effort was not considered worth continuing at the time.[35]

Also stemming from the SUR work are the linear predictive codes later used in the Morse Code reader effort by MIT's Laboratory for Computer Science,[36] discussed separately in Chapter XXII; and in secure speech systems used by the military. SUR-generated technology has also had an impact on voice recognition used in military training systems, such as TRIO, developed in 1983 for radar intercept operators.[37] In the late 1970's, IBM began research on speech recognition, partly building on the SUR results, and adding some new approaches.[38]

Dr. G. Heilmeier, upon becoming DARPA Director in 1975, raised "very fundamental and pragmatic questions about the AI research field."[39] Heilmeier says,[40]

> I tried to apply my catechism questions: What are the limitations of current practice? What is the current state of technology? What is new about these ideas? What would be the measure of success? What are the milestones and the "mid-term" exams? How will I know you are making progress? I asked these of all the programs, but for AI I didn't get any answers. This sent the AI community into turmoil -- apparently no one had challenged them in the past.

"It wasn't that I was never a believer in AI, I just wanted them (the AI program leaders in IPTO) to answer basic questions, and they couldn't."[41] Heilmeier recounts that he "saw no investment strategy -- this was the ultimate in laissez faire research." The AI

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[34] Ibid., describes the HASP and follow-on SIAP projects.

[35] "Later Years at IPTO," by R. Kahn, in Bartee, ibid., p. 248. H.P. Nii, et al., "Signal-to-Symbol Transformation...," ibid., discusses analyses by the MITRE Corporation of experiments comparing the performance of SIAP with expert sonar analysts. Also, discussion with H. Aurand, 3/89.

[36] Discussion with Mr. A. Vezza, 4/89,

[37] BB&N, *Science Development Program*, Annual Report 1988.

[38] Lea and Shoup, ibid., p. 30.

[39] R. Kahn, in Bartee, ibid., p. 246.

[40] Interview with Dr. George Heilmeier, 8/29/89.

[41] Ibid.

researchers, in his view, wanted "a cashiers booth set up in the Pentagon--give us the money and trust us." The essential issue in Heilmeier's mind was one on "faith versus accountability." The perspective that he was given was that AI researchers were too busy to write proposals or even to write papers on their research. Moreover, AI was too complex and difficult to explain to non-experts. Energized by this challenge, Heilmeier reviewed the AI researchers' ARPA proposals and their research material ("Apparently I was the first ARPA Director to read their proposals.")[42] He concluded that the AI program was insufficiently structured and focussed to justify the level of funding and attention that it had been receiving.

Not receiving a satisfactory answer, Dr. Heilmeier asked the JASONs[43] to look at the AI program and got "a lukewarm endorsement."[44] Heilmeier's solution was to specify some military applications where AI could be applied and focus a major portion of the DARPA program on these. The result of his review was a major shift in the balance of work toward applications.[45] Heilmeier identified several specific applications programs for AI, notably the ACCAT (Advanced Command and Control Applications Testbed), and the automatic Morse Code reader at MIT.[46] The total AI budget did not go down under Heilmeier, but the balance between fundamental and applied definitely shifted.

There were misgivings in the community (and still are) about expecting too much too soon from AI without sufficient research foundation. Heilmeier contends that his focussing on applications supported the development of the technology and that he recognized the need to provide continued funding for basic research. However, he made it very clear that continued funding of basic research was contingent on the conduct of applications work as well.

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[42] Ibid.

[43] JASONs are a group of leading U.S. physical scientists who devote their attention to problems of science and national security. The JASONs (named after Jason of Greek mythology) were organized originally in 1960 at the Institute for Defense Analyses with the support of the then Director for Defense Research and Engineering, Dr. Herbert F. York. See, H.F. York, *Making Weapons, Talking Peace*, Basic Books, New York, 1987, p. 153.

[44] Heilmeier, ibid. DDR&E also asked an external review group to assess the DARPA AI programs in the 1970s; their conclusions were parallel to Heilmeier's communication from Dr. A. Flax, IDA, 2/90.

[45] This change is discussed by Licklider and Kahn, IPTO directors at the time, in Bartee's, p. 225 and p. 246..

[46] Heilmeier says he also pushed two other application areas, ASW signal understanding (HASP) and image understanding. See also Kahn, ibid., p. 247.

In the command and control areas DARPA believed that not only was the technology that had been developed in the AI and ARPANET networking programs far in advance of what was available to the Services, but also that this technology could solve existing problems including, importantly, those due to widely differing computers and the management of distributed files at different locations. ACCAT was set up as a joint DARPA-Navy effort towards embodiment and test of many of these technologies, including management of distributed, relational data bases, RITA for file query management, and the LADDER natural language system, in a controlled laboratory environment at NOSC. The ACCAT simulated a Navy command center and would communicate via networking with other command centers and data and computer resources.[47] ACCAT also provided additional capabilities for war games played by the Pacific fleet. Changes in the existing ARPANET technology were also required for ACCAT to interface with "MIL spec" computers. ACCAT was also a test bed for developing and testing approaches to a secure network environment, since several data sources in classified facilities were linked together with unclassified nodes of ARPANET.[48] Chapter XXIII further reviews the ACCAT project.

Another response to the DARPA push toward more AI applications was a project at MIT's Laboratory of Computer Science (LCS) to design and construct an automatic translator for manually generated Morse Code, using AI expert system techniques. Building on previous work at the Lincoln Laboratory, and some of the results of the SUR project, AI techniques were applied to the interpretation of somewhat garbled and incomplete word streams and brief introductory transmissions from actual Morse Code tapes to make a "best" translation. The Morse Code project was considered successful by MIT and the results were communicated in the late 1970's to U.S. government laboratory groups. The National Security Agency considered the results sufficiently promising to continue making further improvements toward practical applications.[49] Chapter XXII elaborates on the Morse Code Project.

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[47] Discussion with D. Small, NOSC 3/89 with R. Brumderberg, 6/89. Cf. also an article in *J. Defense Research*, "ACCAT: A Testbed for Exploring C^2 Change," by F.H. Hollister, Special Issue 78-1 on Tactical Command and Control, 1978, p. 39.

[48] "ACCAT and FORSCOM Guard Systems," by M. Soleglad, address at the 4th Seminar on DoD Computer Security Initiative, Aug. 1981.

[49] While the MIT Morse Code effort went on for nearly four years, the main results were apparently available by the second year and the government laboratory simplifications and improvements were made after that. Discussion with Dr. S. Squires, May 1989.

Other defense applications of AI have been pursued based on the work initiated by ARPA. In the late 1970's a system for planning Air Forces missions, Knowledge-Based Systems (KNOBS), was developed by MITRE with Air Force support, and tested on DARPA supported computers at project MAC. Later, a similar planning system, Knowledge-Based English Entry Crew Activity Planner (KNEECAP), was developed by NASA for use with the space shuttle.[50] Late in the 1980's, the SDI battle management program began to construct a test bed facility which incorporates many of the advances in computers, software, and AI pioneered in the DARPA program.[51]

2. Commercial Developments

In the late 1970s, perhaps stimulated to some extent by the new DARPA emphasis on applications, and encouraged by the success achieved in DENDRAL, a number of expert or knowledge-based systems began to be developed for applications. These applications have been developed mostly in industry and many by individuals whose training in AI technology was supported by DARPA. Some AI application systems which appear to have reached the most advanced stage of commercialization include: DEC's R-1 or XCON for designing computer circuits; the DIPMETER ADVISOR for oil well logging data analysis, by Schlumberger, the ACE line fault diagnosis program by AT&T, the EXPLORER geological exploration program by SRI, and the STEAMER computer-aided instruction systems for Navy engine-room personnel, by BB&N.[52] A recent review listed approximately 150 expert systems in use.[53]

Several companies sprang up to supply expert system assistance in areas such as financial investment, information services, and computer circuit design.[54] By the late 1970s some ten companies in the AI software and hardware areas had spun off from the MIT AI group alone.[55] A handbook of AI, supported by DARPA and NIH, was published by Feigenbaum.[56] Robotics-type activity in industry increased considerably in the late

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[50] "Applications 1 - Space," by Edward L. Lafferty, in Bartee, ibid., p. 9, and discussion on June 1989.

[51] "Computer Aided Better Management" by D. Dalun and Y. Smith, *Aerospace America*, June 1989, p. 40.

[52] "Amplifying Expertise with Expert Systems," by R. Davis in Winston, ibid., p. 188.

[53] E. Feigenbaum, P. McCorduck, and H.P. Nii, *The Rise of the Expert Company*, Times Books, 1988, pp.273-312.

[54] "Artificial Intelligence is Here," Cover story, *Business Week*, July 9, 1984.

[55] "Project MAC," ibid., foldout.

[56] "Seeds of Artificial Intelligence," ibid., p. 63. A later encyclopedia was edited by Shapiro.

1970s.[57] While there was earlier IPTO interest, higher level decisions at DARPA were not to emphasize robotics, at that time, although it was one of the main areas of interest of the MIT and Stanford AI groups still supported by IPTO.[58] Later, the DARPA IPTO program included substantial robotics support, including the recent Strategic Computing program effort towards an autonomous land vehicle.

An important impetus to the application of AI in industry occurred with the appointment of former DARPA Director, G. Heilmeier, as the Senior Vice President and Chief Technical Officer of Texas Instruments (TI). Under his direction TI became one of the first major companies to embrace AI as a central business thrust.[59] Today, TI is regarded as the leading AI company with its products, including its Explorer Lisp machine, an expert system shell, Personal Consultant, custom expert system for industrial and military applications.[60] Heilmeier's predecessor as DARPA Director, Dr. Steven Lukasik, as Corporate Vice-President for Research at Northrup Corporation, supported the development of an expert system manufacturing process planner for internal use.[61] More recently, IBM, GE, DEC and other larger companies have shown some interest in AI.[62] A recent estimate is that the commercial AI market is approximately $600 million today, growing from about $20 million in 1983.[63]

DARPA AI support also contributed to development of several aspects of computer-aided instruction (CAI). Many of those active in CAI and AI were very interested in the prospects of an intelligent computer systems for education and training. An MIT AI group under S. Papert made a major contribution in writing a LISP program for LOGO during project MAC in 1960.[64] LOGO was used in many elementary school experiments, and improvements were supported eventually by NSF and the U.S. Department of Education.

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[57] A review is given by J. Michael Brady in Winston, ibid., p. 179, and a brief historical review is given in *Robotics* by K.S. F., et al., McGraw Hill 1987, p. 4.

[58] Perspectives on early robotics initiatives at ARPA and ONR are given by Bartee, ibid., by Roberts, p. 231 and Denicoff, p. 298.

[59] E. Feigenbaum, P. McCorduck, and H.P. Nii, *The Rise of the Expert Company*, Times Books, 1988, pp. 174-188, describe Heilmeier's leading role in advocating AI development as a business thrust for Texas Instrument. Heilmeier's activity, at DARPA and Texas Instrument's regarding AI also is discussed by Licklider and Kahn, in Bartee, ibid.

[60] E. Feigenbaum, P. McCorduck and H. Nii, ibid.

[61] ibid., pp. 24-30.

[62] *Business Week*, ibid.

[63] H. Ullman, "Machine Dreams: Future Shock for Fun and Profit (Failure of Artificial Intelligence to Meet Expectations)," *New Republic*, Vol. 201, July 17, 1989, pp.12-13.

[64] *Information Technology R&D*, OTA, ibid., p. 160.

In 1980, LOGO was implemented on microcomputers and in 1982 a company, LOGO Computer Systems Inc. was formed by some of the MIT group to supply a growing market for LOGO diskettes.[65]

Another AI-based computer-aided instruction tool was STEAMER, developed by BB&N for the Navy to teach ship engine-room procedures. STEAMER was, apparently, an outgrowth of SOPHIE, an intelligent circuit analysis program, in turn based on a University of California (Berkeley) circuit analysis program, SPICE, which had been supported by DARPA.[66] SOPHIE was regarded as one of the first "Intelligent Computer-Aided Instruction" (ICAI) programs and led also to several military training programs such as QUEST for troubleshooting.[67]

In general, the relation between AI and CAI seems to be paced by progress in the fundamental AI area of knowledge representation. Some feel the interaction has benefited AI more than the other way around.[68] DARPA-supported AI efforts on low-cost computer imaging, combined with results of its networking programs, particularly by satellite between widely supported areas were essential to the development of SIMNET, now being used by the U.S. Army to simultaneously train tank crews in the U.S. and Europe in battlefield tactics.[69]

3. DARPA Strategic Computing Program

In 1983, DARPA commenced its Strategic Computing Program, challenging advances in computer technology and AI applications.[70] This program approximately quadrupled annual Federal funding of AI and related hardware R&D.[71] Three specific AI application areas are featured in this program: (1) A "pilots associate," incorporating natural language interactions with computers and expert systems to monitor vehicle performance and control, and generate alerting statements, giving new impetus to speech recognition

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[65] Project MAC 25th Anniversary, ibid., foldout.

[66] *Targeting the Computer*, by K. Flamm, Brooking 1987, p. 69.

[67] QUEST was developed by BB&N in 1986. BB&N, ibid., p. 46.

[68] In the late 1960's and early 1970's one of the greatest impacts of the advances in AI was on the field of psychology. Together with the intensified study of activity of the neural system and the processes involved in perception, AI opened up the field of cognitive psychology. This has had considerable influence and interaction with efforts to automate military training and testing. D. Fletcher, ibid.

[69] SIMNET was first demonstrated in 1987. BB&N and *Information Technology R&D*, OTA, ibid.

[70] *Strategic Computing Program*, Annual Reports, DARPA.

[71] *Information Technology R&D*, OTA, ibid., p. 96.

research; (2) Naval battle management, again involving natural language interfaces to access and query extensive data bases, together with graphics, integrating fleet status information and decision aids, (reminiscent of some of the work stated in ACCAT); and (3) robotic autonomous land vehicles, emphasizing computer image-comprehending systems. After extensive preliminary development and trial, systems of each of these three types have advanced to prototype stages and part of at least one (fleet status) is undergoing Service evaluation.[72] Along with these specific projects, a supporting research program is going on to provide needed developments in microcircuits and information processing techniques, together with opportunity for access to all these developments by research workers. Each of these projects involves the most advanced and powerful computers that can be constructed and still be compatible with the respective operating conditions.

C. OBSERVATIONS ON SUCCESS

The major push for the development of Artificial Intelligence can be credited to ARPA's funding in the late 1960's and early 1970's. The interplay and interaction of AI with computer development in this early period was very broad and strong. The needs of AI research for interactive programming were a major factor motivating support for the development of computer time sharing, and for the "user-friendly" characteristics of computers, which have become major characteristics of the personal computer today. At the same time, AI's developments were paced by the great improvements in computer hardware capability and the fall in costs of computing.

The impact of AI on related sciences, such as cognitive psychology, has been very great.[73] The interplay of AI with computer-aided instructions also has been considerable. The first ARPA attempt toward AI application in this early period, the Speech Understanding project (SUR), was motivated by its very high potential payoff for enhancing human-computer interaction. The SUR results, while useful for further work, indicated the expectations at the time had been too high for the existing computer capabilities.

By the mid 1970s, various specific AI applications began to appear. Perhaps the most important of these was the DENDRAL expert system, which was developed as a joint effort between some of the Stanford AI group, who had earlier ARPA support for

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[72] Being essentially software, it may be possible to test parts of the fleet battle management system separately on existing computer equipment.

[73] Cf. Margaret Bodan, "Artificial Intelligence in Psychology," MIT Press, 1989.

"heuristics" which were the basis for DENDRAL, and medical researchers. NIH support was responsible for carrying DENDRAL through a long period of experimentation to success. While ARPA maintained some support to DENDRAL throughout the 1970s, the role of NIH in supporting knowledge-based expert systems as demonstrated in medical applications was instrumental in the visibility of AI.[74]

Greater emphasis by ARPA toward applications in the mid 1970s led to accelerated AI developments in a number of specific areas. Part of the ARPA push derived from an appreciation that AI, with its own great problems of software development, might be able to improve the efficiency and lower the costs of software production, which was beginning to appear as a major economic factor in computer use. The results of this period of ARPA AI support seems to have met this goal, to some extent. After an initial delay, probably due to the ILLIAC IV experience, ARPA funded the LISP machine development at MIT. AI researchers have designed relatively inexpensive LISP computers. Now a commercial item, these are powerful tools for complex software development and used widely by industry and in government laboratories. Corresponding advances in "intelligent" terminals also have been made.

On the other hand, this ARPA applications emphasis has, in the opinion of some AI researchers, retarded programs on more fundamental and difficult problems which underlie the capabilities of all applications. Today, opinion seems to favor the view that progress in the AI applications area in the near future will occur by use of existing AI-related technology in well-defined areas. The majority of military applications, for example, seems to be occurring in the use of expert systems in "smart weapons," planning, C^3I data fusion, repair practices, and training.[75]

The DARPA Director G. Heilmeier's effort to force "top down" AI applications in the late 1970s seems to have been partly successful. The Morse Code Reader, a relatively easy problem compared to speech recognition, transitioned quickly to a laboratory user group in NSA. ACCAT, which pushed a variety of AI technologies, perhaps too hard, within a rather diffuse C^3 training environment, had little direct impact, but did solve some related communications problems and whetted appetites for what might come later. Heilmeier's view is that ACCAT succeeded in changing the view of C^3 in the military: for

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[74] S. Amarel, "Current AI Research," in T. Bartee, ed., ibid., p. 259.

[75] See R. P. Bonnasso, "Military Systems," Chapter 7, in T. Bartee, ed., *Expert Systems...*, ibid., and S. Andriole, "Artificial Intelligence and National Defense," Chapter 19 in S. Andriole, ed., *Applications in Artificial Intelligence*, Petrocelli Books, Inc., 1983.

the first time C^3 was approached from an information management perspective integrating decision aids, AI, and information management technology.[76]

One important outcome of this turbulent DARPA AI period has been a very efficient technology transfer to the commercial sector. The first major industrial application of AI was made in the oil prospecting area, by Schlumberger. This drew broadly, like the other applications in the same period, on the AI technology being developed largely with ARPA support. Much of the development of commercial AI has been spun off from university research programs, chiefly at MIT, Stanford, and Carnegie-Mellon, supported by ARPA. Several key players in ARPA's IPTO AI program have gone into the commercial sector, while others now are pursuing academic research in AI.

Dr. Heilmeier, who was highly skeptical of AI program in IPTO when he arrived, subsequently went to Texas Instruments, where there is now an AI applications thrust with an emphasis on symbolic processing and object oriented computing.[77] He sees "symbolic processing as the future of computer applications." He stated that for TI commercial AI applications are foremost; AI has permeated the commercial sector too a much greater degree than the military. A problem he noted, based on his experience with such projects as ACCAT and HASP, was a reluctance of potential military users to adopt "revolutionary" processes. Thus, he felt that it might be another ten years before widespread application of AI in military systems.[78] However, there already have been some identifiable military AI applications, such as TI's advanced LISP processing chip for "smart" missiles.

In reviewing the AI program at ARPA, it is important to recognize that the field itself was in its infancy when ARPA began its support. The overall vision of Licklider and his successors was to enhance the ability of computers to perform in intelligent ways with an underlying premise that such improvements would be important to defense applications. Reflecting on the impact of this program, Robert Kahn, a former Director of IPTO, noted[79]

> The main impact of AI to date has been to broaden the thinking of some of the research and operational people in Defense, and to make them aware that they can do more with electronics than just some of the programmed kinds of things they were used to in the past - that intelligence in these systems is definitely a possibility in the future.

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[76] Heilmeier, interview, 8/89.

[77] Ibid.

[78] Ibid.

[79] Kahn, ibid., p. 252.

> In one sense, AI hasn't really made an operational impact yet because there are no embedded AI systems in operation, and the policy for supporting them is not there. A few experimental systems are being used and evaluated; however, AI technology has had a significant impact on some contractors who can now develop software more effectively. It has also enlightened a lot of people through concrete demonstrations of what the technology can do -

DARPA's Strategic Computing program, begun in 1983, can be looked on as an attempt to bring AI and computer technology together, with a focus once more in several applications areas. Some of the Strategic Computer objectives revisit, in a more mature fashion and with much improved technology, previous attempts in the speech recognition and C^2 applications.

Recently, with the increased interest in parallel structures to achieve faster computing, the analogy to research systems has been rediscovered, with mutual benefit to computer architecture, to cognitive studies and AI. DARPA outlays for AI up to inception of the Strategic Computing program from project records appears to be about $120 million. A recent estimate of the value of the commercial market is about $600 million.[80] An increasing number of military systems are planned to incorporate AI in a more or less essential way (see Fig. 3b). Expenditures on these systems are estimated as several billion dollars.

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[80] Cf. Ref. 63.

