DEPARTMENT OF THE NAVY
NAVAL RESEARCH LABORATORY
4555 OVERLOOK AVE SW
WASHINGTON DC 20375-5320

IN REPLY REFER TO
5720/FOIA-13-020
1030/13-020
April 10, 2013

Mr. John Greenewald
[redacted]

Dear Mr. Greenewald:

This is in response to your letter to the Naval Research Laboratory (NRL) dated March 18, 2013 citing the Freedom of Information Act (FOIA), and requesting a copy of "NRL Investigations of East Coast Acoustics Events 2 December 1977 - 15 February 1978."

The enclosed document is forwarded per your request. Fees associated with this FOIA have been waived.

If you believe an adequate search for responsive records was not accomplished, you may file an appeal in writing to: Department of the Navy, Office of the General Counsel, 1000 Navy Pentagon, Washington, DC 20350-1000.

The appeal must be postmarked within 60 days from the date of this letter to be considered. Your appeal should contain a copy of this letter along with a statement explaining why you believe an adequate search had not been conducted. It is recommended that the letter of appeal and the envelope both bear the notation "Freedom of Information Act Appeal."

Should you have any questions regarding the foregoing, please contact me at 202-767-2541.

Sincerely,

Richard L. Thompson

RICHARD L. THOMPSON
Freedom of Information Act Officer
By direction of the Commanding Officer

Enclosure

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NRL Investigations of East Coast Acoustics Events 2 December 1977 — 15 February 1978

535 235

March 10, 1978

APPROVED FOR PUBLIC RELEASE - DISTRIBUTION UNLIMITED

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NRL Investigations of East Coast Acoustics Events 2 December 1977 — 15 February 1978

INTRODUCTION

DOD Task

On 5 January 1978, in response to a memorandum from the Department of Defense (Appendix 1), the Chief of Naval Research directed the Naval Research Laboratory to form a study team to carry out a short, intensive investigation to determine the causes of a series of startling acoustic events that had disturbed residents of coastal New Jersey and South Carolina. Significant public response to these events began on 2 December 1977 and continued at intervals to the present (end of February 1978).

Task Force Organization

To meet the objectives set forth by the tasking memorandum, the Naval Research Laboratory established an Ad Hoc Study Team on 5 January 1978. Members of the team were experts in specific areas drawn from the Laboratory's various Science and Technology Directorates as well as from military personnel assigned to the Laboratory. The original team membership was as follows:

Individual	NRL Code	Function
Capt. Lionel Noel, USN	1000	NRL Commanding Officer
Dr. Alan Berman	1001	NRL Director of Research
Capt. Leigh Ebbert, USN	1200	NRL Chief Staff Officer
Mr. Jack Brown	6701	Task Force Chairman
Mr. Robert Proodian	1405	Task Force Coordinator
Mr. Henry Bress	5006	Scientific & Technical Intelligence Liaison
Dr. Homer Carhart	6180	Combustion Phenomena
Dr. Timothy Coffey	6700	Plasma Physics
Dr. Darrell Strobel	6754	Atmospheric Dynamics
Mr. Richard Rojas	8000	Associate Director of Research — Oceanology
Dr. John Munson	8100	Undersea Acoustic Phenomena
Mr. Henry Fleming	8106	Environmental Sciences and Geophysical Research

Additional expert personnel were added to the core Task Force as needed. These individuals included

LCdr Leland Keck	1200	DoD Operations Information
Mr. James Sullivan	1005	Public Media Information
Mr. Evan Wright	8160	Ray Tracing Computations
Dr. Victor Linnenbom	8300	Chemical Oceanography
Dr. Lothar Ruhnke	8320	Atmospheric Physics
Dr. Peter Rogers	8283	Sonic & Transsonic Aircraft Effects
Dr. Wahab Ali	670	Atmospheric Physics
Dr. John Knight	8109	Underwater Acoustics
Dr. John Goodman	7950	Magnetic Disturbances
Dr. Don Uffelman	7950	Magnetic Disturbances

BACKGROUND

Citizens Observations: New York/New Jersey

Reports of observations by inhabitants of the New York/New Jersey area first appeared in local newspapers after the 2 December 1977 event. For the most part, reports included a rough estimate of the time of day and a description of the phenomenon; i.e. an audible sound, a perceived feeling, a visual observation, or some combination of these sensations. Some reports included observations of unusual pet behavior before, during, and/or after the event. Early in January 1978, the NRL team obtained additional observation information from the nonprofit volunteer organization Vestigia Inc., Dover N.J. Vestigia's interest in the phenomen was disclosed by stories in the local press which suggested that individuals write to them. Vestigia provided the Task Force with numerous letters from citizens who reported their observations of events from 2 December 1977 to 12 January 1978. Figure 1 provides a geographic plot of the location of the observers. A review of these reports showed that the majority (94%) of the observers were inside a structure when they experienced the event. A small percentage (6%) indicated that they were outside but within arm's length of a building while observing the events. A small number of individuals reported sighting a flash of light. If the reported flashes were not accompanied by sounds they were not investigated further. A summary of significant citizens' reports in the New Jersey area is shown in Appendix 2.

Citizens Observations: South Carolina

Initially the only "hard" citizens' reports available for events in the Charleston, South Carolina area were found in newspaper reports. However, the NRL investigators obtained supplementary information concerning citizen observations from Mrs. Joyce Bagwell, a faculty member at the Charleston Baptist College. Mrs. Bagwell is well known in the area because of her association with an ongoing USGS program to monitor seismic activity in the Middleton Gardens area of Charleston. Because the events have been reported most frequently by tidewater residents, an informal network of inhabitants of coastal islands (a list of these islands is shown below) report their observations to Mrs. Bagwell on a near real-time basis.

Again, as in the New York/New Jersey reports, the majority of reported observations were made by people that were inside a structure when they sensed an event. Reports are of the type where windows rattle and the structure vibrated. The noise was consistently identified as coming from the direction of the ocean.

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Figure 1 — Geographic plot of observers

South Carolina Coastal Islands

James Island
Fally Beach
Isle of Palms
Sullivans Island
Mount Pleasant
Wadmalan Island
Edisto Island
Johns Island

Media Coverage

The media coverage of the acoustic events along the east coast was most intense immediately after the December 2nd and 15th events. There were subsequent spurts of coverage in mid-January in the Canadian press when acoustic events were reported in the Nova Scotia area.

In most early reports, the probable causes of the events were conjectured as either man-made or noncatastrophic quirks of nature. Conjectures in the media postulated a range of possible causes including supersonic aircraft, artillery firing at Fort Dix, the explosion of large methane bubbles, meteor fireballs, earth tremors, the detonation of tens of tons of dynamite, and even UFOs.

By December 24th, newspaper articles declared that apparently similar phenomena had previously been reported in many places in the world.

It is of interest to note that, while the early newspaper reports employed terms such as trembling, shaking, rumbling vibrations, tremors, and shock waves as primary descriptors of the events, later reports seemed to lose sight of the significance of the shock-wave aspects of the events, and began employing more acoustic-oriented terminology. After mid-December the events were described in the media as booms, blasts, and explosions.