Systems that could incorporate KBS:

ARMY

AH-64 (APACHE)
MSG
OH-58D (AHIP)
AAWS-H
AAWS-M
FAADS (OTHER THAN C2)
H-60A (BLACKHAWK)
STINGER
TOW-2
PERSHING II
MLRS
FOG-M

NAVY

AN/SQQ-89
ASPJ
AV-8B
CG-47 AEGIS
C/MH-53G
CVN 71/72/73
DDG-51
E-2C
E-6A (TACAMO)
EA-6B
F-14 A/D
F/A-18
HFAJ
FFG-7
IMPROVED STRAT COM
LHP
N-ROSS
LSD-41
MK-46 ADCAP
NAVAL AIRSHIP
MK-50 TORPEDO
P-3C
PHALANX (IWS)
V-22 (JVX)
SEA LANCE
SSN-688
TRIDENT II SUB

USAF

C-5B
C-17A
CIS (MK XV IFF)
F-15
F-16
IIR MAVERICK
KC-10A
KC-135R
MLS
OTH-B
PEACEKEEPER
SICBM
TRI-TAC
MINUTEMAN III PEN AIDS

Figure 3A. Major Defense Acquisition Programs That Could Incorporate "Knowledge Based Systems (KBS)

Systems that will incorporate KBS:

ARMY

ATACMS
FAADS C2
MLRS-TGW
RPV
SADARM
LHX

NAVY

SSN-21
SSN-21 COMBAT SYSTEM
SUBACS BASIC
ATA
P-3G
FDS

USAF

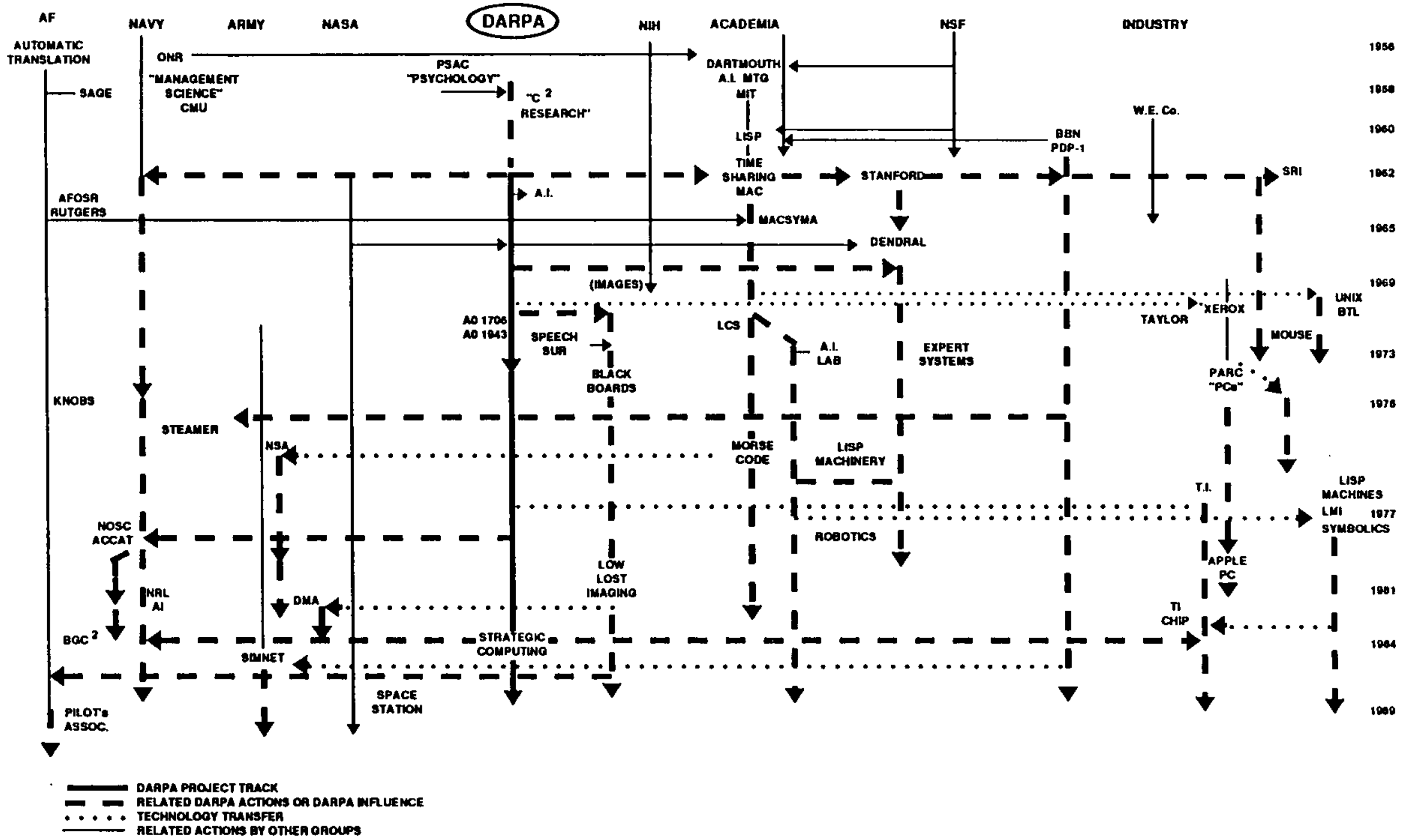
ASAT
ATF
INEWS/ICNIA
ADI
ARARS
B-1B
GLCM
JTIDS
WWABNCP

DOD

WIS
INTELLIGENCE SUPPORT

Figure 3b. Major Defense Acquisition Programs That Will Incorporate "Knowledge Based Systems" (KBS)

ARTIFICIAL INTELLIGENCE



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XXII. MORSE CODE READER

A. BRIEF OVERVIEW

The Morse Code project was undertaken by MIT's Laboratory for Computer Science in the period 1974-78 in response to an ARPA request to look into the problem of replacing a human high-frequency radio operator interpreting manually-generated Morse Code with an "intelligent" computer system. Using available AI techniques, a successful automatic "Morse Code reader" was developed by the MIT group and picked up quickly by NSA.

B. TECHNICAL HISTORY

For many years a substantial fraction of radio traffic in the high-frequency spectrum involved manually-generated Morse Code. These signals were generally characterized by many irregularities, notably in duration of the long pulses (dashes) and spaces between short (dot) pulses, in which individual "senders" often had distinctive patterns.

The problems of "reading" Morse Code is made more difficult by frequent interference of other signals and the characteristic "fading" of high frequency radio transmissions. On the other hand, the patterns in these situations and in the message protocols and language of amateur radio all seem to be used to advantage by experienced radio operators. Recently, most Morse Code transmissions have become "machine" or computer generated, with far less irregularity and so much easier to translate automatically. There are commercially available systems to carry out this function.[1]

As part of an effort to steer the ARPA AI program more towards applications,[2] Dr. G. Heilmeier, ARPA Director in the mid 1970's, generated a list of military problem areas where he felt AI might be helpful. One of these problems, apparently from NSA,

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[1] Gary L. Dexter, *Shortwave Radio Listening With the Experts*, H. Sams Company, 1986, p. 325.

[2] R. Kahn, p. 246 in "Expert Systems and Artificial Intelligence," T.C. Bartee, Ed., H. Sams, 1988, in Bartee's book.

was that of "reading" manual Morse Code traffic.[3] Responding to Heilmeier's pressure, J.C.R. Licklider, then head of ARPA's IPTO, called A. Vezza of MIT's Laboratory for Computer Sciences (LCS) to ask if they might be able to do something on this problem.[4] (Licklider had just come back to IPTO from the LCS.) Besides being quite familiar with the MIT's LCS generally, he had been a collaborator with A. Vezza in the LCS programming technology group. The major occupation of this group previously had been with development of automatic programming technology.

This was, actually, the "second time around" on this problem. In the mid to late 1950's MIT's Lincoln Laboratory had developed MAUDE, which was a computer program to "map" Morse Code symbols into alphabetic and numeric character sets.[5] MAUDE used some rudimentary "rules" in this mapping, some statistical and others including the maximum number of dots and dashes in a legitimate Morse Code character, and dealing with "pairing" of symbols which are often confused. NSA attempted to apply MAUDE to manual Morse but found this impractical.[6] In contrast to machine-generated Morse which was quite easily handled, NSA resigned itself for many years to the view that manual Morse required a human interpreter.

After Licklider's request, Vezza spent about three months reexamining the MAUDE results and thinking about the problem. Vezza concluded that the AI tools and the improvements in computing power then available could lead to a solution. No breakthrough seemed to be necessary, and so the MIT AI group, mainly concerned with new AI developments, was not involved. Vezza envisioned that AI "expert" techniques could map the irregular Morse Code streams not just into characters but onto sets of words taken from stored vocabularies, with corrections for grammatical structure. Compared with the difficult AI problems of translating natural language, the MCR problem was much simpler, a "toy".[7] Further, the problem had been discussed with LCS staff, some of whom were amateur radio "hams" and there was much enthusiasm for the notion of constructing an "artificial ham."[8] In fact, the LCS group began to set up such a "ham" station on the roof of the LCS building. However, the FCC pointed out the possible illegality of copying

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[3] Testimony of Dr. G. Heilmeier, p. 4908 in Hearings on Military Posture, before Committee on Armed Services, DoD authorization for 1976, and 76T, H.O.R. 94th Congress, 1st Session, Part 4.

[4] Discussion with A. Vezza, 6/89.

[5] "Machine Recognition of Hand-Sent Morse Code," by B. Gold, *Trans. IRE*, PGIT, IT-5, 1959, p. 17.

[6] Discussion with R. Alde, 5/89.

[7] A. Vezza, ibid.

only, which was what the MCR project wanted to do first, without going "on the air." As a consequence the "artificial ham" station was never built at MIT.

As a result of the LCS discussions and enthusiasm a proposal to design and construct a computer MCR, named COMCO-1, was made to and approved by ARPA as part of the LCS effort in 1974.[9] The MCR project quickly became the major effort of the LCS programming technology group. The rapidity of responses on both sides probably reflected the high level interest in ARPA and the strong desire of the IPTO group and the AI community to "bet on a good horse," at this time.[10]

The MCR problem was categorized into general domains clearly described by the leader of the MCR effort, A. Vezza, the leader of the project:[11]

> For purpose of organizing our thinking on the Morse problem, we have conceptually divided it into four domains over which processes must work and for which we must have models of expertise. One should keep in mind, however, that a human operator does a marvelous job of integrating the individual processes into a singly whole process, indicating a close interrelationship between the domains into which we have fragmented the problem. The four domains over which processes must perform and for which we must have a variety of models are as follows:
>
> a. The Morse transcription environment -- This domain contains models and processes for correctly transcribing sequences of dots, dashes and spaces in their symbolic representation, that is, outside the radio environment. In order to do the task properly, processes must have a knowledge base of the domain of discourse. For instance, if COMCO-1 is in a negotiation phase with another operator, then the processes transcribing the Morse must have knowledge about the protocol and special macro symbols used in negotiation in order to transcribe the signal correctly. The structure of a message must be understood if the header, body, and signature are to be properly transcribed and the word count checked. Similarly, the processes must at least have knowledge of a reasonably sized lexicon in order to properly perform the transcription of the body of the message. (The tacit assumption is that the message is not ciphered. However, if ciphered Morse were to be handled, then one would need not the lexicon but rather the length of the cipher groups, the group count and the characteristics of the class of

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[8] This idea is discussed in the earliest 1974-75 LCS progress reports of the MCR project.

[9] LCS Progress Report XII, July 74-75, MIT, p. 107, contains a general description of the problem and prospective application of "expert system" technology to it.

[10] R. Kahn, ibid.

[11] LCS Progress Report, ibid., p. 110.

operators associated with a particular network which sent the cipher group.)

b. The radio environment -- This domain contains models and processes for the radio environment. Here exist models of: how individual Morse sound in terms of tone, drift, chirp, hum, etc; the effects of environmental conditions, such as fade, multipath, etc.; the effects of interfering signals, how to deal with them and when signals can and cannot be separated properly into individual signals. Clearly these processes must provide the ability for receiver and transmitter tuning and for tracking signals.

c. The Morse network environment -- This domain contains models and processes for understanding the special network negotiation language used by operators in a Morse network. In this domain the models and knowledge must be most complete in addition to a lexicon of the vocabulary, understanding of the syntax and semantics of the language is required in order to understand the meaning of what is being "said." The task is complicated by the fact that not only are most words of the vocabulary ambiguous, but even what one could term a "clause" or a "sentence" can be ambiguous. Thus, a rather global view of what is being said is required in order to understand what is transpiring in the Morse network environment.

d. Sender recognition -- This domain contains models and processes for recognizing a sender, if possible, and providing information about his or her idiosyncrasies, to aid the processes of transcription, signal tracking and understanding. Typical kinds of information that help identify operators are the statistical variance of a particular operator's rate, the proclivity for a particular operator to deviate from the network negotiation protocol in a particular manner, and the probability that a particular operator mis-sends 'AN' as 'P'.

The initial approach was to use MAUDE to get a first order transcription, to which corrections were applied such as "mark run length" -- the number of dots and dashes in words, which had some success on sample Morse Code records. A little later, it was found desirable to add a phase-lock loop signal processing system to more accurately determine a signal's mark and space lengths and to simulate, to some degree, the ability of a human operator to identify a specific sender's transmission. The output of this filter fed into a MAUDE decoder. A vocabulary (later, vocabularies) of English words and of the radio operators' standard language (Q Signs, Pro-signs, call-signs, headers) was compiled, and AI techniques of lattice search applied in an approach, called COMDEC, to systematically identify alternative word translations. Further elaborations were made to COMDEC, applying grammatical rules, and eventually incorporating AI "augmented transition network" (ATN) techniques to the resulting sentence options. A somewhat similar set of procedures was adopted in CATNIP, which dealt with the Q-language and message header structure.

Figure 1 outlines the relation between these major modules of the COMCO-1 system as of 1977 (some two-years into the project). About Fig. 1 the project leader remarked:[12]

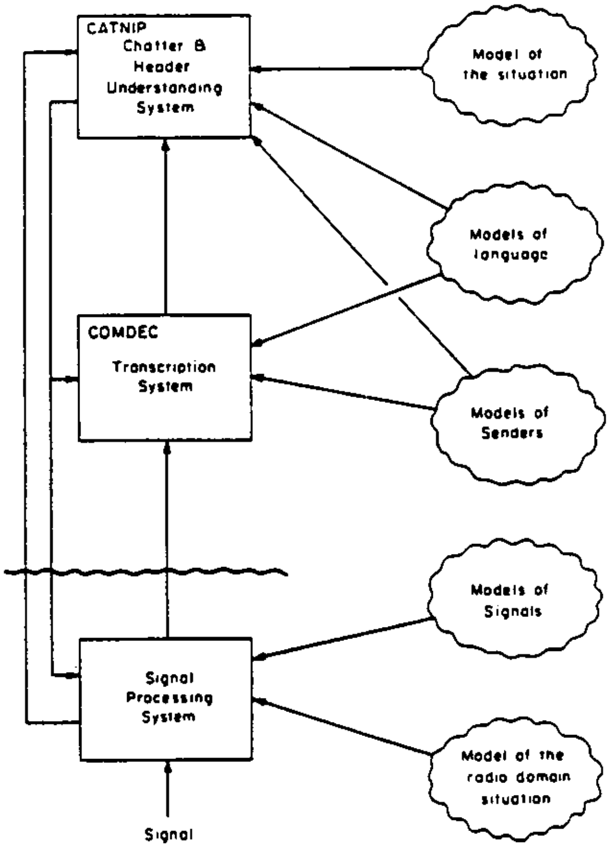

Figure 1. The Three Major Modules of the Morse Code System and the Domain Models They Use

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[12] LCS Progress Report, XV, July 1977-78, p. 197.

Figure 1 shows a block diagram of the three major modules of the Morse Code system COMCO-1. Also shown are the necessary domain models required by each module in order for it to perform its task properly. The wavy line in the diagram indicates that the signal processing system, which is composed of special hardware and a PDP-11 computer, is not integrated with the other major modules which are COMDEC, the transcription (or translation) module, and CATNIP, the chatter and header understanding module. The last two are software modules written in MDL. (A LISP-like language) and running under TOPS-20 and ITS. Experiments are conducted independently for the signal processing system, and human intervention is required to transfer the results to the other two modules. COMDEC and CATNIP are well integrated, with appropriate feedback, and externally they appear to behave as one system.

The MDL programming language had been developed earlier by the same group, when working in automatic programming.

Eventually CATNIP included the ATN module for COMDEC as well as the "chatter" of Q-and Pro-Sign and headers, and was also able to interact with COMDEC regarding quality of translation and storage of results for further examination.[13] MAGE, a further extension of the CATNIP ATN grammar, was constructed to handle additional words and phrases. Finally, the CODEPARSE "expert" module was added to handle transcription of Morse Code "groups," not subject to the same structural analysis procedure as word groups. CODEPARSE used such information as the number of marks and spacings consistent with code groups of a uniform number of characters; the use of numbers or alphabetic characters, but not both, in all groups; the number of code groups in the message, if known; and the end of the message. Despite this small set of rules, CODEPARSE apparently was often more successful than human operators.

The COMCO-1 system was tried out in numerous experiments using tapes supplied by various groups including the Army and radio amateurs and the environment of an actual HF network was simulated early on (1975) using these tapes in a laboratory setting.[14]

The MCR project results were briefed at DARPA in fall 1978. There had been earlier briefings, and considerable interaction with S. Squires, then of NSA, over a period of about a year. The NSA computer laboratory group was soon able to simplify the MIT results and reprogram them in a more precise language, more suitable for practical use.[15]

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[13] LCS Progress Report XVI, July 1978-79, p. 201.

[14] LCS Progress Report XIII, July 1975-76. This was done instead of the original plan for an artificial "ham."

[15] Discussion with Dr. S. Squires 5/89 and A. Vezza 6/59.

As far as known the MCR project did not impact the commercially available Morse Code Readers.[16]

C. OBSERVATIONS ON SUCCESS

The MCR project originated in a question raised by DARPA Director, Dr. G. Heilmeier, and put by DARPA's IPTO to a group in LCS at MIT, whose capabilities were intimately known. The problem was a very good fit to these capabilities and the LCS group "took off". DARPA's role was to fund, approve and ensure that the results were communicated to NSA. The MCR project is an example of successful, efficient AI applications technology transfer to a laboratory group in an operating agency. Because of the competence of this laboratory group and the facilities available to them, the communication and assimilation of results was very efficient. Dr. Squires stated that the last year of MIT's work was in fact not necessary, because the NSA group had by then already replicated and improved the (primarily software) product .[17]

Apparently no "breakthrough" or new AI research was needed. A. Vezza states that he felt confident, after the first three months, that they could solve the problem to a satisfactory extent using techniques that were available. He terms it a "toy" level problem, compared to that of English language translation.[18] Several student contributions were at the Master's thesis level.

Vezza feels that it is very unusual in his experience to have a problem that "came down from the top" lend itself to this type of solution and efficient transfer.[19]

MCR's success also helped the credibility of the AI program generally. Dr. Heilmeier required a review of the IPTO AI program by the JASONs which Kahn describes as a "little bit of a confrontation."[20] However, Vezza also briefed the JASON group and had no difficulties with them.[21]

Vezza also credits much of the success to the fact that this project had a single, well defined objective, was carried out by a single group under a single leader and had very

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[16] A. Vezza, ibid.

[17] Squires, ibid.

[18] Vezza, ibid.

[19] ibid.

[20] Kahn, ibid.

[21] Vezza, ibid.

good communication at a technical level with a competent "user" group leader. The fact that the LCS group involved was intimately known to the ARPA program manager at the outset probably enhanced the efficiency of start-up, which also added to the probability of success.

The MCR project cost about $2 million and was not funded separately from the LCS "umbrella" task.[22]

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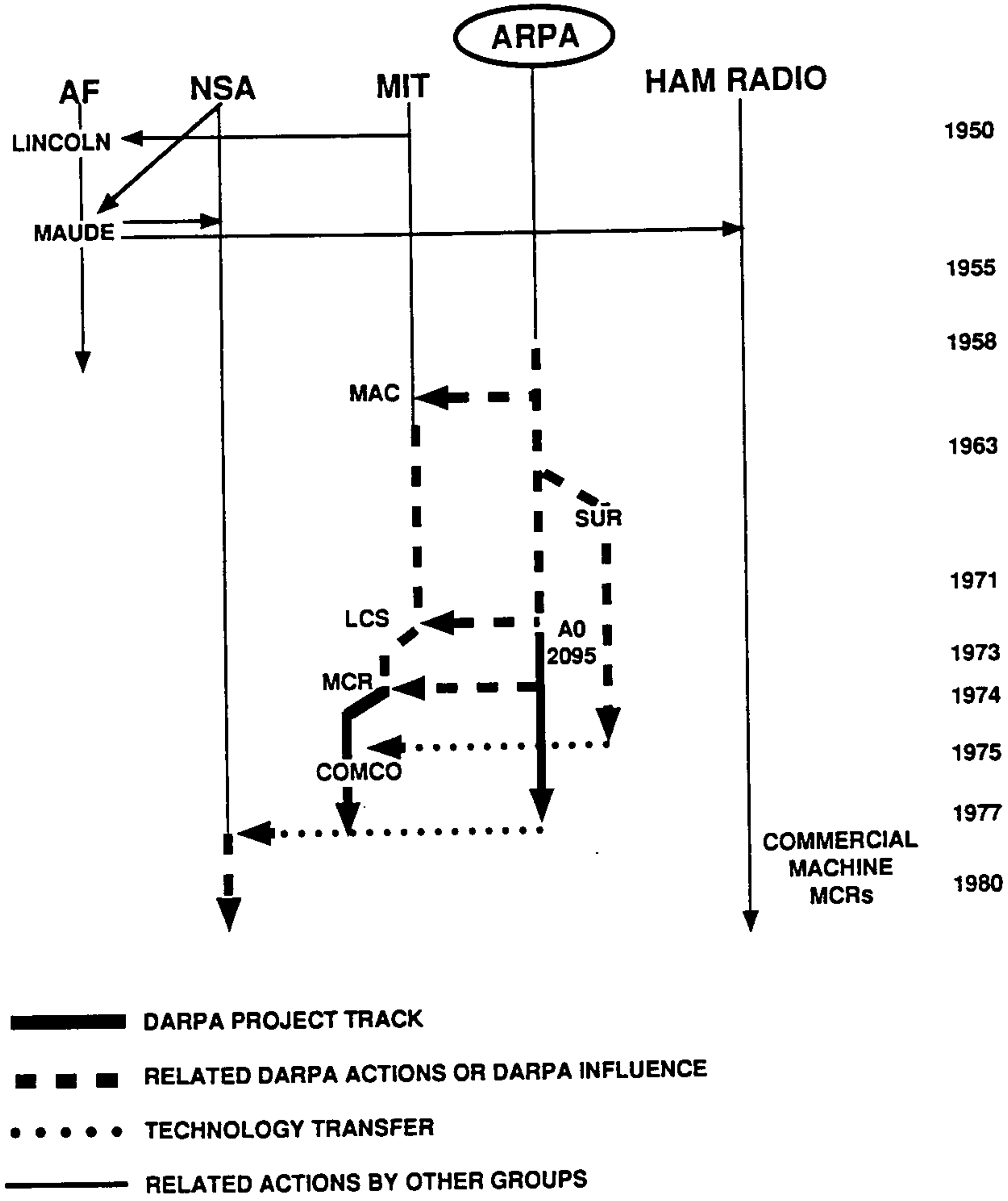
[22] A.O. 2095 of 1/72.

MORSE CODE READER



7-24-89-11M

XXIII. ACCAT

A. BRIEF OVERVIEW

In mid 1976, DARPA and the Navy (NAVELEX) began a joint five-year program to speed up the application of new artificial intelligence, computer, and networking technologies into the military command and control area. The centerpiece for this program was the Advanced Command and Control Architectural Testbed (ACCAT) facility which was located at NELC (later NOSC), near their "Warfare Evaluation Simulator" in order to allow interaction with the war games going on there. ACCAT included prototype mobile remote terminals linked via satellite by a secure subnet of the Advanced Research Projects Agency Network (ARPANET). In addition to demonstrating and testing new technologies using AI techniques for distributed, relational data base management and natural language query, ACCAT was also a testbed for extending ARPANET to some types of militarized computers, and of approaches for ARPANET security. While specific ACCAT influence is hard to trace, recent renewed command control (C^2) efforts with AI technology and similar objectives indicate its positive influence.

B. TECHNICAL HISTORY

In 1976 the Navy Electronics Systems Command (NAVELEX) had C^2 projects under way to develop a prototype task force command center (TFCC) and a fleet command center, with supporting efforts at NELC and NRL, and related research on decision aids at ONR. The Defense Communications Agency (DCA) had also begun efforts toward their AUTODIN II for data communications. The Navy projects soon ran into difficulties in interfacing the different types of computers involved in their C^2 systems. ARPANET technology offered a way to deal with this problem, but had not yet been implemented on militarized computers such as the UYK-20. There was also an appreciation in the DoD that C^2 had lagged in making use of applicable state-of-the-art technologies.

Dr. G. Heilmeier, who became ARPA director in 1975, also felt strongly that the DARPA-supported efforts on AI technology should be directed more towards applications such as the Navy needed.[1] As a result of discussions with Chief of NAVELEX, DARPA and the Navy signed a memorandum of agreement for a five-year program beginning in FY 1976 to set up ACCAT, a C^2 testbed at NELC incorporating the most up-to-date computer, networking, and applicable AI technologies.

Preliminary ACCAT activities consisted in obtaining DEC KA-10-2, 11-20, and 2040T computers, TENEX and UNIX operating systems, installation of these at NELC, and arranging ARPANET interfaces with necessary security. There were a number of challenges involved, including setting up ARPANET, which had "grown up" on commercial computers, on militarized computers such as the UYK-20, and providing security systems with ARPANET bandwidths.[2] Prototype "mobile" terminals to be linked with ACCAT in a satellite with ARPANET were set up at the U.S. Navy Postgraduate School and the Fleet Numerical Weapons Center at Monterey. This ACCAT effort on networking techniques appears to have had some impact on the Worldwide Military Command and Control System (WWMCCS), which was dealing with similar problems at that time.

The University of Southern California's Information Sciences Institute (ISI) was linked to ACCAT by ARPANET to provide additional computer support and other services. A study was also undertaken by NELC to define prospective tasks for ACCAT.[3]

One of the first ACCAT tasks in 1977 was a typical C^2 problem of obtaining timely information from distributed data bases at the Fleet Command Centers in Hawaii and Norfolk. The ACCAT approach to this problem involved application of new relational and distributed data base management and query technologies. A modification was made of Computer Corporation of America's SDD-1 system for management of relational, distributed data bases. The extensive data bases were to be handled by "modules" of the Datacomputer, developed by the same company with DARPA support, initially to provide a very large storage memory for seismic data developed by the programs of DARPA's Nuclear Monitoring Research Office. The data modules were linked via satellite and

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[1] Testimony of Dr. G. Heilmeier, Hearings before the Committee on Armed Services, H.O.R., for Department of Defense Authorization and Appropriations for FY 2976 and 1977, 94th Congress, 1st sessions, Part 4, p. 4908.

[2] DARPA archives for AO 3175 of 1/76 and discussion with D. Small 5/88.

[3] "A Digest of Research Applications for the Advanced Command and Control Architectural Testbed (ACCAT)," by D.C. McColl, NELCTN 3198, 1976.

ARPANET. Some fleet data bases were simplified and "sanitized" for use over the unclassified sections of ARPANET. To assist personnel not familiar with the data bases in information searching, the Rand Intelligent Terminal Agent (RITA) AI program for file search, previously developed by the RAND Corporation with DARPA support, was implemented on the ACCAT computers.[4] To deal with the further problem of access to the data bases by personnel unfamiliar with computers, a new "naval vocabulary" was incorporated in the LADDER natural language interaction system also set up at ACCAT by SRI. The new ACCAT capabilities also involved advanced display systems which were to be used in connection with simulated war games played on the Warfare Evaluation Simulator at NOSC, the reorganized NELC. These displays could allow interaction and evaluation by both fleet and laboratory personnel.[5]

The results of working with ACCAT generally indicated the potential of the new AI technology.[6] But limitations in a number of the technologies involved soon became apparent. For example, while the SDD-I modification would allow some ACCAT data base management, its speed was limited because the ARPANET communication bandwidth limited the rates of exchange of data between data modules. Also, problems of consistency and concurrency of the relational data base management system were not completely solved. Eventually, only one large data base, on one Datacomputer, was used by ACCAT.[7]

This ACCAT experience with relational data bases appears to have been one of the earliest. It appears to have had some impact on later work by Computer Corporation of America (CCA) which led eventually to the M-204 relational data base management system, now implemented on IBM 9370 computers and used in several military applications involving localized, but not distributed, data bases.[8]

The CCA SDD-I experience also seems to have had some influence on standards for data base management systems and also on a current effort (written in Ada) for Army

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[4] Discussion with D. Small, NOSC, 5/88.

[5] D. Small, ibid.

[6] R. Bradenburg, NOSC, discussion 5/89.

[7] R. Brandenburg, ibid.

[8] D. Small, ibid.

data base management. The ACCAT experiments can be credited with showing Navy's C^2 systems builders how to use relational data bases.[9]

A localized relational data base with a corresponding display is now used in the data base management systems in the Navy's Developmental Task Force Command Center, and in the ship's data management system (SDMS) testbeds on the carrier U.S.S. Carl Vinson, supported by DARPA and ONR.

Some of the other technologies used in ACCAT had less success. The RITA system was implemented in ACCAT, but after some early trials seems to have had little use. One of the early trials, on a simple navigational problem, indicated RITA was slower than the standard manual procedure. The Language Access to Distributed Data with Error Recovery (LADDER) natural language system, was also used together with SDD-1. However, after a few trials the conclusion was drawn that its capabilities were too limited.[10] The current prototype Tactical Flag Command Center (TFCC) at NOSC does not use a natural language system. The strategic computing program for a facility at CINCPACFLT, however, now includes a new natural language system.

One of the main recommendations from the NOSC planning study was to exercise ACCAT in a large experiment using Planning Research Corporation's SURVAV Decision Aids programs to simulate ships' routing to minimize detection by satellite.[11] This exercise was run, but SURVAV does not seem to have been used subsequently in war games. However, ACCAT terminals and facilities were used in NOSC war games during the 1978-1981 time period. ACCAT computers and the ARPANET connections made available by the project were also capitalized on extensively by NOSC for its own projects and are still used today.

DARPA participation in the ACCAT joint project terminated in 1981 and the ACCAT facility was transferred to the Navy. For some three years thereafter, apparently, Navy funding was not available, and the ACCAT facility was not used. In the period 1984-1987 a copy of the *U.S.S. Carl Vinson's* data base management system was installed in the ACCAT space. Near the end of this period, the ACCAT facility was replaced by a

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[9] ibid.

[10] ibid.

[11] A.O. 3958, and 4430.

new C^2 testbed incorporating more recent AI techniques, but in a conservative fashion, and using extensive local area networks.[12]

C. OBSERVATIONS ON SUCCESS

ACCAT apparently originated in high level discussions between the DARPA director, Dr. Heilmeier, and Navy officials anxious to make more rapid progress in C^2.[13] It was not an Information Processing Technology Office (IPTO) initiative. R. Kahn states that while Dr. Heilmeier pressed hard, there was no way to get him what he wanted at the time.[14]

CDR F. Hollister came from the Naval Electronic Systems Command (NAVELEX) to run the project.[15] It is not clear, however, that mid-level NAVELEX support was enthusiastic. There were multiple objectives: to test current AI and related technologies, acquaint those in C^2 R&D with their potential, and to challenge AI researchers to come up with useful applications. ACCAT, which formerly transferred to NOSC, did not, apparently, lead directly to adoption by the Navy of any of the AI technologies specifically implemented or even to immediate follow-on projects. It did allow some degree of test of those technologies attempted to be applied and in so doing achieved many of its basic objectives. ACCAT apparently stimulated a general interest at NOSC.

The networking technology aspects of ACCAT apparently were transferred effectively to the NOSC environment. ACCAT also was useful for demonstrating how different militarized computers could "communicate" with each other and to develop approaches to ARPANET security. This part of the ACCAT effort apparently was rapidly assimilated into NOSC. It appears also to have had some impact on the directions taken by the DCA's WWMCCS system with similar problems.

Despite the lack of specific AI systems impact, recent Navy C^2 programs at NOSC are trying again to incorporate some AI expert systems. This new program seems more conservative and uses a less ambitious data base management systems than ACCAT. The DARPA Strategic Computing joint project with CINCPACFLT, started in 1984, also

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[12] Discussion with LCDR Ted Kral, 7/89.

[13] R. Kahn, p. 247 in *Expert Systems and Artificial Intelligence*, Ed. T. Bartee, Howard Sams & Co. 1988.

[14] Kahn, ibid.

[15] CDR F. Hollister, "ACCAT: A Testbed for Exploring C^2 Change," in *Journal of Defense Research*, Vol. 78-1, Jan. 1978, p. 39.

appears to have many of the same kind of objectives as ACCAT, for its complex of AI and computing technology.

The lack of Navy momentum in the early 1980's is attributed by some as a consequence of the small degree of involvement of fleet personnel. It is difficult to get fleet people seriously involved when away from operations.[16] Partly, it may have been due also to skepticism by mid-level NAVELEX staff. The performance capabilities of the then available AI technology was very much stressed by the ACCAT. Whether this challenge inspired new advances in AI technologies is not clear. Some key Navy personnel feel that there are problems with a testbed approach to C^2, and do not expect any kind of "quantum jump" in performance. Their view is that improvements in C^2 should be cautiously evaluated and developments expected to be more "evolutionary."[17] Perhaps for reasons such as just mentioned, DARPA-Navy CINCPACFLT testbed experiments are run in parallel with the regularly operating systems, by fleet personnel.[18] The testbed gradually has been taking over some of the operational load.

From project records, DARPA's outlay for ACCAT was $15.7 million. NAVELEX outlay, for the five-years to 1981, was about $1.5 million.

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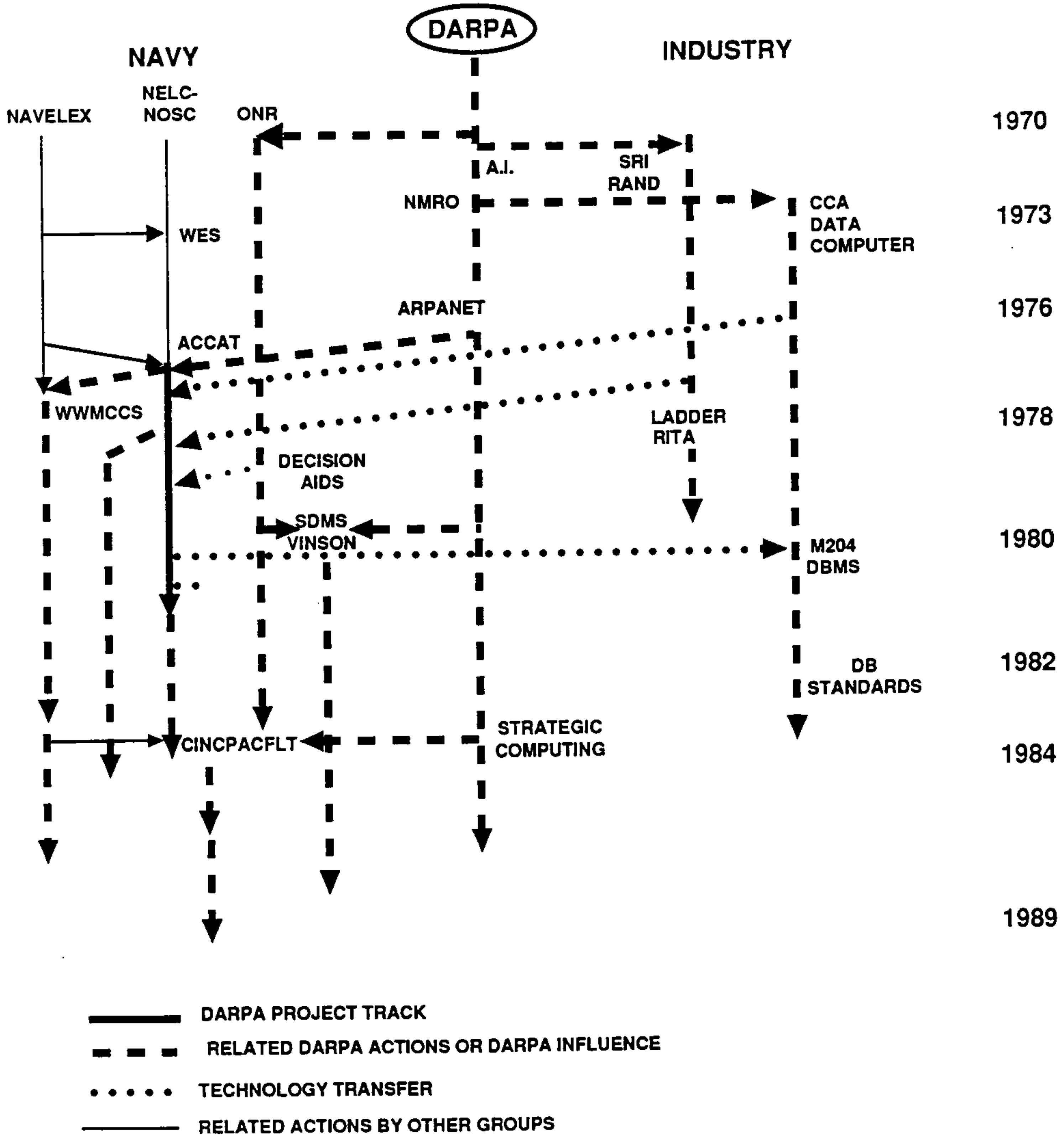
[16] Discussion with CAPT R. Martin, 7/89.

[17] Discussion with R. Le Fande, Office of the ASN R&E, 5/89.

[18] R. Martin, ibid.

ACCAT



7-24-89-10M

F. NAVAL TECHNOLOGIES

acoustic frequencies. Such arrays were used in the Navy's Interim Towed Array Surveillance System (ITASS), which was operational in the late 1960s.[2]

Aurand's proposed objective to explore the coherence of acoustic signals over wide apertures, together with the favorable propagation expected at low frequencies, had been a matter of discussion by those active in the area for some time, and dovetailed with new ARPA interest in exploring the limits of submarine detection systems in the ocean.[3] The fact that much of the technology for this phase of exploration was nearly off the shelf and might be low cost, were additional incentives. There was some technical risk, since previous measurements by Bell Laboratories indicated that usable apertures might be limited.[4]

ARPA responded quickly with funds to rent a modified seismic towed array (together with the handling and towing gear) and the towing ship itself.[5] This ARPA-sponsored activity excited some Navy interest, and the Navy's NAVELEX ASW surveillance office (PME 124) provided funding for modification of the on-board analog processing equipment. ARPA further prescribed that sophisticated digital processing methods be also applied off-line.[6]

The first at-sea experiment in a low noise environment with the long seismic array, rented from a commercial geophysical exploration company, gave spectacular results. This success quickly led to the establishment of a joint R&D program and a formal steering committee for the project, with equal funding from the Navy and ARPA. The technical problem for this steering committee was to choose between extending the length of telemetry-type arrays then being developed by the Navy, for the SURTASS program, versus towing the seismic arrays at greater depth than had been used in their geophysics work. The shorter Navy arrays had been towed at desirable depths, and had been refined

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[2] Discussion with G. Boyer, Engineering Research Associates, May 1988.

[3] ARPA had recently been assigned a responsibility for a research program in Fleet Ballistic Missile (FBM) Submarine vulnerability, by DoD. An ARPA contractor studying options for the new program attended one of Aurand's presentations to the Navy, in summer 1971, and recommended that Aurand go to ARPA with his proposal. Discussion with H. Aurand, NOSC, April 1988.

[4] Discussion with H. Aurand, April 1988. Aurand felt initially that the LAMBDA arrays might in fact be too long, but they would find out how much aperture was useful by experiment.

[5] ARPA Order # 2001, "LAMBDA," of 12/2/71, for $100K.

[6] In the mid to late 1960's, ARPA had funded development of such processing techniques for detection of underground nuclear tests. Application of the geophysical processing techniques on the first LAMBDA results, however, did not prove useful. Discussion with H. Aurand and T. Ball at NOSC, 4/7/88.

XXIV. LAMBDA: LARGE APERTURE TOWED ARRAYS

A. BRIEF OVERVIEW

The ARPA Large Aperture Marine Basic Data Array (LAMBDA) program used available geophysical seismic array technology to demonstrate the potential of large acoustic apertures for ocean acoustic surveillance. The first LAMBDA results decisively influenced the Navy to lengthen the towed arrays developed for its Surface Ship Towed Array Surveillance System (SURTASS). LAMBDA's performance and technology allowed the Navy, in 1978, to make a timely switch to the seismic technology to complete its evaluations and obtain DoD approval for SURTASS.

B. TECHNICAL HISTORY

The Navy had developed towed arrays (strings of acoustic transducer-receivers, connected to processors on board the towing ship) for submarines beginning with an ONR program in the early 1960's, and a little later for surface ship, short-range tactical ASW. In the late 1960's the Navy was beginning a program to develop arrays to be towed by surface ships for longer range submarine surveillance, using technology which was an extension of that used in the earlier Navy systems.

Based on some preliminary ocean acoustic noise measurements using a long, moored, laboratory-built array, together with information on long towed arrays of the type used for science exploration by oil companies in the early 1960's, a proposal was made to ARPA by H. Aurand of Naval Ocean Systems Center (NOSC). The proposal was to obtain and modify such a long seismic array for deeper tow than the practice in seismic oil exploration surveys, with associated low frequency signal processing, for measuring coherence of long-range acoustic propagation and noise.[1] Previous attempts by Aurand to obtain support from the Navy for his proposal had not been successful. Apparently, the Navy's NAVELEX was mainly interested in shorter towed arrays, for use at higher

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[1] Aurand had previously worked on the Office of Naval Research project SEA SPIDER, a large moored array to measure acoustic coherence at favorable ocean depths. This project failed, due to deep mooring difficulties.

to have low noise characteristics. The noise properties of the seismic arrays, when towed at depth and at acceptable speeds, were then unknown.