Several hundred thousand people reside in the area between where the events were reportedly "heard." If the events which occurred were primarily in the normal response range of the human ear, then virtually the entire population in that area should have experienced the events. As it turned out, those who were quoted in the newspapers as having sensed the events were those who were in or near "sounding boards." Typically, they were in houses where the floors trembled, windows or mirrors rattled, dishes vibrated, etc.; apparently they detected the response of houses to shock waves as they translated these events into acoustically detectable phenomena. The rest of the population in the area, out on the streets or otherwise not in the proximity of any vibrating surface, were apparently not even aware of the events until after they had happened. Some of them did not know about the events until they read about them in the newspapers.

One of the more interesting aspects of the phenomena was the geographic distribution of citizens' reports. For example, the large events of 2 December were reported along the New Jersey coast from about Beach Haven to Asbury Park. The events were rarely detected more than 15 or 20 miles inland. No citizens' reports came from the Sandy Hook, Staten Island, or

Far Rockaway. Indeed, there was only one report from all of Long Island, N.Y., and that report came several weeks after the event. On the other hand, very strong signals were detected by the Lamont Doherty observatory, north of New York City, and by a least four seismometers in Connecticut and Massachusetts. The ground pattern of the event was characterized by well-defined zones of silence and zones of insonification.

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Lamont-Doherty Measurements

The Lamont-Doherty Observatory operates a microbarograph station at Palisades, N.Y. The station consists of two arrays. Each array consists of three sensors in a triangular configuration. Data from these sensors are recorded on paper charts and are usually recorded in parallel on tape. One major task of this station is to monitor the long distance signal from Concorde aircraft serving JFK and Dulles airfields.

At about 1503:50 Z (1003:50 EST) the microbarograph system recorded a signal which grew in amplitude until about 1504:20 Z (1004:20 EST), when the recording pen was thrown to the top of the chart paper where it hung up until it was released manually about 15 seconds later. The signal record was different in character for another two minutes, but it is not clear that this was due to the 1505 Z signal. At about 2045:20 Z (1545:20 EST), a second large signal was received at Lamont-Doherty. The signal lasted 38 seconds. The instrument saturated at a value equal to 5.0 Pa (50 microbars) peak-to-peak. The tape recorder was not operating on 2 December. The paper chart record is reproduced as Figure 2a. Figure 2b shows a signal received by the same system from a previous refinery explosion. Based on a comparison of signals, Dr. Donn estimated the 2 December 1530 signal as equivalent to a release of 10 to 100 tons of TNT at 100 to 200 km.

15-19 December — The Lamont-Doherty microbarograph station was not operating 15 December nor 19 December. No significant signals were detected.

20-22 December — High winds at surface level created extreme difficulty in recording acoustic data at Lamont-Doherty during this time. No significant signals could be seen against the background noise. Special signal processing may find some.

23 December-15 January — Significant signals of the type seen 2 December were seen by the Lamont-Doherty array on 11 and 12 January. These were recorded on tape.

16 January — Lamont-Doherty detected significant signals similar to the 2 December events at 1614 Z, 1640 Z, 1705 Z, 1721 Z, 1716 Z, 1846 Z, 2023 Z (very large) and 2059 Z EST. These were recorded on tape.

Weston Observatory Measurements

The Weston Observatory monitors a network of seismometers throughout New England. Twenty high frequency *Z* axis seismometers are connected by phone line to a central recorder at the Observatory in Weston Massachussets where accurate time signals are superimposed on the record. In Figure 3, the Weston network stations' detections of the acoustic events are shown as solid circles.

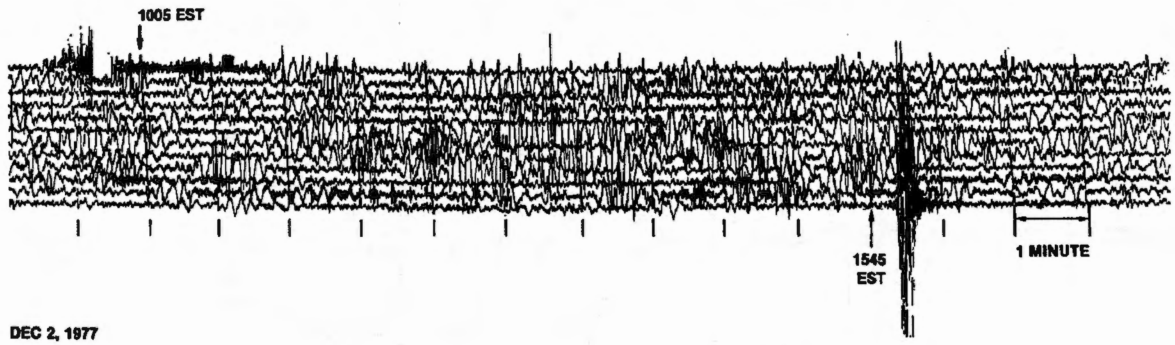
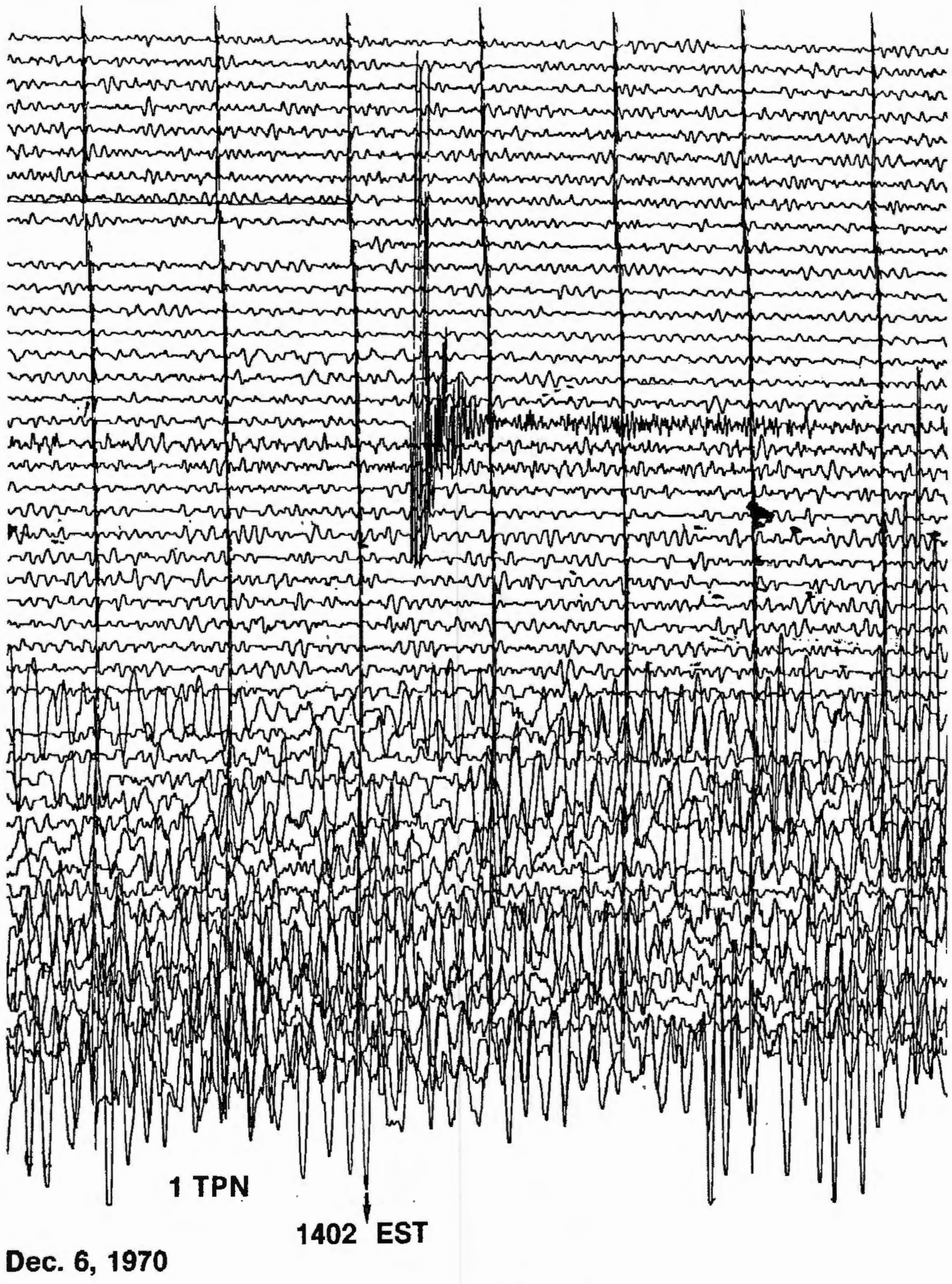


Figure 2a — Lamont-Doherty recording 2 December 1977



LINDEN, N.J. OIL TANK EXPLOSION 5/DEC/1970
> 10 TONS TNT ~ 50km RANGE

Figure 2b — Lamont-Doherty recording of refining explosion

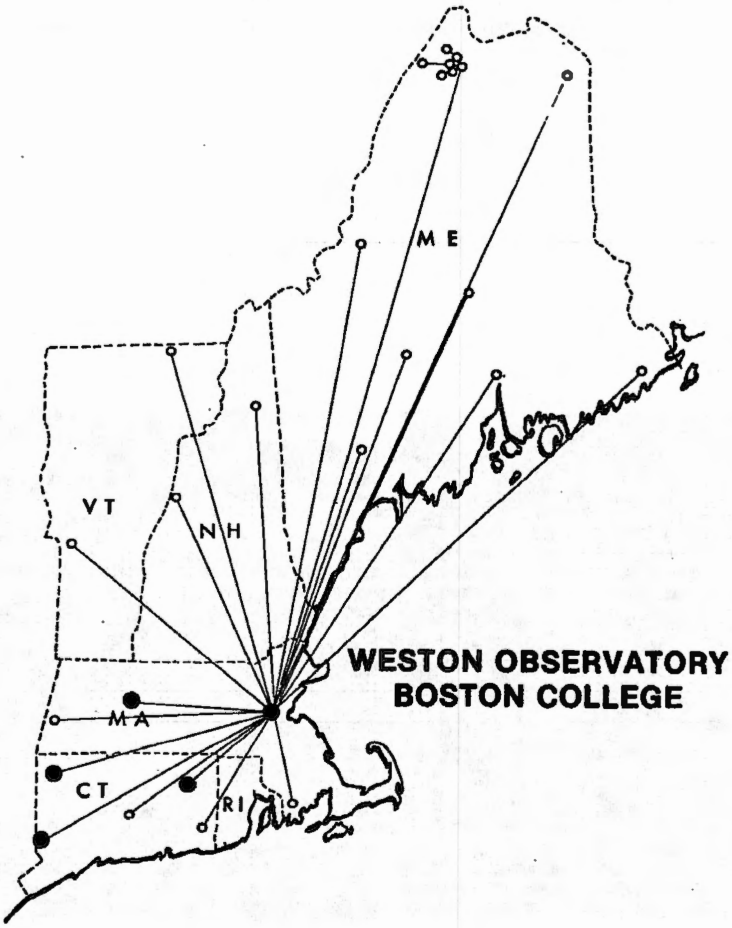


Figure 3 — Location of Weston Network Stations

2 December — The Weston seismic station near Danbury, Connecticut recorded a large acoustic signal at 1507:08 Z (1007:08 EST). It was recorded at Ellsworth, Connecticut at 1513:54 Z (1008:54 EST) and at Quabbin Reservoir, Massachusets 1513:182 (1031:18 EST). The signal was about 25 to 30 seconds in duration, large in amplitude, and moved across the network at approximately the speed of sound in air. Similar signals (larger in amplitude) were seen at BCT, Danbury 2048:30 Z (1548:32 EST), ECT, Ellsworth 2050:14 Z (1550:14 EST), UCT, University of Connecticut 2052:30 Z (1552:30) and QUA, Quabbin Reservoir 2055:02 Z (1555:02 EST). Figure 4 shows reproductions of 2 December signals recorded at these stations.

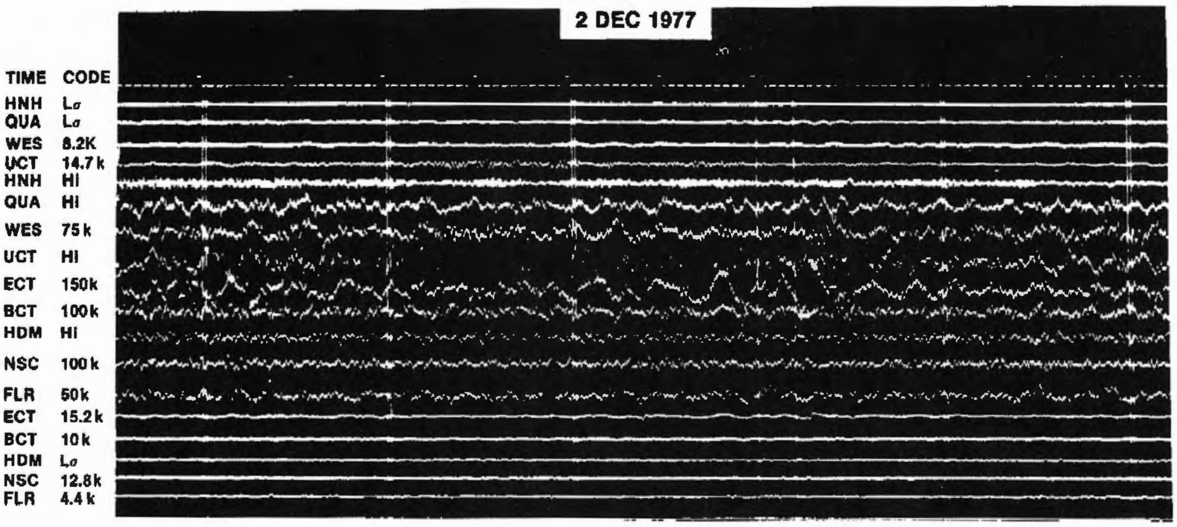


Figure 4 — 2 December signal recorded by Weston

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3-15 December — The Weston network detected a number of significant acoustic events during this period which were of the same character as those of 2 December but of less amplitude. The first detecting station was always Danbury and the times shown below are for that station.