The initial approach of the joint program was to extend the telemetry array technology then under development to longer dimensions.[7] This, however, soon led to difficulties, and as a result a new seismic array, the first LAMBDA, was built with DARPA funding.

The LAMBDA technology incorporated the same array structure, strengthening members, skin materials, and hardwire connectors as did the geophysical seismic exploration arrays, and was built by the geophysical exploration service companies in the same shop as were their seismic arrays. There were some differences: in transducer "loading," and in the arrangements for deeper towing than for the geophysical arrays. The depressor for the deeper tow had been developed earlier, in 1968, by Aurand, then at Lockheed, for an ONR research program. There were also differences in economics, due to the fact that commercial competition had led the geophysics industry to low-cost, robust systems. Compared to the telemetry arrays, however, the hardwired seismic arrays had larger diameters, were heavier and had a limited number of channels for data transmission.

The joint program entailed a combination of ocean-acoustic measurements, the Long-Range Acoustic Propagation Program (LRAPP) under ONR, together with engineering tests and exploration of operational utility of the towed arrays. In time, the latter two motifs dominated the more fundamental question of limits of useful aperture.[8] The LRAPP program, however, indicated the practicality and robust quality of the LAMBDA technology.

During this period, the Navy's SURTASS program continued efforts to extend to longer array lengths the approach derived from the telemetry array technology which had been successfully used in shorter towed arrays. Full-scale development for SURTASS was approved in 1974. However, difficulties were encountered with the telemetry array

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[7] The Navy had used hardwire technology, as well as telemetry technology in some of its earlier towed array work. The telemetry approach had won out in a competition for a total system, including data processing, etc., in addition to the towed array. Communication from H. Cox, 1/90.

[8] Aurand, however, left the program because he felt it was not sufficiently oriented toward research on limits of coherence in the ocean, as he had originally proposed.

that was being tested and in 1978 a major failure occurred.[9] The SURTASS program, then managed by Capt. H. Cox, who had previously been in charge of the DARPA program also had a number of serious software problems, besides that of the telemetry array.[10] The availability of a LAMBDA type array, and the confidence in its performance, led to a quick adoption of this technology for the remainder of the SURTASS program evaluation. The LRAPP experience, together with the positive results from the evaluation of the SURTASS LAMBDA-type array, were also helpful in obtaining DoD quick approval for production of SURTASS in 1981, without a requirement for a new array R&D program as normally would be the case for a major shift in technology. Such a R&D program would have caused considerable further delays.[11]

LAMBDA 1, the original LAMBDA array, was given to the Australian government under a cooperative program for ASW research. In all, three LAMBDA arrays were built and used in the LRAPP program. LRAPP continued until the late 1970's. ONR continues long-range acoustic propagation research in the Advanced Surveillance Experiments at Sea, (ASEAS) program.

In 1974, DARPA set up its SEAGUARD program, a large-scale effort to explore the limitations placed on ASW surveillance that result from ocean structure and dynamics. SEAGUARD involved theoretical work, construction of a very large fixed array, ocean measurement and array technology (OMAT), and experiments linking fixed and LRAPP mobile arrays (the fixed mobile experiment [FME]), with the ILLIAC IV signal processing capabilities at the Acoustic Research Center (ARC) at Moffett Field. While OMAT gave some valuable data, the ocean engineering problems concerning the stable deployment of a very large undersea array, together with appreciation of the vulnerability of such a large-fixed system, eventually led to its discontinuance.[12] The ILLIAC IV was very effective when operating, but reliable real time processing was not possible, owing to its many breakdowns.[13] The FME, after delays, was successfully concluded by the ARC, however, using several PDP-10's run in parallel.

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[9] Hearings, Subcommittee on DoD Appropriations, H.O.R. 96th Congress, 1st Session, Part 6, p. 1147.

[10] These problems were overcome in a straightforward program under Capt. Cox. Cf. HOR Hearings, ibid., 1/62.

[11] Senate Armed Service Committee, Hearings, FY 79, pt. 6, p. 2998.

[12] Discussion with R. Cook, and Capt H. Cox, ibid.

[13] Discussion with E. Smith, ex-ARC Director, 7/88 and H. Aurand, 4/88. See Chapter 18 on ILLIAC.

technology for the remainder of the SURTASS evaluations and for the first operational arrays. The software adjustments which had to be made in this switch were accepted as part of a broader software "fix" effort. These performance factors were also important in getting DoD approval in 1981 for SURTASS production, without the normally required new R&D program to develop and test a new array. The additional ARPA funding of ~ $12 million was needed (together with a comparable Navy outlay) in this period to develop this seismic array performance information.

LAMBDA was not a hi-tech program. In fact, the Navy's telemetry array approach involved riskier technology. This telemetry array technology has become more robust, and is now used in the newer SURTASS telemetry arrays. The LAMBDA seismic technology was good enough to save the SURTASS program at a critical juncture.

Aurand's motif was to get a low-cost, low-risk tool for addressing the fundamental question of maximum useful aperture in the ocean. However, Aurand's original plan to conduct a program of ocean measurements using LAMBDA, was apparently only partly carried out in LRAPP--the priorities of engineering and operational experiments won out. OMAT, a fixed system, was not altogether successful in answering this important question. ARPA's FME also provided some important information on coherence of acoustic signals between widely separated points. Recently, however, due to the Soviet submarine quieting threat, Aurand's original LAMBDA (and OMAT) questions about maximum useful apertures have arisen again, and are being addressed in new programs.

The DARPA outlay of $12 million for LAMBDA does not include the later funding for MFA, the FME, or OMAT.

Estimated life cycle costs for SURTASS, including the special T-AGOS ships, were about $2B in 1980.[16]

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[16] HASC Hearings, ibid, p. 1131.

In the 1970's, DARPA played a major role in developing the Medium Frequency Array (MFA). MFA was a modification of the LAMBDA-type array and associated processing which extended the frequency range of the array to improve signal-to-noise characteristics.[14] The MFA has been transferred to the Navy and has been used in several Navy R&D projects. The MFA technology also had some impact on the design of the improved SURTASS scheduled for deployment in 1988.[15]

C. OBSERVATIONS ON SUCCESS

The LAMBDA concept and some pertinent preliminary data were brought to ARPA by H. Aurand of NOSC. This was very timely because of a new DoD assignment to DARPA on SSBN vulnerability. Aurand was "found" by an ARPA contractor who was engaged in a study to scope approaches to the new DARPA program. Aurand's suggestion that existing low risk seismic array technology would provide a way to explore the utility of large aperture acoustic systems got a quick response from ARPA. This "seed" money probably would not have been obtained from the Navy for some time, since the Navy did not respond positively to Aurand's proposal. The first $100,000 ARPA investment clearly showed that the use of long arrays to conduct surveillance at low frequencies was promising, and might be achieved at lower cost than many had believed possible. The Navy reacted quickly to participate in a joint exploratory program and to revise its plans for SURTASS toward longer arrays. This decisive step toward longer arrays was probably the major impact of LAMBDA.

However, the Navy did not then adopt the seismic technology for those longer arrays but continued along the direction it had been going in SURTASS with telemetry array technology. There were trade-offs, and the Navy apparently felt that their experience with the deeper telemetry arrays and the apparent advantages of such arrays outweighed the difficulties the joint program had experienced earlier with the first long telemetry array. Eventually, after the SURTASS telemetry array failed at a critical stage of its evaluation, the Navy turned, in 1978, to the seismic array technology. The facts that the then SURTASS program manager, Capt. H. Cox had previously been in DARPA, and was thoroughly familiar with the performance of the seismic technology in LRAPP and other tests, together with the availability of an array for test, were key factors in switching to the seismic array

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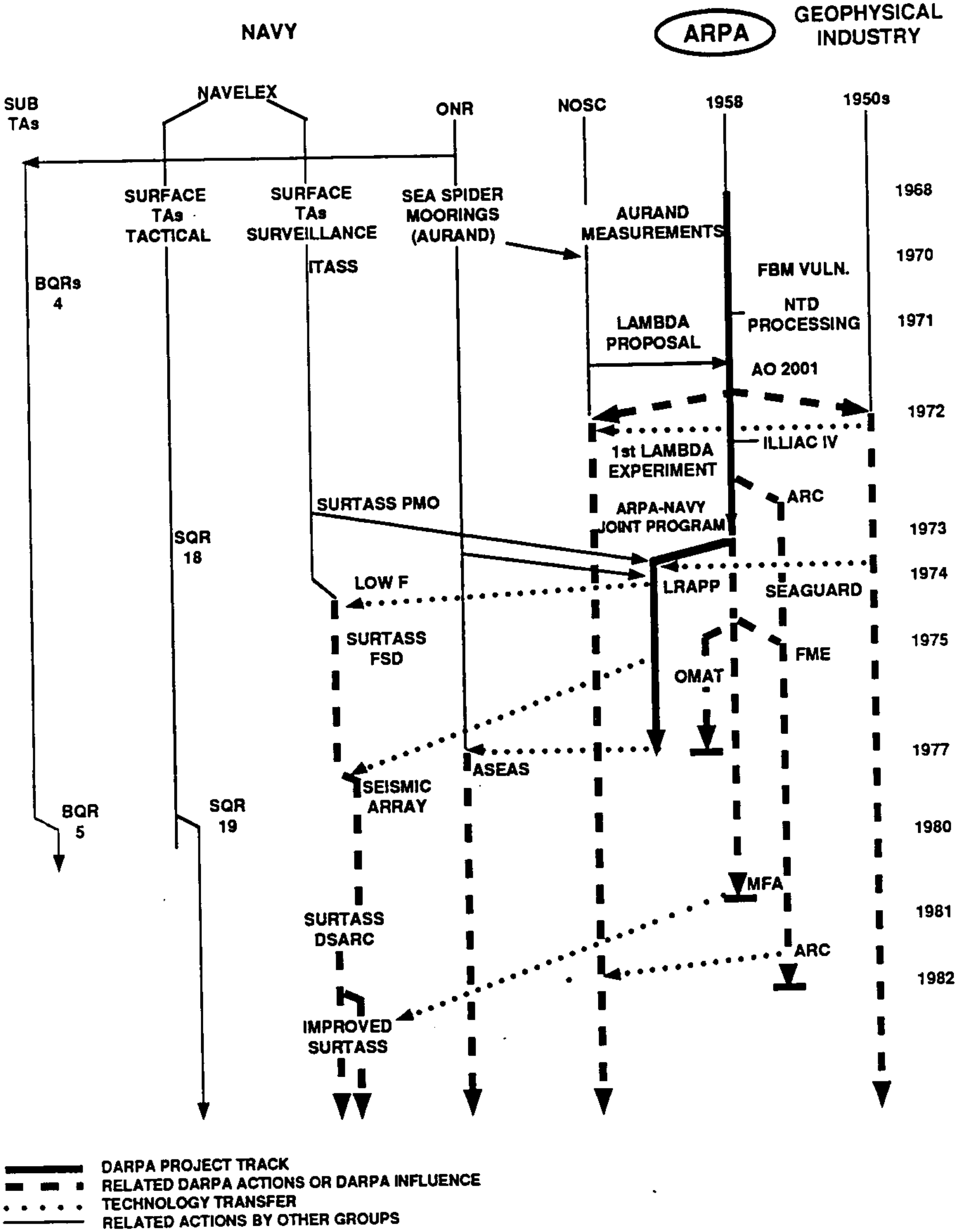
[14] AO 3447 of 6/77.

[15] Discussion with Capt. H. Cox, 6/88.

Figure 1. SURTASS

LAMBDA



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XXV. SLCSAT

A. BRIEF OVERVIEW

Building on earlier Navy and DARPA efforts, in 1978 a joint DARPA-Navy project began with the objective of achieving a laser communications link between aircraft, space platforms or mirrors, and submerged submarines. The ground-based laser-space mirror part of this effort built largely on efforts toward high powered visible lasers in the DARPA Strategic Technology program, and developed techniques for compensation of atmospheric propagation effects which were transferred to the SDIO. An efficient laser-receiver and a narrowband, matched-wavelength excimer-Raman converter laser system were developed and used in successful demonstrations of aircraft-to-submerged-submarine communication, in 1988, after transfer of the Submarine Laser Communications-Satellite (SLCSAT) program to the Navy in 1987.

B. TECHNICAL HISTORY

The existence of a favorable wavelength range in the blue-green for optical transmission in the sea has been known for a very long time. The potential of a suitable laser in this spectral range for communicating with and detecting submarines was recognized soon after the discovery of the laser in the early 1960's. However, for some time it has proved difficult to find a practically useful laser in this wavelength region.[1] In the early 1970's Navy Electronics Laboratory Center (NELC), later Navy Oceans Systems Center (NOSC) commenced an effort, with ARPA support,[2] to develop an optical system for communicating between aircraft and submarines, using available high power arc lamp sources. This led, in the 1971-75 time period, to NELC's Submarine Air Optical Communication System programs in the 1971-1975 period, which also included exploration of two-way communications between aircraft and submarines. Results of this

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[1] One of the earliest lasers, found in 1961 by Gould at TRG under ARPA sponsorship, was the green copper vapor laser. While further development to reduce power demands has led to its use for a major approach to laser isotope separation and other commercial uses, it has not yet proved practical for Navy communications use.

[2] A.O. 1871.

early work underlined the need for more powerful and efficient blue-green light sources and sensitive receivers.

In the late 1960's, the Lincoln Laboratory had developed atomic vapor resonance receivers for optical communications systems, and had recognized the potential of the Cesium vapor as an atomic-resonance filter (ARF) receiver in the blue-green for the Navy. Proposals to carry out further development were made by Lincoln Laboratory to the Navy and others, but no interest was found and the Lincoln group turned to other things.[3]

In the mid 1970's the Office of Naval Research (ONR) and NELC began Optical Satellite Communications (OPSATCOM), aimed at eventual use of lasers in satellites for communicating with submarines. In this project the sun was used as a source to make measurements of the characteristics of light penetrating to increasing depths in the ocean. In 1977, a study was made of the relevant state of the art of electrooptical devices and associated light propagation modeling.[4] The resulting OSCAR program was mainly concerned with lasers in aircraft to communicate with submarines, since the high powers required and corresponding state-of-the-art sizes of the blue-green lasers seemed to rule out space systems. However, as part of OSCAR long range studies were made by industry of ground-based lasers and space mirrors, and space-based lasers for future systems. The potential utility of an atomic resonance narrowband filter optical receiver was mentioned, but not emphasized, in the 1977 report.[5]

In 1976, the advantages for a laser receiver of properties of a Cesium vapor atomic resonance filter (ARF), with narrowband sensitivity to blue light and a fluorescence in the red, were rediscovered by Marling at the Livermore Laboratory, in an effort suggested by the Navy.[6] Excimer lasers, having emission in the ultraviolet, began to be investigated in the early 1970's, initially using powerful large e-beam exciters but with generally low efficiency. In the late 1970's, a more compact discharge mode of excitation was

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[3] Discussion with R. Lerner, Lincoln Laboratory 9/88.

[4] Technical Chronology of Satellite Laser Communications (SLC) and Related Efforts, ORI Technical Report 259, 9 March 1987.

[5] In 1978 a McDonnell Douglas study of Cs atomic resonance receivers was conducted which stated that no matching wavelength space-qualified laser was available.

[6] Testimony of Lowell Wood, LLNL, to the R&D Subcommittee of the Senate Armed Services Committee, 5 Apr. 1979, p. 3326. Wood describes the origin of the LLNL involvement in the submarine communication problems as due to a challenge by S. Karp of the Naval Oceans System Center (NOSC) to develop a suitable receiver. Wood also outlines a ground-based laser/submarine communication system concept and suggested program plan for a GBL system exploiting the LLNL ARF development.

demonstrated at the Naval Research Laboratory (NRL), which had been working on excimer lasers with DARPA support. NRL also found a way to increase efficiency by adding HCl as a Cl supplier for the XeCl excimer halide laser. A little later, conversion of the XeCl transition into the blue by "Raman" conversion in an oscillator-cell involving lead vapor was discovered at NRL and a little later at Northrop.[7]

In 1977, ONR opened discussions with DARPA to form a joint Navy-DARPA project to investigate laser communications to submerged submarines.[8] Earlier, the Navy had developed an Extremely Low Frequency (ELF) electromagnetic system to communicate with submerged submarines, but in the 1970's was having difficulty finding an acceptable place to locate it. Congress was becoming increasingly sensitive to environmental considerations which many people associated with the ELF system, and was urging the Navy and DoD to generate some alternative. However, the ELF approach was relatively mature and the Navy had spent a great deal of time and high level effort to have it approved.[9] At this time DARPA had several ongoing programs to develop blue-green lasers. The largest of these was for directed energy weapons (DEW) applications in space, or from ground to space, and there were other efforts related to submarine detection from aircraft (ODACS), and for deep-sea search (DEEP LOOK). One of the main objectives of a joint DARPA-Navy program was to exploit these other technological developments, the largest of which was in the DEW area, for the communications objective. Another was to be able to use investigations of the lower power communications laser to explore technologies that were also of interest to the directed weapons application area, without having all the technical and economic problems of high energy laser systems.

Initially, the joint program followed two approaches. One envisaged high-powered ground-based lasers (GBL) at locations where cloud-free upward propagation would occur, and mirror-satellites to reflect the laser beam down to chosen areas of the sea. This approach built on the previous DARPA DEW efforts toward high-power, short-wavelength lasers and precision, lightweight space optics, and on techniques to compensate for propagation effects due to atmospheric irregularities. In the joint program, the GBL approach was to be emphasized by DARPA. The other approach, emphasized in the Navy part of the program, involved a laser in a space platform or aircraft. In this approach it was

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[7] Discussion with J. McMahon, NRL, 3/89.

[8] Discussions with D. Lewis, 4/88.

[9] "The ELF Communication System Arrives at Last," by Capt. Ronald Koontz, *Signal*, Jan. 1, 1986, p. 21.

considered that a message could be sent from the ground to the elevated platform by conventional electromagnetic transmissions, and then sent optically from the platform to selected areas of the sea surface. In both approaches it was soon recognized that to send a message by laser pulse modulation simultaneously to very large areas of the sea would not likely be practical, because of the very high laser energy and large optical systems required. Instead, smaller "spots" on the ocean surface would be illuminated by the laser beams, sequentially in time, in some random pattern covering the submarine operating area.[10] Common to both approaches was the need for a suitable optical receiver to be carried by the submarine which could selectively match, as closely as possible, laser wavelength and narrow optical bandwidth in order to provide more pulse signal photons than would come from fluctuations of sunlight in the day or bioluminesence at night. Common also were questions relating to laser light propagation, including time-spreading of pulses, through atmospheric clouds and through the sea water.

This joint program took place in several phases. The first phase occurred between 1978 and 1982, and featured several demonstration-experiments, together with a broad program investigating laser sources including frequency-doubled Nd-Yag, atmospheric and ocean optics measurements, and systems studies. The first of these experiments, in 1979, involved measurements of laser light transmission through clouds. Some of these experiments included participation by an aircraft from the Air Force Space Communications Project-405B, in order to determine how low their system, designed for space links, could reach in the atmosphere.[11] Comparison of the 1979 experimental data with simplified computer models of through-cloud transmission apparently showed only fair agreement.[12]

In the late 1970's the University of Arizona Optical Science Center[13] began work to exploit some of their optical coating techniques in the construction of a more efficient ARF,

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[10] "Submarine Laser Communication," by Cdr. Ralph Chatham, *Electronic Defense*, March 87, p. 63.

[11] Discussion with Monte Ross, 7/88, Ref. 3, p. 2-4.

[12] "Temporal and Angular Spreading of Blue-green Pulses in Clouds," G.C. Mooradian and M. Geller, *Applied Optics*, Vol. 21, # 9, 1 May 1982.

[13] U. of Arizona Optical Science Center was started with ARPA assistance, in the early 1960's. In the later 1960's the Air Force gave support to assure its survival. "The Optical Science Center," U. of Arizona, undated.

building on the previous work by Wood's group at Livermore.[14] Apparently, this effort began as a result of a suggestion by the Navy program managers.[15]

The ARF receiver that resulted incorporated the special coatings previously developed by the University of Arizona, one of which (on the "top") accepts the blue laser light exciting the Cs, and containing the subsequent red fluorescence, and another coating on the "bottom" contains the blue light and allows the red to pass through to photo detectors. The cell contains a rare gas buffer, together with the Cs vapor, found necessary to adjust the partial pressure of Cs and the red line broadening to allow the optical depths in the blue and red lines to have desirable properties, as well as to avoid nonuniformities in Cs vapor concentration due to uneven temperature distribution.