15 Dec	0847, 0850(2), 1001(2), 1007(2) EST
22 Dec	0924, 0925, 1023, 1024, 1025, 1027, 1030, 1032, 1159, 1201, 1418, 1428, 1545, 1550, 1552, 1600 EST
26 Dec	1141, 2020 EST
27 Dec	1903 EST
28 Dec	0854, 0956, 1128, 1512, 1959 EST
29 Dec	1546, 1548 EST
2 Jan	1132 EST
4 Jan	0804, 0812, 0906, 0912, 0936, 1018, 1300, 1518, 1710 EST
5 Jan	0752, 0756, 0809, 1039, 1042, 1048, 1057, 1058, 1100, 1146, 1330, 1332, 1333, 1334, 1355, 1515, 1525, 1548, 1622, 1631, 1726, 1800, 2018 EST
6 Jan	1110, 1209 EST
10 Jan	1132 EST

16 January — This date was marked by a large number (39) of acoustic signals detected by the Weston network between 1714 Z (1214 EST) and 2230 Z (1730 EST). One pulse was very large, at some stations exceeding the 2048 Z events of 2 December which up to this time had been the largest detected.

The Weston Observatory reexamined their records for the period from 1 November 1977 to 16 January 1978. 183 acoustic events were discovered which had the same characteristics as the large 2 December and 16 January events. The set of 183 events began on 28 November and occurred through 16 January, which was the last day of the data sample.

Baptist College Observations

The Baptist College of Charleston, S.C. is under contract to the US Geological Survey to monitor government-owned and -installed seismic equipment located in the greater Charleston, S.C. area. The equipment and the locations of the sensors are shown below (Table 1). Mrs. Joyce Bagwell, a faculty member, is in charge of the project for the College. The information recorded in Charleston is forwarded to the USGS Project Manager in Las Vegas for expert analysis.

Since Summer 1977 the citizens in the Charleston area have provided descriptive accounts of events to Mrs. Bagwell.

The description of events in the South Carolina area had much in common with the description of events in New Jersey. Typically they referred to windows shaking, doors rattling, and crockery jarred on shelves. These citizens' reports prompted her to check the seismometer records. No evidence of seismic activity was evident for these reported events. It was not until 2 December 1977 event that she suspected acoustical energy bursts as a cause.

Table 1
Equipment and Location of Baptist College Sensors

Latitude	Longitude	Station Location	Seis. Type*	Gain (dB)	Attenuation (dB)
32°58'52"	80°04'18"	Baptist College	L4C	60	60
32°49'25"	80°02'24"	Pierpont	L4A	54	66
32°48'58"	80°15'19"	Cawcaw	L4A	66	54
32°58'08"	80°14'53"	Slandville	L4C	66	54
32°53'49"	80°08'27"	Middleton Grd.	L4C	54	66
32°53'49"	80°08'27"	Middleton Grd.	L7Z	0	24
32°53'49"	80°08'27"	Middleton Grd.	L7E/W	0	24
32°53'49"	80°08'27"	Middleton Grd.	L7N/S	0	24
33°06'26"	80°09'46"	Mt. Zion	L4CZ	72	18

*Frequency range, 1-35 Hz; resonant frequency, 1 Hz. Recorded on Geotech recorder Model No. 32300; 14 channels, 1-9 stations, 10 WWV, 14 chronology. Equipment checked daily, recalibrated monthly.

Upon examination of the seismograms for that day, she noted that seismometers mounted in the vertical axis had recorded bursts of energy at the reported times. Furthermore, the delay times between the reporting stations confirmed her suspicions that it was indeed an acoustical phenomenon. A check was made by the task force with Mr. Kenneth King, the USGS project monitor. Mr. King verified that the signals were indeed acoustic (see Appendix 3).

Since 2 December 1977, all events reported to the College have been checked against the seismometer record to determine whether the event was seismic or acoustic. A review of these reports (thru 10 January 1978) provided by Mrs. Bagwell shows that the acoustic events occur primarily during week days (Monday-Friday) and between the hours of 1400 Z (0900 EST) to 2130 Z (1630 P.M. EST) The direction of the source is in general easterly, from the sea.

Oceanographic Systems Report

The Oceanographic System Atlantic was queried on 9 January 1978 on the subject of explosions reported in the period 2 December 1977 to 6 January 1978 off the New York, New Jersey, and South Carolina coasts. No detections were made by any stations queried.

While the signal processing employed is not optimized for their detection, high-intensity impulsive signals can often be recognized by oceanographic sensors. The fact that none of the stations queried detected any such signals in the time periods in question lends credence to the belief that the phenomena reported were not of oceanic origin.

It was assessed that no useful information would be obtained by repeating the request for further postanalysis to be conducted at the stations.

PRELIMINARY ANALYSIS

Time Correlation of Citizens Observations with Measured Data is Shown in Table 2

Table 2 (Continued)
Citizens Observations and Measured Data

2 DECEMBER — THURSDAY	
NE/N.Y./N.J.	S.C
0900-1000 Citizen Reports — East Coast of N.J. 1004 Acoustic — Lamont Observatory, Palisades 1005 Seismic — Consolidated Edison, N.Y. 1007 Seismic — Danbury Conn. — Weston Network 1545 Citizen Reports — Forked River, N.J. 1545 Acoustic — Lamont Observatory, Palisades 1546 Seismic — Consolidated Edison, N.Y. 1548 Seismic — Danbury Conn. — Weston Observatory	0930 Seismic Signal — Baptist College, Charleston, S.C. 0930 Many Citizens Reports — Charleston, S.C.
15 DECEMBER — THURSDAY	
NE/N.Y./N.J	S.C.
0850 × 2 Seismic — Weston Network 1001 × 2 Seismic — Weston Network 1007 × 2 Seismic — Weston Network Nothing 16 Dec, Friday Nothing 17 December, Saturday Nothing 18 December, Sunday Nothing 19 December, Monday	0837 Citizen Reports — Charleston, S.C. 0837 Seismic — Baptist College, Charleston, S.C. 0847 Citizen Reports — Charleston, S.C. 0847 Seismic — Baptist College, S.C. 0958 Citizen Reports — Charleston, S.C. 0958 Seismic — Baptist College, S.C. 1013 Citizen Reports — Charleston, S.C. 1024 Citizen Reports — Charleston, S.C.
20 DECEMBER — TUESDAY	
NE/N.Y./N.J.	S.C.
0838 Seismic — Consolidated Edison, N.Y. 1027 Weak Seismic — Consolidated Edison, N.Y. 2343 Citizen Reports — N.J.	0856 Citizen Reports — Charleston, S.C. 0856 Seismic — Baptist College, S.C. 1356 Citizen Reports — Charleston, S.C. 1356 Seismic — Baptist College, S.C.