In 1980, a memorandum of agreement regarding a program to develop laser communications with submarines was signed by DARPA and the Navy. Another demonstration experiment, in 1981, was done by NOSC again using a frequency doubled 1-watt Nd-Yag laser in an aircraft, this time with a receiver employing a birefringent "Lyot" filter and a photomultiplier tube, mounted on the R&D submersible DOLPHIN. The wider acceptance angle of this filter allowed more photons to be captured than the standard multilayer interference filter which had a narrow angular field of view, proportional to the filter band-pass.[16] The technical objective of this task was to obtain performance data with which to compare calculated results from models, using measured optical properties also obtained under the program. This time there was encouraging agreement between models and data.

After this successful demonstration of communication from an aircraft to the experimental submarine DOLPHIN, NOSC studied the application of the available technology to communications from aircraft with SSN's in direct support of battle group operations.

Also, an intensified examination was made of a number of other candidate laser systems with optical output in the blue-green, such as HgBr. Toward the end of this first phase in 1981, attention began to be focused on the potential of the XeCl-lead vapor Raman

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[14] A.O. 3623 5/78. See also Fn. 18 below.

[15] The University of Arizona's new coatings were "in search for a problem" for application. The ONR and NOSC managers suggested the ARF. Discussion with Dr. M. White, ONR, 8/88.

[16] See, e.g., "Detecting High Altitude Explosions by Observation of Air Fluorescence," by T.M. Donahue, *Proc IEEE*, Vol. 53, No. 12, 1965, p. 2072, where problems of discrimination against sunlight are discussed.

laser system, with emissions that provided a very close match in wavelength and bandwidth to the blue resonance of the Cesium vapor atomic resonance filter (ARF). In 1981-82, several industries developed competing space-based system concepts. At this time the program began to to be called "Strategic Laser Communications" (SLC).

In the second phase, roughly 1981-1983, there was greater confidence, since the XeCl laser efficiency was now a few percent, and the lead vapor Raman converter, in an oscillator-amplifier configuration, operated at about 50% efficiency. More emphasis was now given to improving the receiver properties.

During the period of these two phases there were also several developments more specifically applicable to the GBL approach. Thus the EMRLD laser, a state-of-the-art high-power excimer laser, was built primarily for DEW applications, but could be adapted also for the GBL communications role. Lincoln Laboratory also conducted experiments at the ARPA Maui Optical Station (AMOS) on atmospheric transmission compensation techniques, which would be needed for both DEW and GBL applications.

Several studies of both types of system designs, GBL and SLCSAT, were made in this same time frame. Statements were made, in DARPA testimony to Congress, that a decision would be made in about 1984-85, as to which of the two approaches, ground- or air-based (or space), would be chosen.

Another airborne-laser field experiment (SLCAIR 1984), was conducted in 1984, using a more powerful, high-pulse-rate Nd-Yag laser, and two types of birefringent Lyot-filters. A second MOA was also signed between DARPA and the Navy.

When the SDI program began at this time the GBL laser technology was transferred to it, along with a major portion of the DARPA high-energy laser effort. SDI proceeded to conduct further tests of some of the GBL atmospheric compensation techniques using rockets, the Space Shuttle, and the (now Air Force) AMOS facility.

From this time the DARPA program focused primarily on a satellite-borne laser communications system, potentially useful in communicating, oceanwide, with all types of submarines.[17] The next phase can be considered to have begun with the transfer of the ground-based part of the program to SDI and plans with the Navy for another experiment, SLCAIR, in 1986, to determine capabilities of communicating with a submerged submarine

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[17] AO's 3623, 4011 and 5069. An additional motive for choosing the space-based system was a persuasive approach to Congressional staff by a contractor interested in the space system.

under environmental conditions that could be considered both unfavorable and potentially operationally important. This experiment used the same Nd-Yag green laser source as in 1984, with two types of Lyot filter, one involving CdS with a wider field of view.[18] This experiment also involved "scanning" of the laser beam simulating the pattern on the sea surface that might occur in an actual, air- or space-based system.[19] With scanning, it was possible to better determine actual communications rates.[20] The new program name "Satellite Laser Communications" began to be used about 1985. The program now focused chiefly on technology for receivers of high overall efficiency, including photosensitive materials with higher quantum efficiencies for detection of the red Cs fluorescence, building on previous work by the Army's Night Vision Laboratory (NVL).[21] Efforts with industry toward an engineering model XeCl-Raman laser-converter system, suitable for use in space, also intensified.

The improvements of receiver parameters reduced the space laser output power required, thereby allowing the use of solar cells for prime space power. DARPA funded construction of a XeCl-Pb Raman Laser System by Northrop which had a compact design for space qualification. This design, however, did not permit easy access to the laser. Because of this it was difficult to operate the laser as designed, and tests were not completed by the time the Navy took over primary responsibility.[22] Laboratory tests of another (not space qualified) system indicated a "lifetime" exceeding 10^8 pulses, with a goal of 10^9. A field test in July 1988 included an XeCl Raman (but not the space qualified) unit in an aircraft, and a prototype ARF receiver on an SSN, and was, apparently, quite successful.

The SLCAIR and SLCSAT programs also included some effort on alternative lasers, notably solid state lasers that could be efficiently pumped by semiconductor diodes. A compact, diode-pumped glass laser constructed under this program apparently has been of considerable interest to the SDI effort. Solid-state lasers of this type are considered by

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[18] Work on CdS was apparently dropped because of the difficulty in obtaining sufficient material of the requisite quality. NOSC memo to authors, 11/89.

[19] Discussion with G. Mooradian, 7/88.

[20] In Congressional testimony the average rates expected for a SLCSAT system were stated by DoD to be roughly comparable to those of the ELF system. Cf. Department of Defense Appropriation for 1984, 98th Congress, lst Session, Part 8, USGPO, 1983, p. 399.

[21] SLCSAT requirements involve integrating photons over the receiver bottom surface area, less stringent than for NVL imaging devices. However, along with this improved photon sensitivity there is an increase of internal noise.

[22] Discussion with Cdr. R. Chatham, 8/88, and NOSC Memo, ibid.

many to more likely be practical in space than gas systems such as XeCl, which cause sharp vibrations when pulsing. However, no "matching" (to the Cs ARF) wavelength source of the glass type has so far been identified, and costs of semiconductor diode pumps have been high. There are, also, strong interests in diode-pumped lasers for commercial applications, and for a huge laser for the DoE's Inertial Confinement Fusion program. It is the opinion of most experts that a diode-pumped solid state laser will be the eventual system of preference in space.[23]

A new MOA indicates the Navy's desire for a continuing R&D program on solid state lasers for eventual possible use in aircraft or satellites, to be conducted jointly with DARPA.[24] The ongoing DARPA Tactical Airborne Laser Communications (TALC) program continues, with Congressional interest, to investigate the use of lasers for tactical, possibly two-way communications between aircraft and submarines, and provides opportunities for test and demonstration of new laser and receiver technologies.

C. OBSERVATIONS ON SUCCESS

In retrospect, it would seem that at the time the joint Navy-DARPA program began, most of the key technologies, the excimer laser, Raman converter techniques, the Cs vapor atomic resonance filter, the characteristics of optical receivers working against solar background,[25] and propagation of light through clouds and water, were all known to some degree. However, the eligible lasers appeared to be too large for space use and confidence apparently had to be built up by those involved in the quantitative characteristics of ARF's. An aggressive program plan, outlined by L. Wood in 1979, was greeted with skepticism by DoD.[26]

DARPA initially emphasized the ground based-space mirror combination because of the DEW motif. On the one hand this may have slowed progress toward a space-based system, pushed by the Navy with less funds, and on the other may have kept developments going which were not possible standing alone. The main technical barriers to a space-based laser system were removed when compact discharge excitation of the XeCl laser was worked out, and later when the Cs vapor filter characteristics had been improved far

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[23] M. White, ibid.

[24] Discussion with Dr. L. Stotts, DARPA, 3/89.

[25] Cf. Donahue, Ref. 9, p. 2072-2073.

[26] L. Wood, ibid., Ref. 6, and subsequent comments by G. Dineen. An *ad hoc* panel of the Defense Science Board looked into Wood's proposal, ibid, pp. 3740-1.

enough to reduce the power requirements of the space-based laser system to an acceptable level. The GBL approach was removed as a competitor when it was transferred to SDI. The program then focussed on reducing risks of the space-based gas laser.

The DARPA program managers kept high level interest up by a succession of successful field demonstrations. SLCSAT and its predecessor were looked on by NAVELEX as a "poor horse," in comparison with ELF, and was supported only because Congress wanted it. But the demonstrations turned out "better than expected" in every test, which kept Congress supplied with ammunition and also maintained some high level Navy interest. The persistence of a dedicated NOSC program manager, G. Mooradian, was responsible for much of the success of these demonstrations.

One of the critical Navy arguments for ELF was that it is not "high technology," is available now even if only in a quite limited system, cost is not great and it meets a current need.[27] Further, SSBN communications requirements have been constantly stated by the Navy to be adequately covered by available technology. In any case, the Navy had "closed ranks" in the early 1980's in support of ELF. The advantages of the SLCSAT system--specifically, less restriction on the operating envelope and possibly a slightly faster rate of transmission--are not seen by the Navy as outweighing the merits of ELF, which is regarded as good enough for now. However, the requirements for communications for attack submarines may change in the future, due to such factors as submarine quieting by the Soviet Navy. The same threat development also caused the "direct support" SSN mission to diminish in attractiveness, and with this, general Navy interest in aircraft-submarine communications waned. Because of the change in the threat environment, the SLCSAT system definition, as well as its cost, is correspondingly unclear.

The weight of expert opinion currently judges the development of an XeCl gas laser for a space-based system to be more risky than the development of a new solid state laser for space deployment. There seems to be confidence that solid state lasers can perform well in space systems. Also, efficient diode-pumped solid state lasers, which are being developed by several groups, may provide eventual cost reductions. A new MOA, initiated by the Navy, seems to be prompted by these considerations and provides for a joint effort in this direction. TALC can provide an important opportunity to demonstrate this technology.

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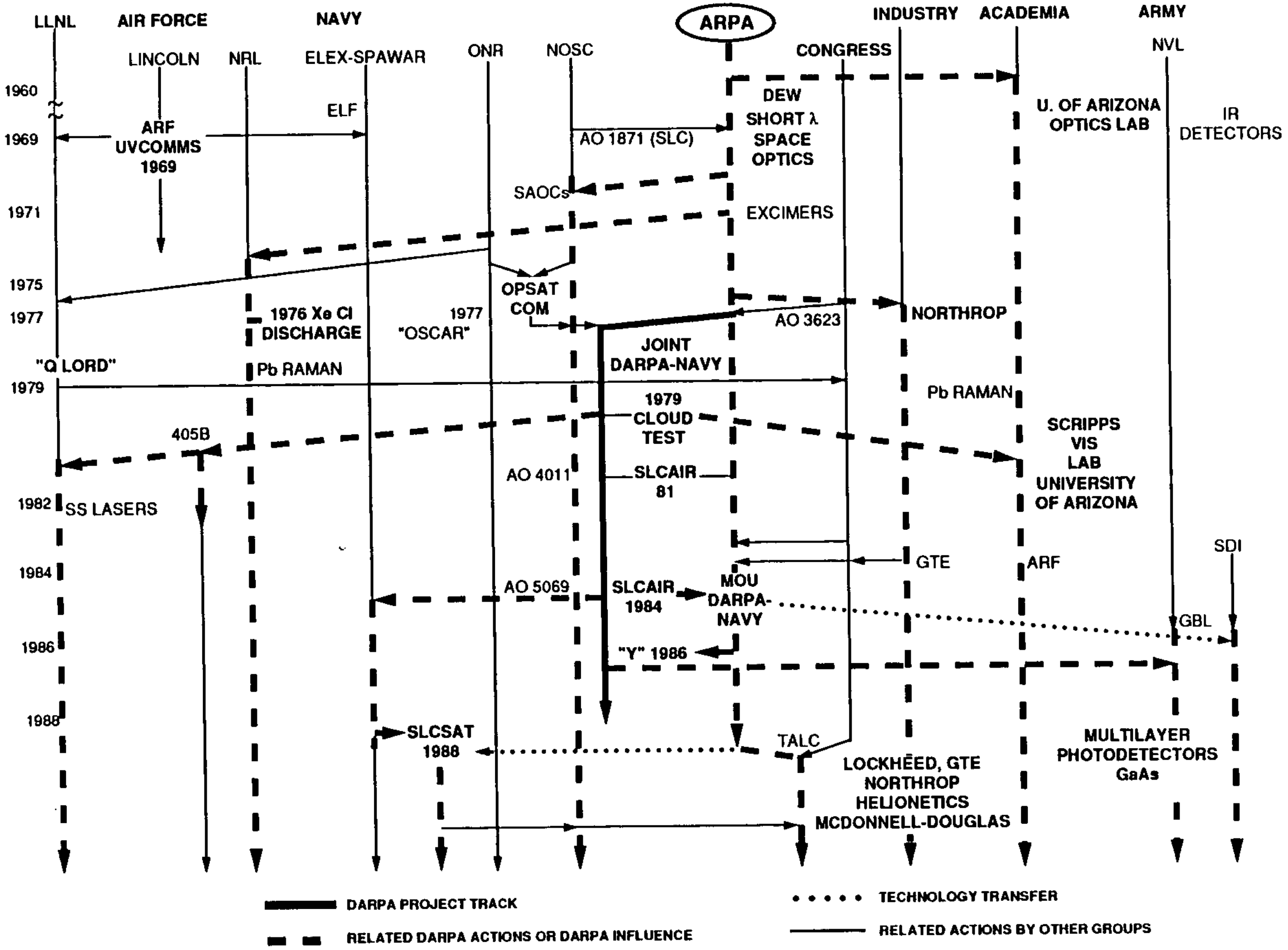
[27] An "austere" ELF system had IOC Summer 1986. Ref. 5.

SDI-type developments may eventually improve the general technology of gas lasers in space, and increase confidence also in a gas laser for SLCSAT. Also, SDI work toward GBL technology for DEW programs may suggest reevaluation of the ground-based laser plus space mirror approach.

The DARPA expenditures for the space-based laser approach, the demonstrations, and the ARF receivers were about $150 million at the time of transfer. Expenditures for the communications aspects of the specifically GBL approach were difficult to separate out clearly from work for the DEW motif.

The Navy SLCSAT program office estimates that development of a operational system could be achieved in the late 1990's, with acceptable risks, but cost estimates vary widely from $2 to $30 billion.

SUBMARINE LASER COMMUNICATIONS



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G. TACTICAL TECHNOLOGIES

XXVI. TANK BREAKER

A. BRIEF OVERVIEW

Tank Breaker was undertaken by ARPA in the mid to late 1970's in order to address deficiencies in man-portable, anti-tank and anti-air weapons. These deficiencies were becoming more acute due to advances in armor and other capabilities being fielded by the Warsaw Pact forces. Evaluated in a shoot-off in 1987-1988 against several competitors, tank breaker technology has been selected for full-scale development by the Army as its new man-portable anti-tank system, replacing the DRAGON.

B. TECHNICAL HISTORY

In the early 1970's the Army Infantry Center and the Marine Corps Development and Engineering Command identified a number of deficiencies in the DRAGON and REDEYE man-portable weapons systems then available to counter tanks and aircraft. A problem identified by the Army and Marine Corps study groups was the vulnerability of the soldier due to DRAGON's launch signature. The groups also brought out other characteristics that would be desirable, such as being able to "fire and forget" the missile and the capability of launching the missile in confined spaces in urban combat. However, a follow-on study by several contractors concluded, in the late 1970's, that the state of the art could not achieve the desired capabilities in a man-portable weapon.[1]

In the early 1970's DARPA set up the ATADS (Anti-Tank, Air Defense System) program, to develop a single missile system to counter both tanks and the air attack threat. ATADS used a "laser beam rider" (LBR) guidance scheme, with a flat trajectory. However, the Army wanted separate missile systems for the anti-air and anti-tank missions partly because of organization and C^3 problems.[2] The C^3 restraints on launching an air defense missile over the battlefield could seriously inhibit anti-tank fire. Apparently there were also some NATO discussions about development of two families of weapons, with

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[1] Discussion with Mr. R. Moore, 6/89.

[2] Memo to Dr. Colladay, by J. Entzminger, DARPA, 2/89.

co-production.[3] The Army did undertake a competitive test, for the anti-air role, of the ATADS beam rider, against their own infrared (IR) homing system, and selected the IR system. This later became the STINGER. The DARPA anti-air LBR system was later designated STINGER ALTERNATE. The Army Anti-Armor Command, however, adopted the LBR DARPA-generated technology for their primary approach to the anti-tank problem.[4] More recently, the Army has used the LBR technology in their line-of-sight forward-heavy air defense anti-tank system (ADATS) mounted on the Bradley Fighting Vehicle.[5]

In the mid 1970's, a number of discussions with DARPA Tactical Technology Office (TTO) contractors, and some trials by the Hughes Aircraft Company using helicopters, led to the conclusion that advances in DARPA-funded focal plane arrays and other technologies might offer significant potential for a new man-portable system that could achieve the desired military characteristics identified by the earlier studies, and also deal with threat armor improvements. However, due to the relatively recent negative studies by some industrial groups, previously mentioned, DARPA first undertook to define and develop an experimental "baseline" system concept that could be tested by the Services.[6] The concept that resulted embodied (in 1979) a number of DARPA-developed technologies including: (1) infrared focal plane arrays and associated processing technology, capable of acquisition and tracking of a tank target; (2) a thrust-vector control system developed by DARPA to meet low cost objectives, and allowing a "lofted" missile trajectory to attack the top, thinner tank armor; (3) an advanced shaped-charge warhead. A smokeless, off-the-shelf propellant allowed a low-velocity missile launch with low signature and permitting operation in confined spaces. This new systems concept, using the infrared focal plane arrays, departed significantly from DARPA's earlier LBR approach, which the Army Anti-Armor Command had already adopted. The concept envisaged a "lock-on before launch" mode of operation, with the soldier being able to sight the target through the missile acquisition optics. Once locked on and fired the missile was on its own in a "fire and forget" mode. LSI processors and advanced algorithms permitted different modes of guidance in earlier and later stages of the missile flight. The overall

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[3] Discussion with Mr. R. Moore, 6/89. The problems of establishing a NATO program apparently were not resolved.

[4] Dr. J. Entzminger, ibid.

[5] OTE Report to Congress, FY 1988, p. 111-13.

[6] A.O. 3239 of 3/76. "Fire and Forget Science and Technology."

system was lightweight, about 35 lb, to meet portability objectives. There was also potential for system growth to allow distant launch from helicopters.

This concept, illustrated in Fig. 1, became "Tank Breaker," a coordinated program with the Army's Intermediate Man-Portable Anti-Armor Weapons Systems (IMAAWS) program, and the Marine Corps. The first Tank Breaker program was to have two phases, the first phase (12-months) starting in 1980 to demonstrate component technologies and their integration, and the second phase (24-months) for missile system and warhead demonstrations.[7]

There were four industrial groups involved, following two different approaches. The progress was rapid in the first phase, demonstrating all the critical technologies and the superiority of the Texas Instruments-Hughes approach. As a result the Army cancelled its IMAAWS program plans. In fact, significant advances in the state of the art of focal plane array seekers and trackers had been achieved and demonstrated to work in this first phase, and further questions remained only in the selection of seeker wavelengths and the design of the tracking and guidance system.

By the end of the second phase, more of the key questions were resolved and several successful flight-test demonstrations had been conducted. In accordance with the DARPA-Army agreement MOA, Army took continuing responsibility, in 1979, under its new Anti-Armor Weapons Systems-Man Portable (AAWS-M) program. For nearly four years, however, further Army action was held in abeyance, apparently due to controversy regarding the technical risks, costs, and operational utility relative to approaches based on LBR designs, which were still favored by some Army developmental groups. Because of continuing pressure by the Army and Marine Corps user communities, however, the Army decided in the late 1980's to have a "shoot-off" between the contractors. A new LBR design was involved in this test as were two vendors of Tank Breaker with differing designs. Evaluation of the results led to selection of the Texas Instruments Tank Breaker design based on the DARPA-developed technology. DSARC Milestone II review was scheduled for early 1989,[8] and approval was given, in June 1989, for full-scale development pending additional operational tests to compare with an upgraded DRAGON.

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[7] A.O. 3974, "Anti-Armor Assault Missile" of 3/80.

[8] Discussion with M. Barr, IDA, 7/89.

Some continuing concerns also have been expressed about the costs and reliability of sophisticated "fire and forget" technology.[9]

C. OBSERVATIONS ON SUCCESS

Tank Breaker represents a timely interaction of technologies to meet a pressing and fairly specific statement of needs by military user communities. Tank Breaker's approach to meeting these needs did not imply a radically different mode of operations, but would allow a large improvement in infantry anti-tank capabilities by allowing much more flexibility and providing reduced vulnerability. The early industry reaction to the need statement was that meeting it would be beyond the state of the art. However, the potential of the new DARPA-developed focal plane array technologies as a key element of a system to meet these needs was indicated by industry initiatives. DARPA undertook further development and integration of this and several other technologies involved in such a system. Because of the complexity of the technology this was seen by some as a fairly risky endeavor. Throughout, there was strong support from the user community, and resistance from some of the Service development groups.