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Table 2 (Continued)
Citizens Observations and Measured Data

21 DECEMBER — WEDNESDAY	
NE/N.Y./N.J.	
0900-1000 Citizen Reports — East Coast of N.J. 1855 Citizen Reports, N.J. 1858 Citizen Reports, N.J.	0930 Seismic Signal — Baptist College, S.C.
22 DECEMBER — THURSDAY	
NE/N.Y./N.J.	S.C.
0200 Citizen Reports, N.J. 0924 Seismic — Weston Network 0925 Seismic — Weston Network 1000 Seismic — Consolidated Edison, N.Y. 1018 Seismic — Consolidated Edison, N.Y. 1023 Seismic — Weston Network 1024 Seismic — Weston Network 1025 Seismic — Weston Network 1027 Seismic — Weston Network 1027 Seismic — Consolidated Edison, N.Y. 1030 Seismic — Weston Network 1032 Seismic — Weston Network 1034 Seismic — Consolidated Edison, N.Y. 1159 Seismic — Weston Network 1201 Seismic — Weston Network 1418 Seismic — Weston Network 1428 Seismic — Weston Network 1545 Seismic — Weston Network 1550 Seismic — Weston Network 1552 Seismic — Weston Network 1600 Seismic — Weston Network	0848 Citizen Reports — Charleston, S.C. 1008 Citizen Reports — Charleston, S.C. 2130 Citizen Reports — Charleston, S.C. 2145 Citizen Reports — Charleston, S.C.
23 DECEMBER — FRIDAY	
Nothing	
24 DECEMBER — SATURDAY	
0237 Citizen Report — N.J.	
25 DECEMBER — SUNDAY	
0900-1000 Citizen Reports — East Coast of Nothing	0930 Seismic Signal — Baptist

Table 2 (Continued)
Citizens Observations and Measured Data

26 DECEMBER — MONDAY	
0340 Citizen Reports, N.J. 1141 Seismic — Weston Network 2020 Seismic — Weston Network	
27 DECEMBER — TUESDAY	
1903 Seismic — Weston Network	
28 DECEMBER — WEDNESDAY	
0854 Seismic — Weston Network 0956 Seismic — Weston Network 1128 Seismic — Weston Network 1512 Seismic — Weston Network 1959 Seismic — Weston Network	
29 DECEMBER — THURSDAY	
1546 Seismic — Weston Network 1548 Seismic — Weston Network	
30 DECEMBER — FRIDAY	
Nothing	
31 DECEMBER — SATURDAY	
Nothing	
1 JANUARY — SUNDAY	
Nothing	
2 JANUARY — MONDAY	
1132 Seismic — Network	
3 JANUARY — TUESDAY	
0900-1000 Citizen Reports — East Coast of 1435 Citizens Reports — Charleston, S.C. 1505 Citizens Reports — Charleston, S.C.	0930 Seismic Signal — Baptist
4 JANUARY — WEDNESDAY	
NE/N.Y./N.J.	S.C.
0804 Seismic — Weston Network 0812 Seismic — Weston Network 0906 Seismic — Weston Network 0912 Seismic — Weston Network 0936 Seismic — Weston Network 1018 Seismic — Weston Network 1300 Seismic — Weston Network 1518 Seismic — Weston Network 1710 Seismic — Weston Network	0900 Citizen Reports — Charleston, S.C. 1047 Citizen Reports — Charleston, S.C.

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Table 2 (Continued)
Citizens Observations and Measured Data

5 JANUARY — THURSDAY	
NE/N.Y./N.J.	
0752-0809 Seismic — Weston Network	0830 Citizen Reports (em Charleston, S.C.
1039-1100 Seismic — Weston Network	0937 Citizen Reports — Charleston, S.C.
1330-1355 Seismic — Weston Network	0943 Citizen Reports — Charleston, S.C.
1515-1548 Seismic — Weston Network	
1622-1631 Seismic — Weston Network	
1726-2018 Seismic — Weston Network	
6 JANUARY — FRIDAY	
NE/N.Y./N.J.	S.C.
1110 Seismic — Weston Network	0927 Citizen Reports — Charleston, S.C.
1209 Seismic — Weston Network	0928 Citizen Reports — Charleston, S.C.
	0930 Citizen Reports — Charleston, S.C.
	0940 Citizen Reports — Charleston, S.C.
	0959 Citizen Reports — Charleston, S.C.
7 JANUARY — SATURDAY	
Nothing	
8 JANUARY — SUNDAY	
Nothing	
9 JANUARY — MONDAY	
Nothing	
10 JANUARY — TUESDAY	
1137 Seismic — Weston Network	

Localization of Events

Elementary acoustic theory indicates that the velocity of sound in air is given by the approximate relationship

$$C = \sqrt{\frac{P\gamma}{\rho}} \quad (1)$$

where P is the pressure, ρ is the density, and γ is a constant related to the ratio of the specific heat of a gas at constant pressure and constant volume. For air γ is about 1.4. Since the pressure is given by the relationship

$$P = \rho RT, \quad (2)$$

inserting equation (2) in equation (1) eliminates the effect of density and gives the simple relationship that the velocity of sound is proportional to the square root of the temperature and may be written

$$C = C_o\sqrt{T} \tag{3}$$

where C_o is a proportionality constant. Equation (3) is deceptively simple in appearance. In the real atmosphere the temperature will vary with height above ground in a complex manner that is a function of local meteorological factors. Thus as a minimum it is important to think of the velocity of sound as an explicit function of altitude and rewrite equation (3) in the form

$$C(h) = C_o\sqrt{T(h)}. \tag{4}$$

Figure 5 shows the computed velocity of sound as a function of altitude for the New York, New Jersey region for 2 December. The profile of temperature versus altitude needed to construct this curve was obtained from archival data provided by the National Oceanic and Atmospheric Administration (NOAA).

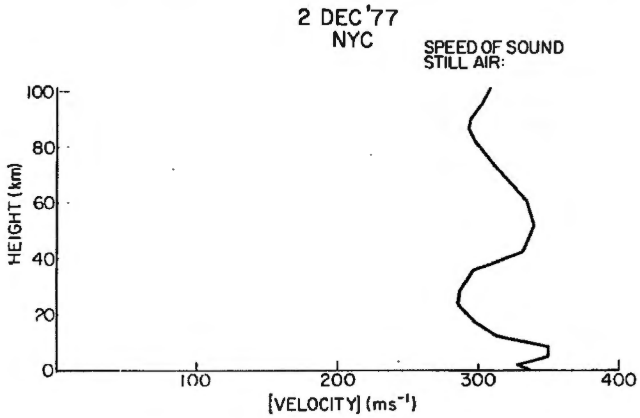


Figure 5 — Velocity of sound as function of altitude (still air) 2 December 1977

The profile shown in Figure 5 is for a still air situation. Indeed, as will be demonstrated below, winds at high altitudes have a major effect on the local velocity of sound. If sound is being propagated in a direction characterized by some angle ϕ relative to the direction of the wind, then the velocity of sound given in equation (4) must be further modified to include the wind, using the formula

$$C(h, \phi) = C_o\sqrt{T(h)} + U(h)\cos\phi. \tag{5}$$

In equation (5), $U(h)$ is the velocity of the wind which varies at any given moment both in direction and magnitude as a function of altitude. Equation (5) shows some interesting properties. If a signal is being propagated in the direction of the wind, the velocity of sound will be the sum of the still air velocity and the wind velocity

$$C = C_{\text{STILL AIR}} + U_{\text{WIND}}. \tag{6}$$

On the other hand, if the signal is being propagated in a direction against the wind, the velocity of sound will be the difference of the still air velocity and the wind velocity

$$C = C_{\text{STILL AIR}} - U_{\text{WIND}}. \tag{7}$$

In directions that are between these extremes, the result is given by equation (5). The complex interaction of wind and temperature are central to an understanding of the effects under study.

In the situation under investigation some event produced an acoustic signal at some altitude h. Initially the investigation allowed h to take any value from 0 to 160 km (top of the stratosphere). Energy released from the source travelled initially in all possible vertical and horizontial directions. The laws of elementary physics tell us in over-simplified terms that when an acoustic ray propagates it follows Snell's law which may be expressed as

$$C_1/\cos\theta_1 = C_2/\cos\theta_2. \tag{8}$$

This rule is illustrated in Figure 6. In this illustration we imagine that two slabs of homogeneous air lie one on top of another. The temperature and wind of the upper layer are such that the velocity has the same value C_2. The velocity of the lower lay is C_1. A ray of acoustic energy when propagating in a vertical direction θ_1 will be refracted to a vertical direction θ_2 when it enters the upper region. The value of θ_2 will be determined by equation (8). This equation proves to be a powerful tool in helping one visualize what happens to acoustic signals when they are released in a real altitude with complex temperature and wind structures. Any real profile that accurately represents the wind and the velocity of sound as a function of altitude can be approximated by a series of layered segments wherein the velocity of sound varies linearly with the altitude. Within a segment that is characterized by a linear variation of the velocity of sound, the path of the acoustic signal becomes a sector of a circular arc as opposed to the straight line mode of propagation encountered in an isotropic medium. It is clear that if enough layers are taken, then in the limit the right-hand approximation would become a progressively more accurate approximation for the true curve.

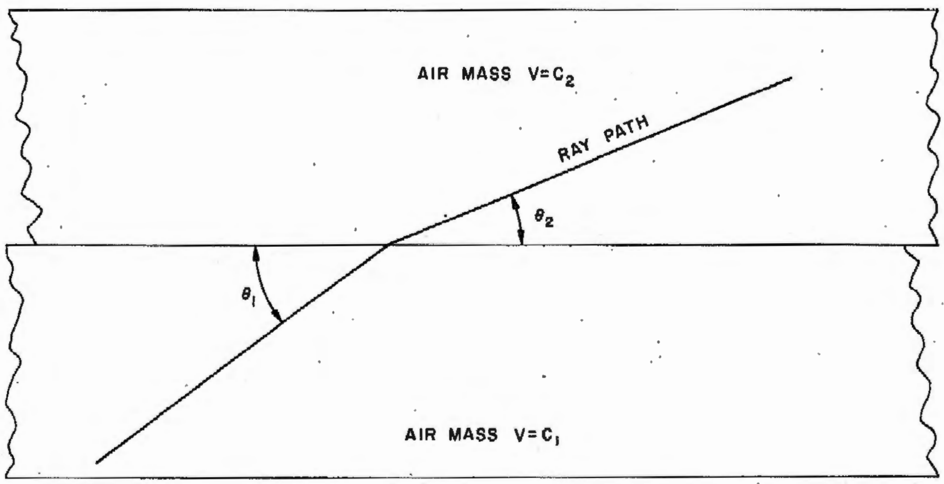


Figure 6 — Ray path refraction

Using equations (5) and (8) gives

$$C_1(h,\phi)/\cos\theta_1 = C_2(h,\phi)/\cos\theta_2 \tag{9}$$

or

$$\left[C_o\sqrt{T(h)} + U(h_1)\cos\phi_1\right]/\cos\theta_1 = \left[C_o\sqrt{T(h)} + U(h_2)\cos\phi_2\right]/\cos\theta_2. \tag{10}$$

Equation (10) can then be used successively to trace rays as they pass from one altitude to another. Equation (10) rapidly approaches a complexity that requires a high speed digital computer to solve. Many computer programs exist which cope with this equation rapidly.

Before describing the ray tracings used to solve this problem, it is worth pointing out some interesting properties of equation (9). Since equation (9) holds at any interface, we have

$$C_1 (h, \phi)/\cos \theta_1 = C_2 (h, \phi)/\cos \theta_2$$

$$C_2 (h, \phi)/\cos \theta_2 = C_3 (h, \phi)/\cos \theta_3$$

$$\cdots\cdots$$

$$C_{n-1} (h, \phi)/\cos \theta_{n-1} = C_n (h, \phi)/\cos \theta_n. \quad (11)$$

This set of equations implies that

$$C_1 (k, \phi)/\cos \theta_1 = c_n (k, \phi)/\cos \theta_n. \quad (12)$$

Now if c_n is greater than C_1 because of wind and temperature conditions, then $\cos \theta_n$ must be larger than $\cos \theta_1$. Since the largest value that $\cos \theta$ may have is unity, equation (12) implies that it is possible to reach a point where $\cos \theta_n = 1$ and

$$\frac{c_1 (k, \phi)}{\cos \theta_1} = c_n (k, \phi). \quad (13)$$

Equation (13) implies that θ_n has a value of zero. The ray is horizontal. In fact it has been reversed in direction. *This situation will occur whenever the velocity of sound at an elevated height is greater than or equal to the velocity at the source divided by the cosine of the vertical angle of propagation.* This phenomenon is called ducting and occurs in optics, underwater acoustics, and radio propagation. In optics the analog of acoustic ducting is the formation of mirages that are sometimes observed in deserts. In underwater acoustics, a similar phenomenon sometimes allows a submarine to escape detection by surface ship sonars because the thermal structure of the water refracts the sound upwards and traps it in a surface duct. In radio reception a similar phenomenon allows one occasionally to detect radio broadcasts from stations hundreds of miles away. During daylight hours, only local stations are received. Occasionally at dusk or dawn, the layering of the atmosphere and ionosphere is sufficient to refract the path of radio broadcast signals very long distances.

In the course of this investigation a massive program of ray tracing computations was undertaken. Wind and velocity profiles were generated for the days and approximate locations where acoustic events were detected. Computer ray tracing calculations were used to establish (a) the initial altitude of the events, (b) the precise location of the events, and (c) the duration of the signal received at the receivers; and to provide an estimate of the relative strength of the signals.

For the events of 2 December a unique solution was obtained. The event must have taken place within a few kilometers of a point located at 39° 30'N, 74° 10'W. The signal was generated by a source at an altitude between 7,500 and 10,000 feet. Because of strong winds aloft at that time, extremely strong ducting conditions existed. Signals from this event were refracted to the earth and were trapped in relatively low-altitude ducts. The focussing within this duct was strongest in directions of propagation to the north and northeast. Propagation of signals to the southwest and east, in directions that largely opposed the winds, were weak. For other events the possibility of long-range reception of acoustic signals was investigated by ray tracing techniques. In every case where a signal was detected, ray tracing computations indicated the existence of a low-loss acoustic propagation path.

The calculations performed resulted in a series of complex profiles in altitude and range where an acoustic source would result in long range propagation and detection. A series of these profiles and a representative ray tracing are shown in Figures 7 and 8a through 8o.