Part of this resistance apparently stemmed from what could be regarded as a previous successful transfer of DARPA LBR technology, which Army's MICOM embodied in their preferred approach to an anti-tank weapon. The LBR technology which had been developed by DARPA under the earlier ATADS program was aimed at a soldier portable weapon for both anti-air and anti-tank use. The Army did not accept this common missile approach which could not be optimized technically for both missions. Although the anti-air LBR lost in competition to the IR-guided STINGER, MICOM did continue work on the LBR for the anti-tank mission and ATADS provided some of the missile technology that was integrated by DARPA into Tank Breaker. The LBR has now been adopted by the Army for their forward air defense system mounted on the Bradley Vehicle.

Part of the Army's resistance also came from concerns regarding the costs and reliability of the sophisticated Tank Breaker technology. However, since Tank Breaker (now AAWS-M) was closer to the users' desiderata, it had their support. The shoot-off test eventually conducted by the Army seems to have settled the problem of selecting between advanced options. However, a recent modification of the existing DRAGON provides a low-cost option which is to be tested against the AAWS-M.

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[9] Discussion with M. Taylor, IDA, 7/89.

From project records, DARPA outlay for Tank Breaker itself appears to have been about $35 million, which does not include earlier development of focal plane arrays or other technologies eventually incorporated. Expected AAWS-M procurement expenditures are about $2.8 billion.[10]

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[10] DMS Market Intelligence Report, Missiles, AAWS-M, Jane's 1988.

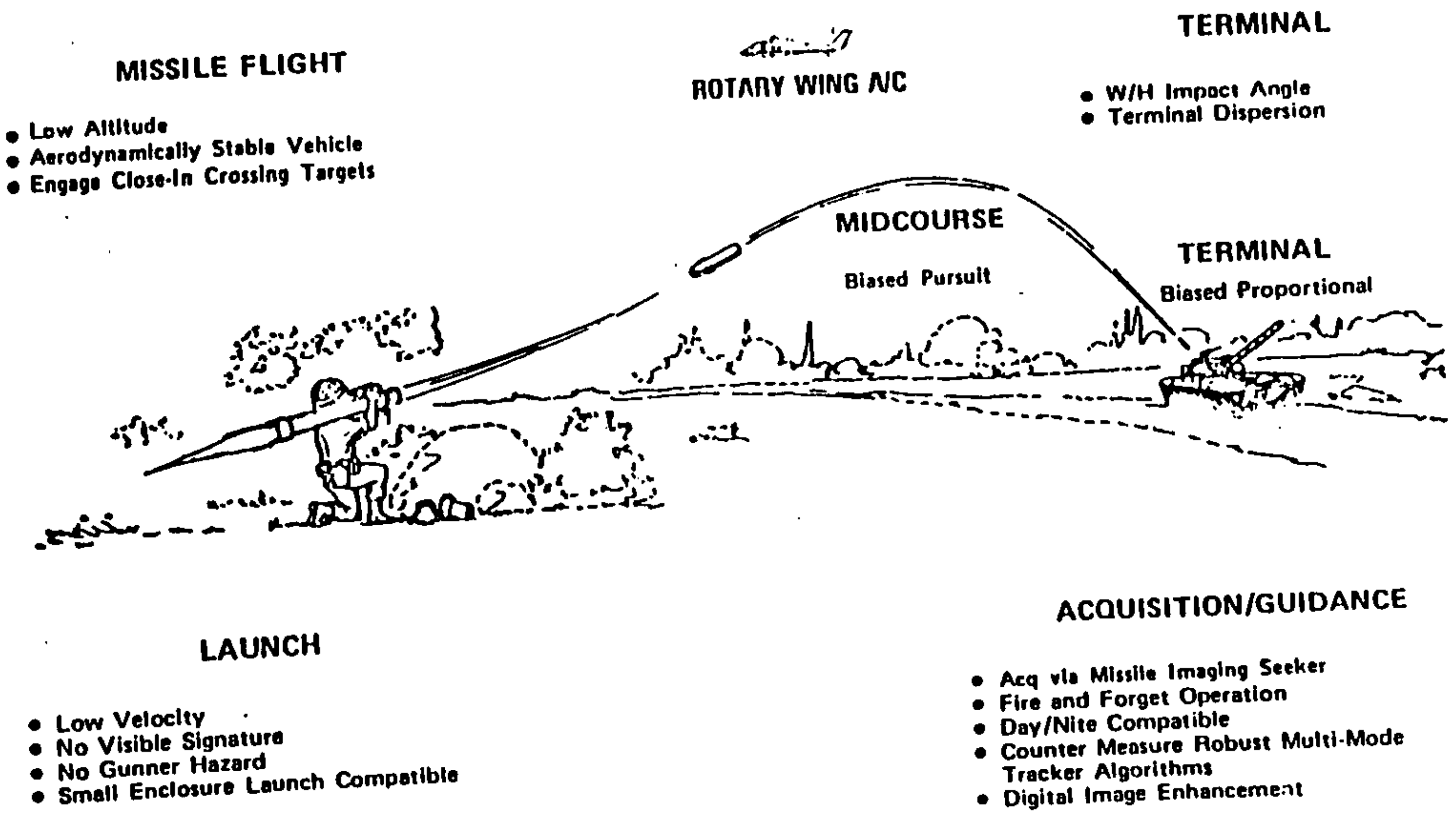
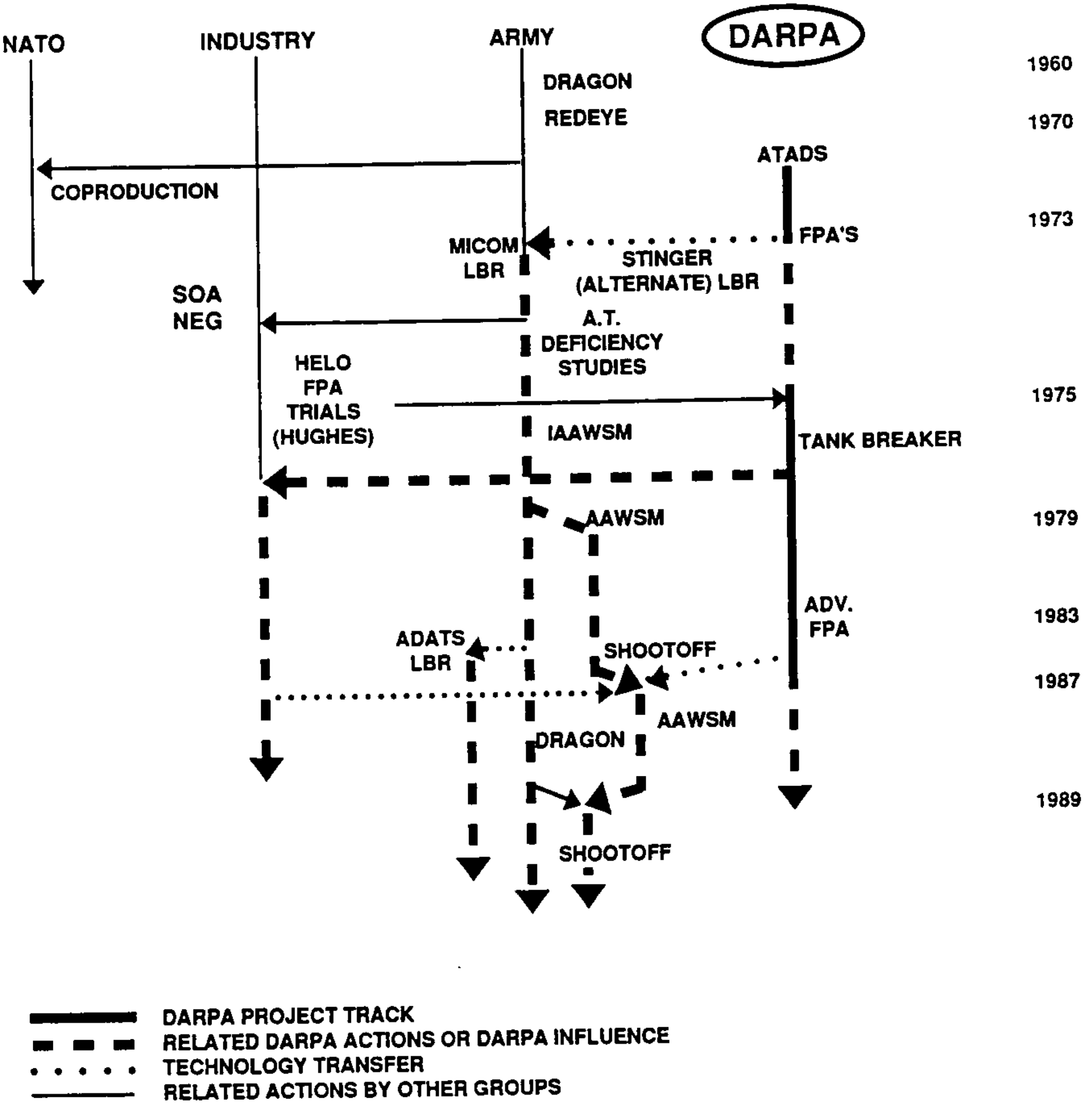


Figure 1. Tank Breaker Concept

TANK BREAKER



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XXVII. HIMAG/HSVT-L

A. BRIEF OVERVIEW:

In 1973 a joint Army-DARPA program constructed a high-velocity, rapid-fire 75 mm gun of novel design, incorporating several emerging advances in ammunition, propellant and fire control technologies. This program was soon expanded to encompass construction of two lightweight test-bed vehicle gun combinations, HIMAG (High Maneuverability-Gun) and HSVT/L High Survivability Vehicle Technology (Light). After successful gun trials, the Army took full responsibility in 1977 for an accelerated HIMAG/HSVT/L test-bed program. Thorough test, evaluations and analysis indicated feasibility and generated for the first time a quantitative data base and modeling methodology relating performance to weight and cost of gun-vehicle combinations. Satisfactory performance against threats in the mid 1980's apparently demanded weights higher than the Army's air transport limits.

B. TECHNICAL HISTORY

In 1973 DARPA began a joint program with the Army aimed at a lightweight, high velocity (HV) cannon for use against medium to heavy tanks and low performance aircraft.[1] Parts of the motif for this program came from earlier DARPA studies of an "anti-tank machine gun" to deal with the large numbers of targets expected on NATO battlefields, the developing concepts within the Army of a completely air-transportable division, and also from the Marine Corps requirements for a helicopter-transportable "mobile protected weapon system," or light tank. Partly also it was felt that a light, agile vehicle carrying a HV cannon might have high survivability and effectiveness on future battlefields with a corresponding impact on tactics. A 75mm caliber was chosen for demonstration of a hypervelocity smooth-bore, lightweight cannon, to be capable of rapid, highly accurate, automatic burst fire.[2] Initially, liquid propellants were investigated but solids were soon

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[1] Testimony of Maj. Terrell G. Covington, p. 3067, in DoD Authorization Hearings for FY 1980, Committee on Armed Services, U.S. Senate, 96th Congress, 1st Session, Part 6.

[2] A.O. #2447, 2/73, "75mm Liquid Propellant Gun."

chosen as more mature technology. The medium caliber anti-armor automatic cannon (MCAAC) was to be designed for low recoil, and also to have new "kinetic energy" penetrating ammunition.

In 1973, also, joint studies began by DARPA and the Army, in a new advanced combat-vehicle technology (ACVT) program, to investigate performance parameters that could be achieved by integrating several emerging technologies, including the 75mm gun, advanced fire control and new lightweight armor, into vehicles with a full-up weight in the range of 12 to 40 tons. In 1975 DARPA and the Army jointly funded construction of HIMAG in the upper (40 ton) weight range.[3] The HIMAG was envisaged not as a prototype, but as a test bed which would be modified almost continuously to obtain performance data at different weights and costs.

> Specifically, the HIMAG System:
>
> basically was fabricated to provide variability and to specifically address mobility, agility, and association with horsepower per ton and suspension systems, and also to address fire control system options.
>
> Specifically, that variability includes being able to vary the power, the weight of the system, the running gear combinations, the suspension system levels, the firing system of automatic, semiautomatic and or single shot firing with the automatic cannon, and a fire control system which can be varied in sophistication from a simple fire control iron sight up though a closed loop, distance sensing, thermal imaging, automatic tracking fire control system.[4]

The 75mm cannon was designed by Stoner (who had designed the AR-15 predecessor to the M16 rifle) and produced by ARES and had a very successful feasibility demonstration in 1975, firing from a fixed platform. This led to an acceleration of the 75mm program, and the fabrication of advanced ammunition, which included a compact "telescoped" APFSD (armor-piercing, fin-stabilized, discording SABOT) round with a long rod kinetic energy penetrator. In the fall of 1976 the Marine Corps joined the DARPA-Army program. Further successful trials were held in 1977, demonstrating penetration of thick armor at long range, acceptable shot dispersion and gun corrosion, and high rates of fire. The results aroused considerable enthusiasm in Congress, which appropriated $11M extra, and in the Army Chief of Staff, Gen. Rogers, who moved up the IOC for the system to 1985 from 1990. In 1977 the Advanced Combat Vehicles

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[3] A.O. 3130, HIMAG, 10/75.

[4] Covington, ibid.

Technology (ACVT) Program Office was formed directly under the Chief of Staff of the Army, who accepted full responsibility for further development and for expansion of the program to meet Marine Corps objectives. DARPA continued support for selected high-risk technology aspects, particularly in fire control, since the 1977 tests showed some weaknesses in this area.

As one of the ACVT's first activities, the Army's Tank R&D command began construction of the HSVT/L test-bed, in the 15,029-ton range, and carrying the 75mm MC/AAAC gun (See Figure 1).

As described by the program manager, who moved to ACVT from DARPA,

> The HSTV/L brings together in the 15- to 20-ton class test-bed a number of technology options for examination. These include the hunter-killer fire control which is represented by two independent sight heads. In this case one member of the crew may select, identify, and acquire while the other sight system is dedicated in conjunction with the gun to firing or engaging against a previously selected target.[5]

And regarding objective,

> The objective is higher targeting and servicing rate, in the functions of an automatic cannon, in combination with a fire control system which allows us to overlay the two actions of identifying, acquiring, and selecting targets with the actual engagement process.[6]

Tests of the HIMAG and HSVT/L began in 1978, with the 75mm gun firing on the run while moving over different types of terrain, and using several different types of fire control systems. Tests of "full up test systems" (FUTS) continued through 1980. Figure 1 shows one such system. Recognizing that the number of actual tests would be limited, provision was made for simulations and modeling. The statistical data and simulation methodologies, developed partly with DARPA support, were judged sufficient to support an evaluation of HIMAG and HSVT/L that year by AARADCOM. This evaluation judged firing performance to have been moderately successful, while identifying a number of desirable improvements, notably in infrared systems for fire control, and also recommended work with a higher caliber cannon, 90 mm or more, to deal with future threats. Studies of a 90-mm cannon-vehicle using the methodologies developed were conducted.

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[5] Covington, ibid.

[6] Covington, ibid.

A number of follow-on studies by Army doctrine and in infantry commands were conducted in the early 1980's, to define systems and describe trade-offs. The conclusions pointed to the feasibility of a 75mm gun-vehicle combination in the 21-ton range. DSARC was anticipated in 1987.[7]

As this date approached, however, it appeared increasingly difficult to meet the requirements for air transport weights with acceptable performance characteristics. The growing appreciation in the early 1980's of improvements in Pact armor also implied a need for a higher caliber gun and heavier ammunition, also discouraging further steps towards acquisition. The Army's present ADATS (Air Defense Anti Tank Systems) approach involves laser-beam-riding missiles mounted on the Bradley Fighting Vehicles chassis.[8]

The Marine Corps, however, with different threat priorities, continued interest through 1986 in the potential of the lightweight 75mm gun for use on its LAV high armored vehicle.[9]

C. OBSERVATIONS ON SUCCESS

HIMAG appears to have originated in a joint DARPA-Army program towards a 75mm, rapid-fire gun for use on lightweight combat vehicles. The 75mm gun system was a new design and was to incorporate a number of emerging propellant and ammunition technologies. However, one of these technologies which was pushed initially, the liquid propellants, was eventually abandoned since the technology proved insufficiently mature.

Early successful trials with the 75mm gun led to program expansion to construct HIMAG, a test-bed vehicle to carry the gun and have the latest armor, engine and fire control technologies. Further success with static firing of the 75mm gun led to enthusiastic acceptance of the program by top levels in the Army in 1977 and extra support that year from Congress.

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[7] "Medium Caliber Anti-Armor Automatic Cannon Programs," (U), Final Report, Vol. 1, USARRAOCOMM 1982, P. 5 (Confidential) Unclassified excerpts have been made from this report.

[8] DoD OT&E Report to Congress for FY 1988, p. 111-13.

[9] *Jane's Armor and Artillery*, 1987, p. 870.