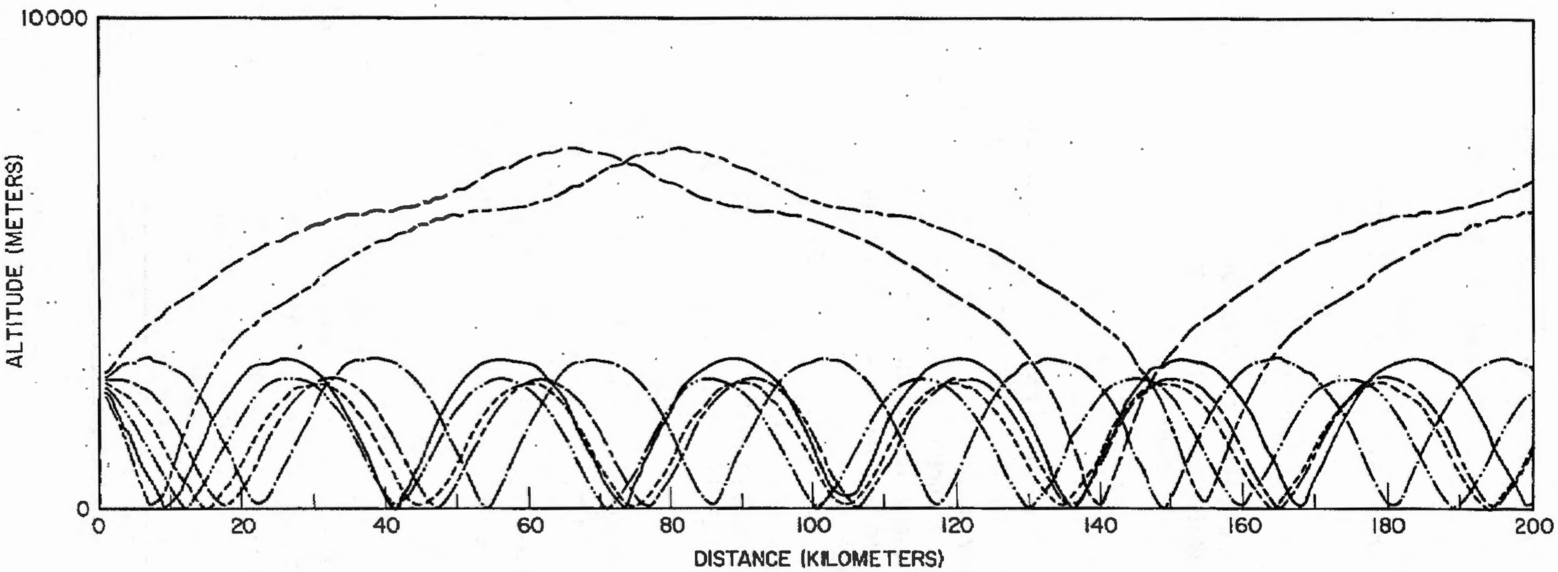
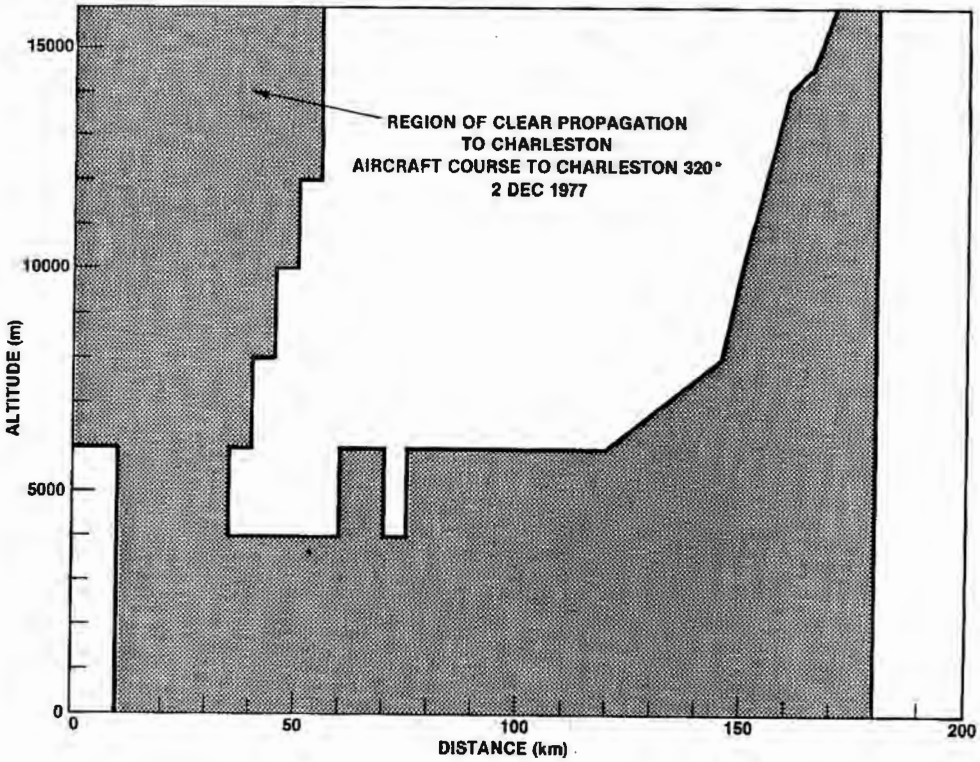
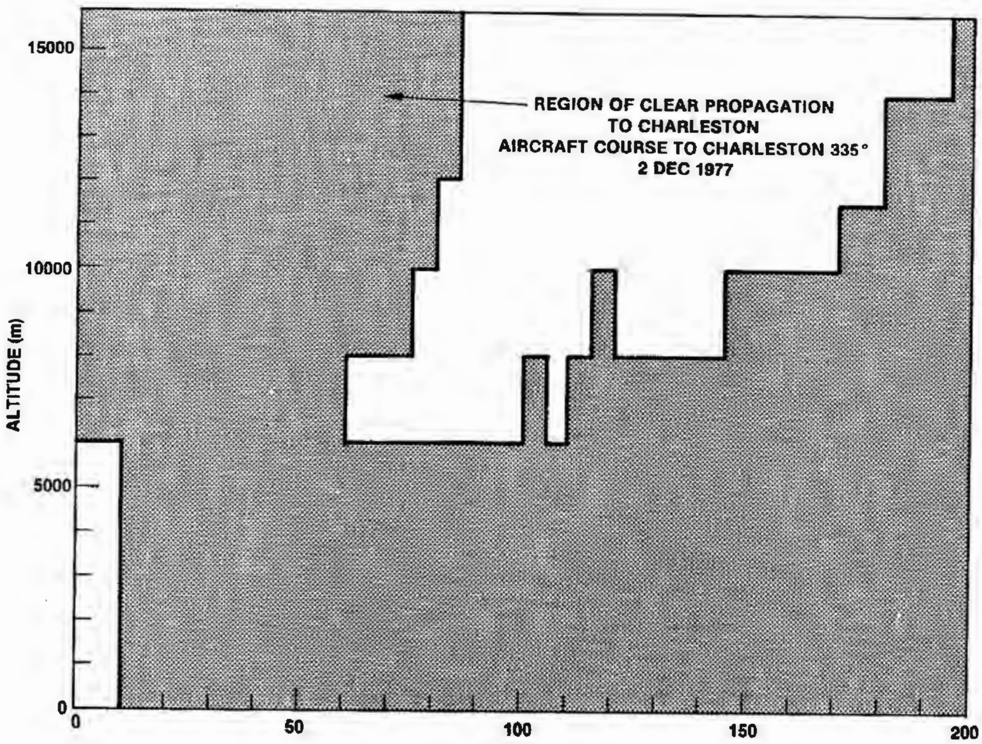