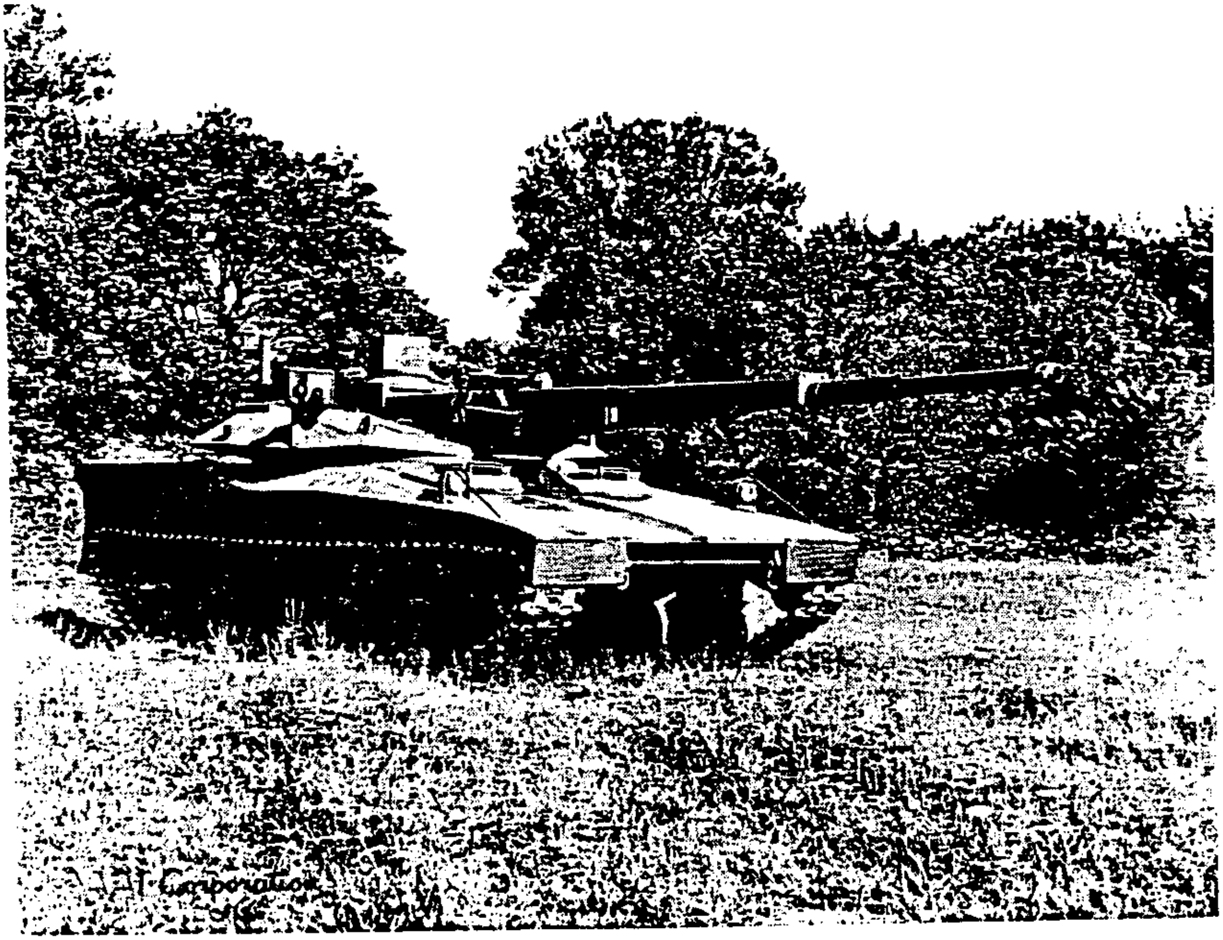


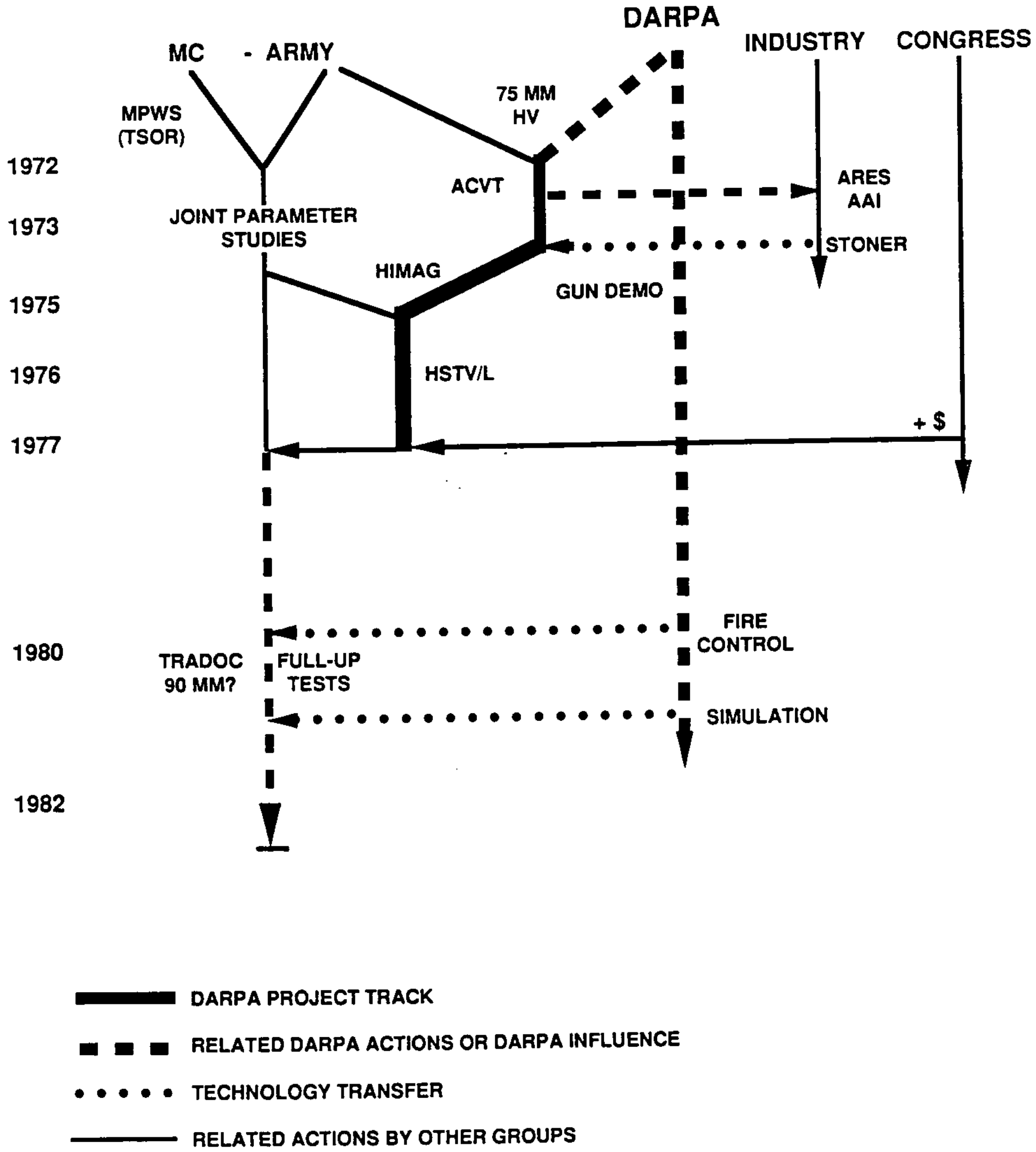
Figure 1. HIMAG/HSVT-L Tank

The HIMAG and the later and lighter HSVT/L were intended to be test-beds which would be modified and evaluated in the course of field trials to judge the range of capabilities provided by emerging technologies. HIMAG/HSVT/L fulfilled the test-bed role, providing for the first time a data base and methodology from which adequate decisions could be made regarding technical performance military utility and transportability. Generally, the technical performance seemed satisfactory, except for IR fire control. By 1980, however, there were some early indications of Pact armor improvements, leading to recommendations for a larger gun. The test results and associated studies indicated, as time went on, that HIMAG/HSVT/L would not be able to meet the maximum weight limits set by air transport, with acceptable performance, especially when taking into account the threat expected for Army priority missions. The Marine Corps, with different priorities, continued interest in the lightweight gun's potential for several more years.

The DARPA lightweight gun and HIMAG program appears to have been a success in that relatively quick transfer took place to the Army, with full backing by Congress. The decisive factor for the Army's decision not to proceed after about 1982 seems to have been the minimum weight required to deal with advances in the threat, which were apparently not fully anticipated until after the transfer had taken place. The HIMAG experience and data, however, appear to have given the Army for the first time a quantitative basis and method of evaluation of trade-offs of vehicle, gun, and fire control characteristics against a given threat.

DARPA outlays, from project records, were about $25 million to the time of transfer. About $22 million more was spent by DARPA on HIMAG after the transfer.

HIMAG / HSTV-L


DARPA
INDUSTRY
CONGRESS
MC - ARMY
MPWS (TSOR)
75 MM HV
1972
ACVT
ARES AAI
1973
JOINT PARAMETER STUDIES
STONER
HIMAG
1975
GUN DEMO
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HSTV/L
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1977
1980
FIRE CONTROL
TRADOC 90 MM?
FULL-UP TESTS
SIMULATION
1982
DARPA PROJECT TRACK
RELATED DARPA ACTIONS OR DARPA INFLUENCE
TECHNOLOGY TRANSFER
RELATED ACTIONS BY OTHER GROUPS

XXVIII. MINI-RPV'S

A. BRIEF OVERVIEW

The potential of mini remotely piloted vehicles (RPV's), integrating new sensors and C^3 technologies with that of improved model airplanes, was demonstrated by ARPA's PRAEIRE and CALERE in the early 1970's. These mini-RPV's affected the Israeli developments of RPV's which were used in the 1982 engagement with Syria, and influenced the Army in its AQUILA program. The U.S. Navy and Marine Corps have acquired Israeli MASTIFF and PIONEER RPV's for operational tests and use.

B. TECHNICAL HISTORY

Attempts to use unmanned, remotely controlled air vehicles go back to about the time of WW I.[1] In the late 1920's remotely controlled aircraft were built in the U.K. and U.S., and used mainly as target drones and guided bombs. Between the wars there were some industrial efforts to construct drones for target practice, and these were greatly expanded in WW II. In WW II, all the U.S. military services also made attempts to use radio-controlled aircraft for special missions, some involving television cameras in the vehicles. Similar efforts continued through the Korean War.

In the mid 1950's, the U.S. Army undertook a program to develop several types of what were then called radio-controlled drones, to be used for a variety of purposes, including reconnaissance, target acquisition, strike, and electronic warfare.[2] Typical weight for these drones was about 450 lb, and the flight duration approximately one-half hour. The vehicles for some of these missions were envisaged to have quite low costs. However, by the early 1960's, and after expenditures of about $800 million, all but one of the projects had been cancelled because of complexity and high costs. Besides the

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[1] Some early history of RPV's is recounted in *War Without Men*, Pergamon-Brassey, 1986, p. 31 ff.

[2] John Kreis, "Background of United States UAV Activity," IDA, unpublished ms. and DSB Summer Study, on Remotely Piloted Vehicles, 1971, Appendix A (Classified). Unclassified excerpts have been made, in this article, from this and other classified reports cited.

tendency to increased complexity, some of the problems that appeared in this early work reappeared in later efforts, notably propulsion engine and communication-navigation systems reliability. In 1964, the Army abandoned most of their program and the Chief of Staff stated that the Army would depend on the Air Force for many of the missions and information which they had hoped to obtain from the radio-controlled drone. In 1965, and apparently in response to pressures of the Vietnam War, the Army declared their surviving drone (the SD-1), which had been used for training, "operational" despite its known deficiencies. The SD-1, redesignated the USD-5, was not used for long, however, and by 1966 the Army was no longer active in the remotely piloted vehicle area, except for conceptual studies.[3]

After the Cuban missile crisis in the early 1960's, the U.S. Air Force began the BIG SAFARI program, a large program including an effort to develop a substitute for the U-2 for reconnaissance in heavily defended areas. This led to a modification of the Ryan Firebee, previously used as a target drone, to produce the first jet propelled drone reconnaissance vehicle, which had operational flights over China in 1963.[4] The Firebee vehicles, designated AQM's and BQM's, were further developed to reach progressively higher altitudes to improve survivability. These Air Force drones, while much smaller than a manned aircraft, could still accommodate sizeable payloads. These were launched from a "mother" aircraft in the successful BUFFALO HUNTER reconnaissance effort in Vietnam. Some of the Air Force drones were modified in 1964 for use at low altitudes in Vietnam. This experience and threat intelligence led to a reappraisal of survivability and to eventual drone redesign favoring very-low-altitude, high-speed runs. Several hundred of these low-altitude drones were obtained and used mainly for reconnaissance and electronic warfare missions in Vietnam, with over 3500 flights and considerable success.[5] Considerable operational experimentation went on to solve the navigation problems, eventually largely overcome by use of TV systems on the drones. In the mid 1970's the Air Force further modified several of their drones to gain a capability to destroy air defense radars and other targets, using TV-guided missiles such as Maverick.[6] In retrospect, the Air Force felt that, while successful, their Vietnam drones had high support costs, which discouraged follow-

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[3] Address by Brig. Gen. W.H. Vinison, "Army Perspective on the Use of Surveillance and Targeting RPV's," in *Proceedings of the Symposium on Remotely Piloted Vehicles*, National Bureau of Standards, May-June 1972, p. 293 (Classified).

[4] *War Without Men*, ibid., p. 31.

[5] Ibid.

[6] John Kreis, ibid.

on efforts. These were high costs in peacetime when the alternative costly manned aircraft were not being attrited.[7]

In 1959 the U.S. Navy began development of the drone-anti-submarine helicopter (DASH) the first helicopter RPV system, mainly to enhance the capability of small vessels for Anti-Submarine Warfare (ASW). However, due to interfering electromagnetic signals aboard these ships, DASH proved difficult to control. The Navy eventually abandoned the DASH program in 1970, but not before several of the helicopters were equipped with low-light-level TV systems, renamed SNOOPY, and used at night to assist the Marines in Vietnam.

In the late 1960's, and apparently in response to a "Zap channel" request from ODDR&E, ARPA's Advanced Sensor Office (ASO) undertook to improve SNOOPY.[8] ARPA added a number of new systems to the DASH, which had considerable payload capability, making two experimental systems called NITE PANTHER and NITE GAZELLE.[9] The payloads at various times included, besides communications and guidance packages and day- and low-light-level TV, a moving target indicator (MTI) radar, a hypervelocity gun, a laser designator-rocket system and a variety of other weapons. The TV's were of both low and high resolution variety, with stabilized optics for the high resolution system. The NITE PANTHER was apparently used first in Vietnam, mainly for tests and demonstration of remote target acquisition capability with accuracy sufficient for fire control. NITE GAZELLE was intended to be a standoff, precision strike system. Both of these were used successfully for training and operational missions in Vietnam until the early 1970's, but were plagued for some time by mechanical reliability problems.[10]

The success of these helicopter systems and the need for greater range for the RPV's led the ASO to the concept of the "extended battlefield," using the tethered balloon-borne systems: EGYPTIAN GOOSE, with an MTI radar for tracking, and the GRANDVIEW for TV-bandwidth communications.[11] A number of tests of the NITE GAZELLE extended range system were conducted in the early 1970's at Nellis Air Force

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[7] Hearings on National Defense Authorization for FY 1988-1989, HR 1748, Title I, p. 208, and communication from Dr. A. Flax, IDA 2/90.

[8] "SNOOPY-Zap Channel," AO 1162, 2/68. The Zap Channel was a quick reaction mechanism by which ARPA would respond to urgent DDR&E requests for Vietnam.

[9] AO 1200 of 3/68, NITE PANTHER and NITE GAZELLE.

[10] Discussion with J. Goodwyn, 3/89. The mechanical problems were eventually solved.

[11] EGYPTIAN GOOSE was the predecessor for POCKET VETO, described in Chapter XVII.

Base, demonstrating the capability to find and designate targets for attack over 100 nmi ranges.[12] The payload in NITE GAZELLE, used in these trials, included a rocket with a laser angular rate seeker which was the beginning of work by Martin Marietta which led eventually to the seeker used in the Army's COPPERHEAD laser-guided munition.[13] The NITE GAZELLE was apparently regarded as an expensive system, since the first one cost over $10 million to develop, and its reputation for reliability difficulties discouraged large scale use.[14]

ARPA intensified efforts, in the early 1970's, toward development of lighter, more compact, higher performance and lower cost electrooptical systems for use in Vietnam, both on the ground and in the RPV's.

Also, in the early 1970's, new technological advances in composite materials, sensors, navigation, and vehicle design and propulsion, together with an increased appreciation of the air defense threat, led to new DoD interest in the possibilities for use of RPV's. In 1970, DDR&E established a special R&D initiative in this area.[15] A number of studies and symposia were held in the 1971-1972 period to help determine the state of the art and define directions for an intensified DoD program.[16] In particular, a 1971 Defense Science Board (DSB) panel on RPV's outlined a set of desirable characteristics based partly on extensions of model airplane technology, and on the previous experience with AF drones and ARPA's NITE GAZELLE.[17] The DSB's list of payload characteristics was similar to those for NITE GAZELLE, but the subsystems involved had to be much lighter and smaller to fit into the mini-RPV concept suggested. Much of the needed technology, the DSB noted, was available, but further research was needed on lightweight infrared (IR) sensors and on C^2 problems. In contrast to the Vietnam experience with drones, the DSB felt that RPV costs could be kept low. The mini-RPV concept outlined by the DSB was given the acronym RPOADS (Remotely Piloted Observation and Designation System), which was used by the Army for their follow-on RPV program. At an early stage of its

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[12] "Advanced Standoff Weapon and Sensor System," Vol. 1, RCA Service Company, 15 June 1972.

[13] Discussion with R. Whalen, Martin Marietta, 12/89.

[14] J. Goodwyn, ibid.

[15] NBS Symposium, ibid., keynote address by H.D. Benington, p.3.

[16] "Remotely Piloted Vehicles, An Idea Whose Time Has Come," Report of the Proceedings of the AFSC/Rand Symposium of May-July 1970; "Report of the Panel on Remotely Piloted Vehicles," DSB Summer Study, 1971; NBS Symposium 1972. Also, Battelle conducted a special study of the RPV/State of the Art for ARPA in early 1971. All these reports are classified.

[17] Defense Science Board study, ibid.

RPOADS program the Army requested ARPA to conduct a number of trials of the NITE GAZELLE system at Nellis AFB, which demonstrated successful designation of fixed and moving targets.[18] In 1972 also, the Army Chief of Staff expressed dissatisfaction with the response of the Air Force to the Army request for battlefield assistance after the Army RPV program was cancelled in the mid 1960's.

In the early 1970's, Israel conducted intensive studies of the possible use of RPV's in engagements against the heavy air defenses being set up by the Egyptians and other possible enemies. (The possibilities of RPV's in this theater were also discussed briefly in the DSB 1971 report.) Apparently Israel was able, about this time, to obtain some of the USAF-type reconnaissance and target drones from the U.S., which they subsequently modified.[19] In their 1973 war these Israeli RPV's were used quite successfully.

In the early 1970's also, apparently during one of the briefings given by ARPA to Dr. John Foster, then DDR&E Director and also a model airplane enthusiast, he recommended that the ARPA program should not continue with expensive and complicated helicopters such as NITE GAZELLE but should be oriented toward use of lightweight, rugged, inexpensive model airplane technology.[20]

The ARPA mini-RPV program began shortly thereafter, in early 1972, as an effort toward the type of lightweight, compact, low-cost sensor/laser target designation system that had been recommended by Dr. Foster and the DSB.[21] The resulting PHILCO-FORD RPV had exchangeable modular payloads, the RPV carrying the daytime TV-laser target designator configuration called PRAEIRE, and the same RPV carrying a lightweight FLIR and laser target designator combination, called CALERE. The propulsion system was an adaptation of an engine that had been used in lawn mowers. The radio command was also adapted from one commercially available, and was operated by a pilot and a sensor controller. Vehicle stabilization was provided initially by an electrical field sensing system developed by John Hopkins Applied Physics Laboratory; later, gyro stabilization was apparently used.[22] Optical stabilization was provided for the high resolution TV, and the laser designation systems used the same optical sighting train as the TV, as had been done

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[18] *Remotely Piloted Vehicle Laser Target Designation Tests*, U.S. Army ECOM Technical Report 4054, November 1972.

[19] J. Kreis, ibid.

[20] Discussion with Mr. James Goodwyn, DARPA, 3/88.

[21] AO 2047 "Zoom" FLIR," 1/72 and AO 2056, "Mini Laser-Sensor Designation System," 1/72.

[22] "*World Unmanned Aircraft*," by K. Munson. Jane's, 1988, p. 155.

in NITE GAZELLE. PRAEIRE I, the first of two versions produced under the ARPA program, weighed 75 lb and had a 28 lb payload and a two-hour flight time.[23] It was described as an austere, low-cost system, with a cost estimate, in mass production, of $10,000/copy.[24] The first flight of PRAEIRE I occurred in 1973 after a joint ARPA-Army program had been started.[25] However, there were some difficulties with performance of the CALERE IR payload, requiring further development.[26]

The Army's effort in response to the DoD initiative included, besides the joint program with ARPA, trials of several other types of available mini RPV's in a program intended to gain a better determination of requirements, called "little r."[27] Part of the "little r" program also was a phased developmental effort of an entire RPV system, together with ground control and support, which led to the Lockheed AQUILA, beginning in late 1974.

During the 1972-1975 period, ARPA produced PRAEIRE II and CALERE II, again built by Ford, based partly on the experience with the previous vehicles, and partly to reduce radar and IR signatures. Sensors and propulsion were also improved, with flight time capability extended to nearly six hours. The extended range vehicle PRAEIRE II B had nearly twice the weight of PRAEIRE I.[28] An electronic warfare payload was also developed. CALERE III was also produced, including a new, lighter FLIR-laser target designator combination.

In late 1974, a joint ARPA-Army effort commenced to develop an integrated communication-navigation system.[29] A little later a PRAEIRE RPV successfully demonstrated the capability of designating a tank target for the Army's COPPERHEAD cannon-launched guided projectile.[30]

The Navy, besides its DASH program and its use for SNOOPY activity in Vietnam also conducted trials of Air Force drones in 1969 and 1970 which indicated feasibility of

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[23] Munson, ibid.

[24] Hearings before the Committee on Armed Services, HOR, 1976 and 76T Appropriations, 94th Congress, 1st Session, Testimony of K. Kresa, p. 3973.

[25] Hearings, ibid., Testimony of Brig. Gen. Dickinson, p. 3985.

[26] Hearings, ibid., Testimony of K. Kresa, p. 3973.

[27] Brig. Gen. Dickinson, ibid.

[28] Jane's, ibid.

[29] "Integrated Communication Navigation System," AO 2922 of 11/74.

[30] "PRAEIRE Mini RPV Laser Target Designation System," Signal, Feb. 1976, p. 70.

operating from carriers.[31] In 1973, with a better picture of its requirements, the Navy joined DARPA in a program to develop an RPV capable of being operated from small ships.[32] This joint effort produced and tested the Teledyne STAR, in a one-year effort. Considerable difficulty was experienced, as anticipated, with shipboard recovery.[33]

Until the early 1970's the Air Force had not been involved with mini-RPV's.[34] In 1973, DARPA began development of the AEQUARE mini-RPV, capable of being launched from an aircraft, for target designation in a heavily defended area. After several demonstrations, the Air Force had a brief follow-on program which ended in 1976.[35]

In the early 1970's also, DARPA and the Air Force conducted a joint program to develop an expendable mini-RPV, capable of loitering and attack, called AXILLARY.[36] The Air Force followed up AXILLARY to a limited extent but has apparently favored the TACIT RAINBOW loiter-capable, air-launched guided missile, classified until recently, for the same mission.[37]

By 1977 DARPA's early mini-RPV effort had nearly concluded. In 1977 also, Israel obtained DoD approval to buy several PRAEIRE II B systems.[38] The laser target designation payload may not have been included in the package sold. Israel went on to develop its MASTIFF RPV, later the SCOUT and more recently the PIONEER. While not identical to PRAEIRE II and incorporating independent Israeli research, these Israeli developments appear to have been influenced by the DARPA developed technology. A photo of PRAEIRE IIB is shown in Fig. 1.

During the mid 1970's, the Army's AQUILA program continued, reaching full-scale development in 1979. After a number of difficulties with engine reliability, recovery procedures, and C^3 technology had been overcome, AQUILA had a series of successful tests in the mid 1980's.[39] AQUILA's weight, however, had grown to 250 lb together with

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[31] Hearings, ibid., testimony of Capt. Hill, p. 3292.

[32] "Ship Deployable Tactical RPVs," AO 2674, of 11/73.

[33] Capt. Hill, ibid.

[34] Hearings, ibid., testimony of Brig. Gen. Hodnette, p. 3997.

[35] Munson, ibid., p. 165.

[36] "Defense Suppression," AO 2456 of 11/73

[37] Cf., e.g., J.D. Morocco, "Development Test of Tacit Rainbow on Navy A6 Set to Begin Next Week," in *Aviation Week*, July 3, 1989, p. 21.

[38] Munson, ibid., p. 55.

[39] DoD OT&E Report to Congress, FY 1988, p. III-2.

a $1 million cost as a result of greater capability and more stringent requirements. For example, the RPV's operations concept, originally to assist artillery battalions, had been extended by 1984 to use by an entire division for a variety of purposes, with corresponding additions to the payload.[40] Target tracking during jinking maneuvers to survive the battlefield were deemed necessary, and anti-jamming requirements for use in the NATO theater were difficult to meet and had increased the size and weight of the key Modular Integrated Communications Operations and Navigation System (MICNS). Test of AQUILA began in November 1986 with the TV payload oniy, because of continuing difficulties with the IR sensor.[41] The AQUILA program was cancelled in FY 1988 after Congress had refused to fund procurement and established the joint RPV, now UAV Program Office (UAV SPO) in DoD. However, the Army apparently is planning a new RPV program in conjunction with the UAV SPO.[42]

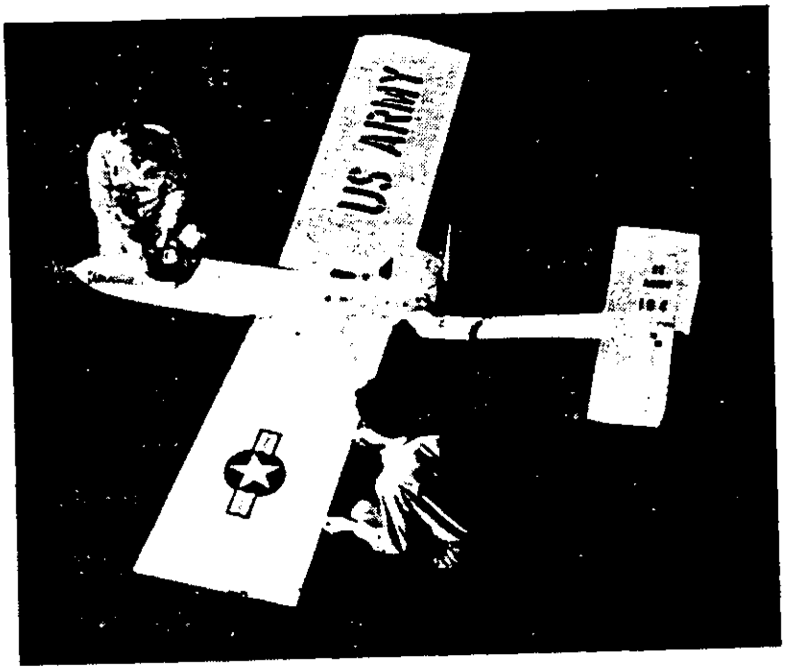

Figure 1. PRAEIRE IIB Mini-RPV

Source: World Unmanned Aircraft, p. 155

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[40] "Results of Forthcoming Critical Tests are Needed to Confirm Army RPVs Readiness for Production," GAO Report: GAO/NSIAD 84-72, April 1984, p. 13.

[41] OTE, ibid.

[42] J. Kreis, ibid.

The successful Israeli use of mini RPV's against Syrian air defenses in 1982, their tracking of Gen. Kelley of the Marines in Beirut by a RPV when he moved about the area, and the Navy's experience in Lebanon in the early 1980's, particularly the loss of an aircraft, led Secretary of the Navy John Lehman to order in 1985 that the Navy obtain a RPV reconnaissance and gunfire direction capability as soon as possible, using available, proven RPV systems.[43] In response, the Navy and Marine Corps rapidly acquired first the Israeli MASTIFF, and more recently the PIONEER. The Navy has apparently successfully operated and modified the PIONEERs for use from several types of ships and had evaluated the PIONEER in operational exercises.[44]

In the 1970's, the Air Force had the COMPASS COPE program for a long-endurance high-altitude RPV to replace the U-2. After a short-time, the Air Force reduced funding for COMPASS COPE, citing high cost and lack of clear mission objectives. In 1983, DARPA undertook a long endurance RPV program, AMBER, taking advantage of new advances in materials, computers, propulsion, and sensor capabilities.[45] While still emphasizing endurance and survivability, the AMBER program became a joint effort with the Army and Navy and has produced a variety of RPV's of different sizes for use at high and medium altitudes, some of which are capable of autonomous, "intelligent" activity. DARPA encouraged innovative industry participation in the AMBER program. DARPA transferred AMBER technology to the Navy and the UAV SPO in 1988. Figure 2 shows one of the AMBER vehicles. Both the AMBER high-altitude RPV and the CONDOR, produced by Boeing Company and supported recently by DARPA, have set new records of altitude and endurance for propeller-driven aircraft. The CONDOR, shown in Figure 3, is a large RPV with a wing span of 200 ft. Operational tests with CONDOR have been performed with the Navy to help develop mission concepts and test sensor suites.

C. OBSERVATIONS ON SUCCESS

ARPA's NITE GAZELLE helicopter RPV program, and a suggestion by DDR&E and DSB to adapt its technology for integration with model airplane dimensions, apparently led to ARPA's mini-RPV programs. Construction and demonstration of the

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[43] J. Kreis, ibid.

[44] OTE Report to Congress FY 1987, p. IV-71.

[45] AO 4981 of 12/83 AMBER.

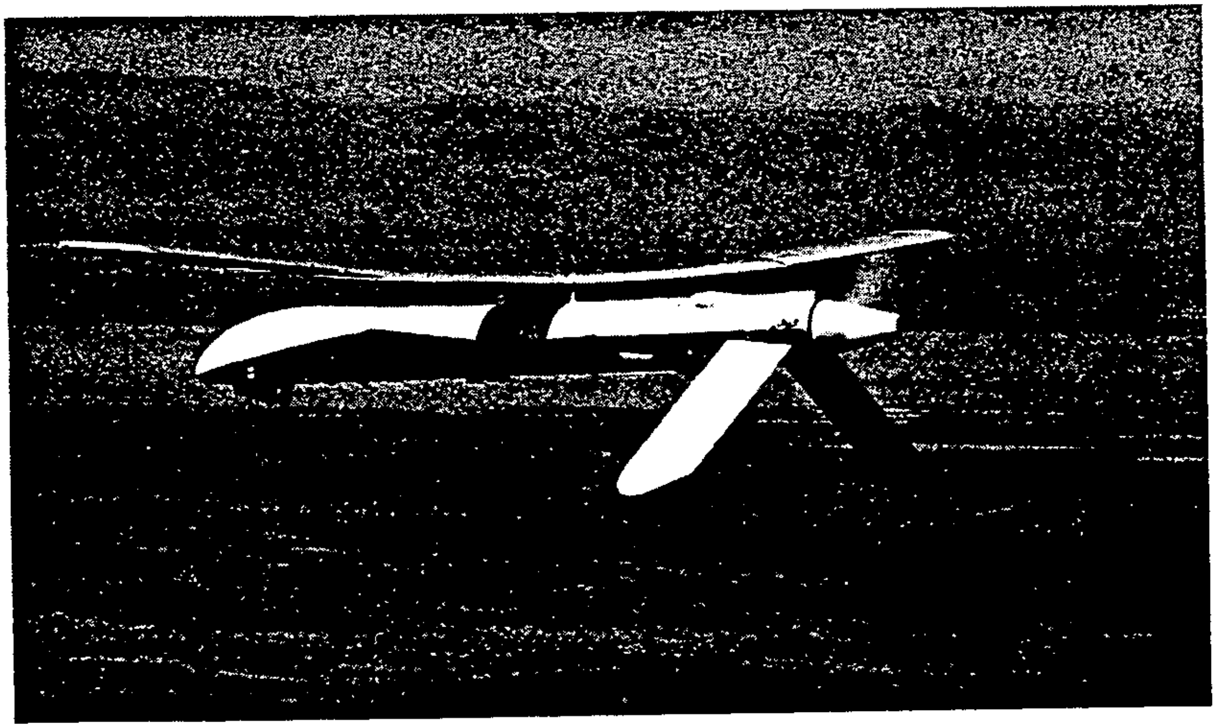

Figure 2. AMBER 500 Flight hrs; 38 hrs. Endurance; 27,800 Ft Photo

Source: From Leading Edge, Inc.

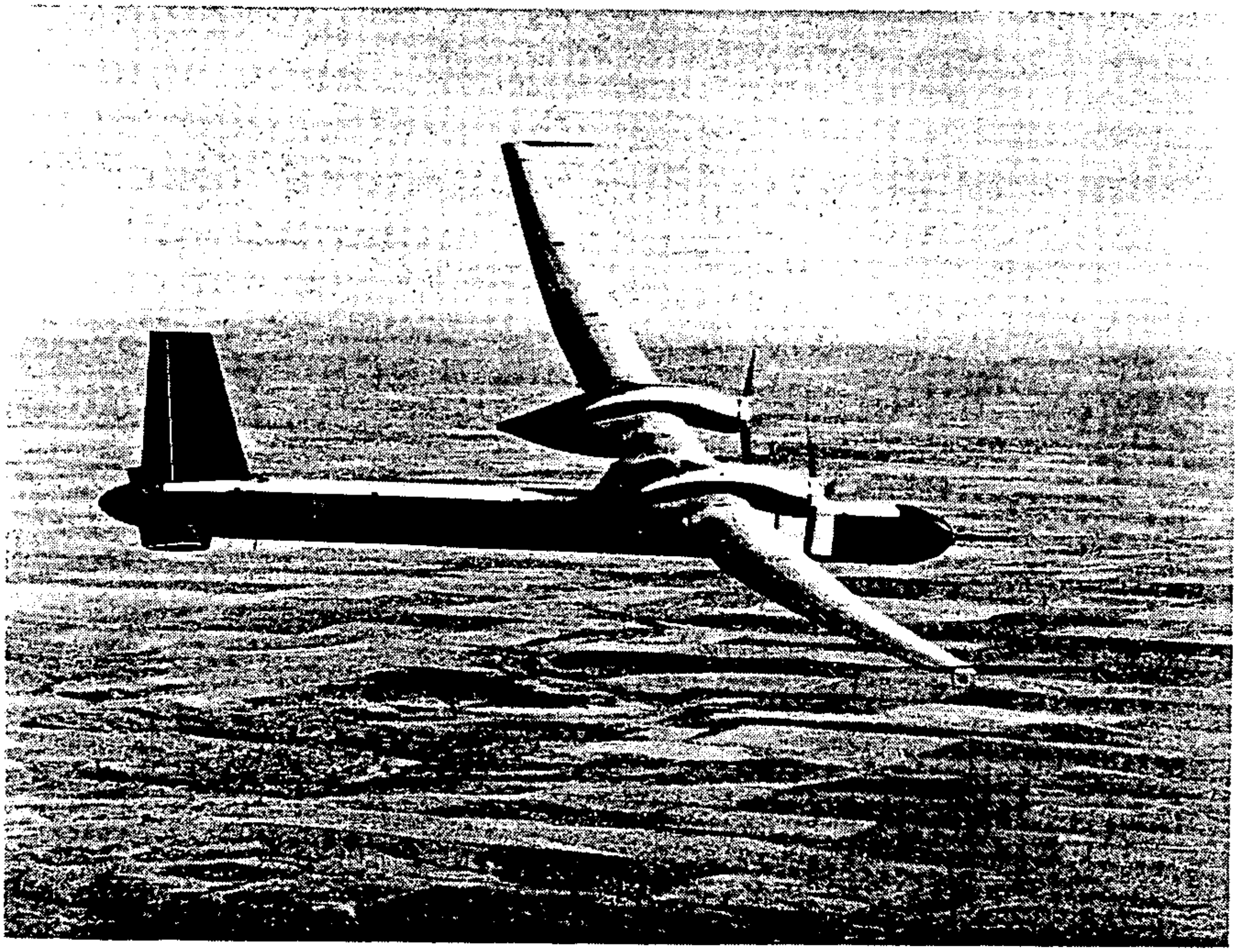

Figure 3. Condor

Source: Boeing Company Advanced Systems

PRAEIRE and CALERE RPV's showed the Services, and the Israelis, what could be done. ARPA's success may have been mainly in this timely meeting of the mini-RPV challenge.

The Army's AQUILA program seems to have been only partly influenced by these ARPA technology demonstrations. Other ARPA mini-RPV programs with the Air Force and the Navy seem to have led to Service programs with short lives. However, the Israeli MASTIFF, SCOUT, and PIONEER seem to be more direct derivatives of the ARPA program. In the Navy and Marine Corps procurement of the Israeli RPV's the mini-RPV technology transfer process seems to have brought the mini-RPV from DARPA nearly full circle.

In the mid 1970's comments were made by Navy and Army program managers, that militarized mini-RPV's are not simple modifications of model airplane technology, but closer to the technology of a weapons system.[46] Trade-offs between low cost and expendable vehicles, more nearly the original mini-RPV motif, and more complex, survivable RPV's or high cost manned aircraft are still being debated.

The AQUILA development led to a complex, heavy, and costly RPV, which was recently cancelled. The Army's reasons for the AQUILA history are based partly on stringent requirements for antijam capability to operate in the NATO theater. Partly also it was due to a change in operational concept, in midstream, from what was mainly a target designator for a battalion's smart weapons, to this plus a more complex intelligence-gathering and electronic warfare device for division-wide use.[47] Somewhat the same type of evolution occurred, apparently, in the Army's earlier program, in the 1950s. These RPV functions seem to have been separated again in more recent Army concepts.[48] Despite the cancellation of AQUILA, the Army continues interest in several RPV programs now under the aegis of the DoD joint RPV (now UAV) program office, set up by Congressional directive in the late 1980's, and is apparently planning for a new mini-RPV to take the place of AQUILA. Use of an RPV in conjunction with COPPERHEAD was for a time an important driving force for continued Army RPV efforts.

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[46] Capt. Hill, Hearing, ibid., p. 3993 and F. David Schnebly, "The Development of the XM2M-105 AQUILA mini RPV Systems," *Proc. Fourth Annual Symposium*, "National Association for Remotely Piloted Vehicles," 1977, p. 24.

[47] GAO Report, ibid., p. 6.

[48] Hearings, Defense Authorization Act of 1987, H.R. 4428, Title I, Testimony of Gen. Knudson, p. 287.

The Israeli RPV success in their 1982 engagements, which has had major impact worldwide, can be credited, partly, to the development of the DARPA technology they acquired in the mid 1970's. The Israeli's success led to Secretary of the Navy Lehman's impression that a useful RPV capability could be quickly acquired. The threat faced by the Navy is not the same as that in the NATO battlefields. The Navy and Marine Corps acquired several PIONEER systems, before Congress prohibited further Service RPV procurements.[49] Congress and DoD, favorably impressed by the Navy's progress, have given the Navy responsibility for running the DoD RPV Joint Program Office.[50] PIONEER, however, is not in the competition for the future joint-Service short-range RPV.[51] It is expected to be superseded by other designs.

The AQUILA anti-jam communications systems (MICNS) was developed by the same contractor (Harris) which had made the earlier ICNS used in PRAEIRE. About $2 million was spent by DARPA on the integrated communications and navigation system (ICNS) and about $100 million by the Army on MICNS. Trade-offs have had to be made between space and weight on RPV's, and antijam capability which depends on the mission.[52]

Difficulty has persisted with IR technology for the mini-RPV's. ARPA had problems with the early CALERE and AQUILA at the time of cancellation did not have a satisfactory package.[53]

DARPA's reentry into RPV's, the AMBER program, was oriented to larger RPV's with long endurance, low observables and sophisticated sensor technology. AMBER has been transferred to the Services. The Boeing-developed CONDOR, recently supported by DARPA, has aroused considerable interest in the Army and Navy.

The DARPA outlay for mini-RPV's, between 1972 and 1977, was nearly $15 million.[54] The Army's outlays for AQUILA were, at the time of cancellation, about $800

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[49] "Pentagon Considers Buying Additional Pioneer RPVs," by John D. Morocco, *Aviation Week*, July 31, 1989, p. 81.

[50] Discussion with J. Kreis, 8/89.

[51] Aviation Week, ibid.

[52] GAO Report, ibid.

[53] The last IR payload contractor for AQUILA was Ford, which had built the FLIRs for CALERE.

[54] Hearings, ibid, Testimony of K. Kresa, p. 3974.

million dollars.[55] By mid-1989 the Navy and Marine Corps had procured nine PIONEER systems, at a cost of about $63 million.[56] The DoD UAV Joint Program Office is expected to have a budget of some $50 million/year when it can produce a coordinated plan to satisfy Congress. However, the formation of this office and its primary concern with RPV acquisition has led to reduction of the DARPA RPV effort.[57]

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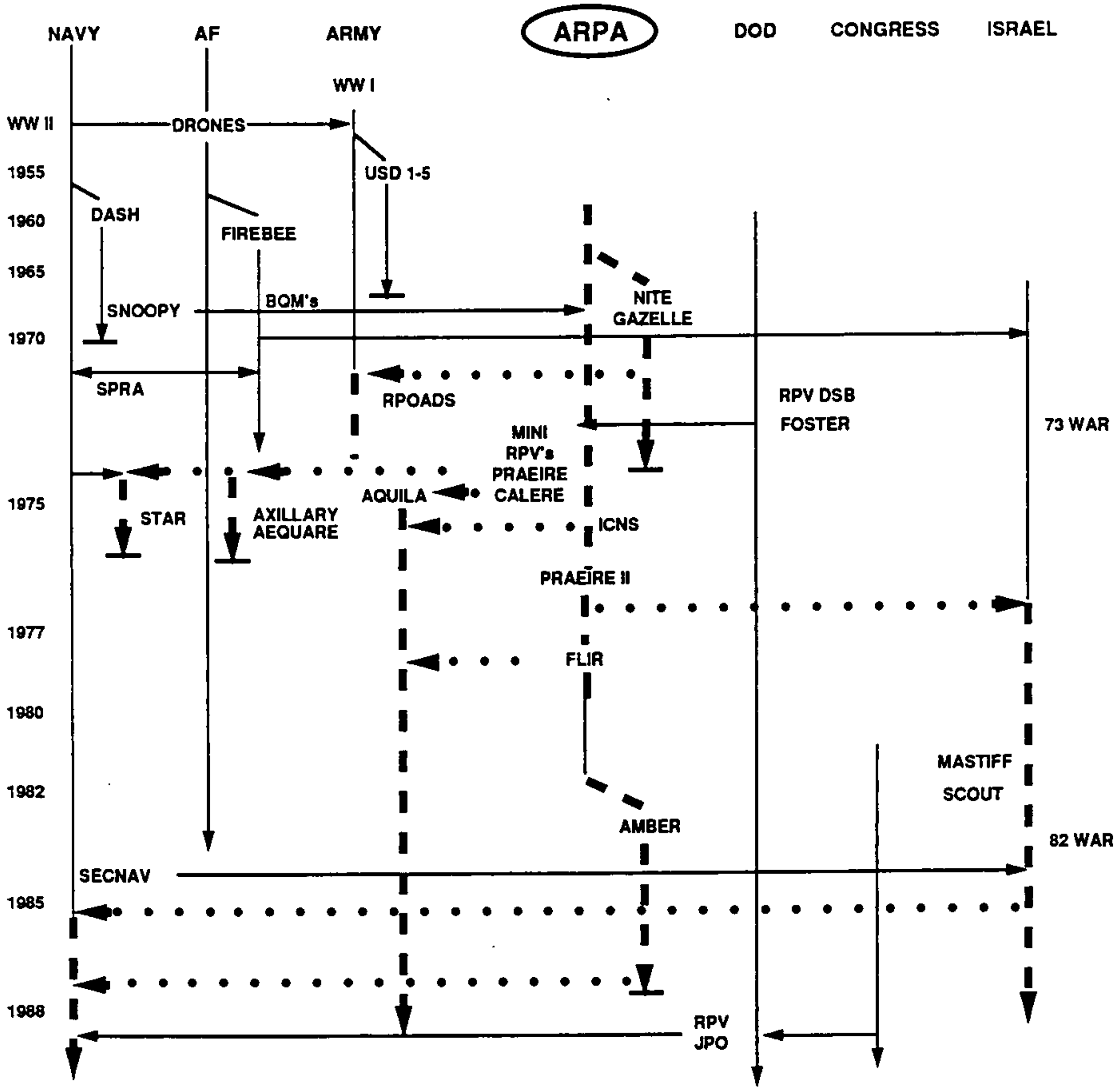
[55] Hearing before the Committee on Armed Services, Department of Defense Authorization for Appropriations, By 1987, 94th Congress, 2nd Session, RDT&E, Title II. Testimony of Gen. Wagner, p. 807.

[56] "Pentagon Considers Buying Additional PIONEER RPV's," by John D. Morocco, *Aviation Week*, July 31, 1989, p. 81.

[57] "DARPA May Use Boeing Drone for Prototype," *Aviation Week*, Nov. 28, 1988, p. 86.

MINI RPV's



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