Figure 7 — Ray tracing to Palisades, NY, azimuth 6°, 2 December 1977

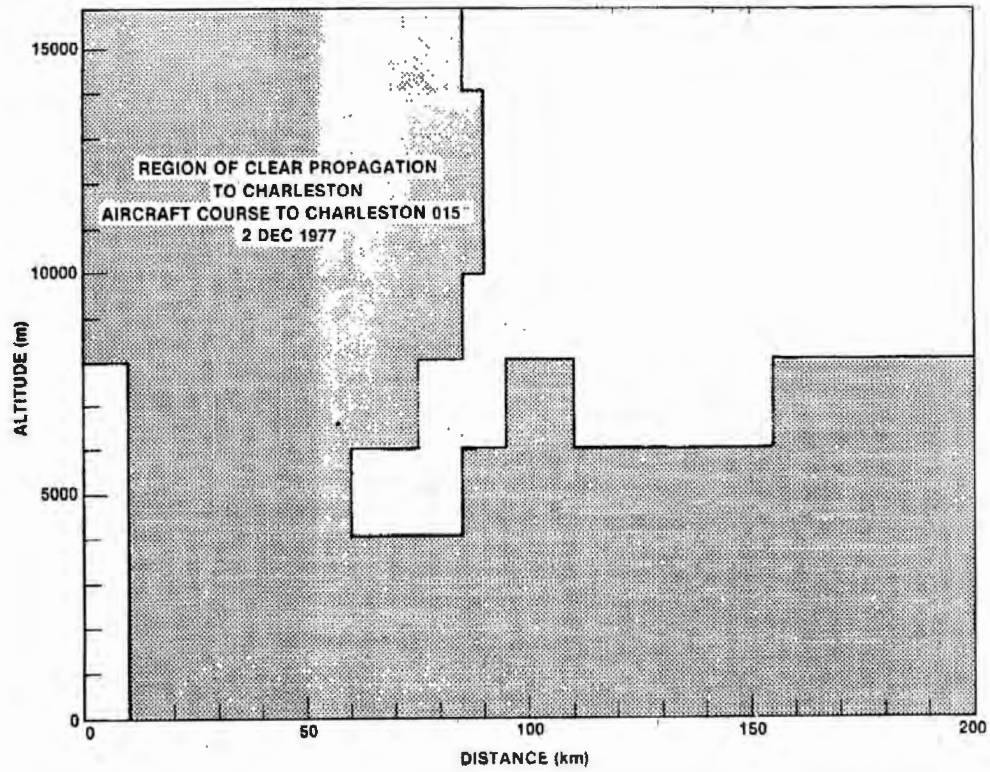


(a)



(b)

Figure 8 — Profiles of clear propagation 2 December 1977



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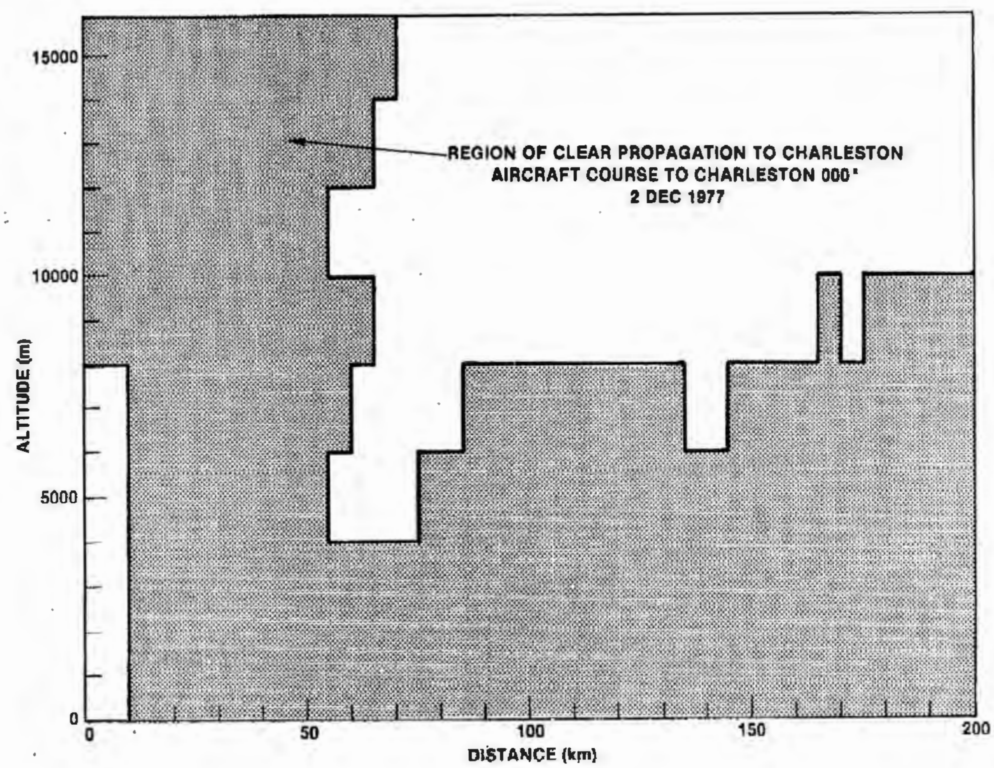
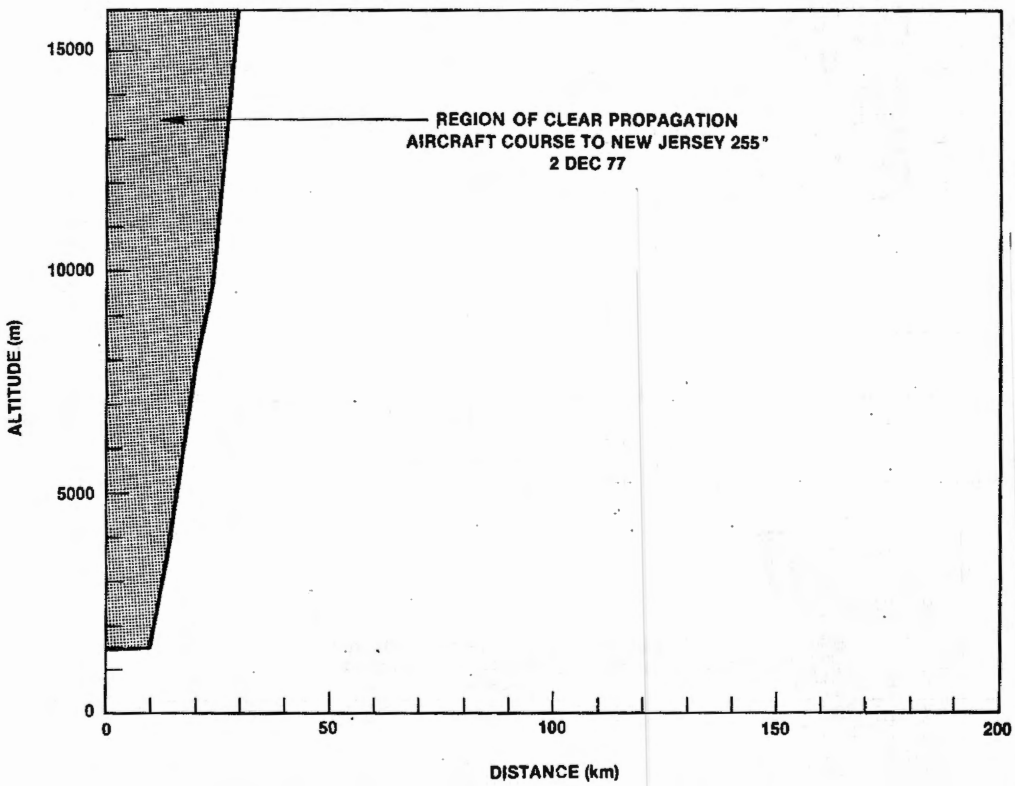


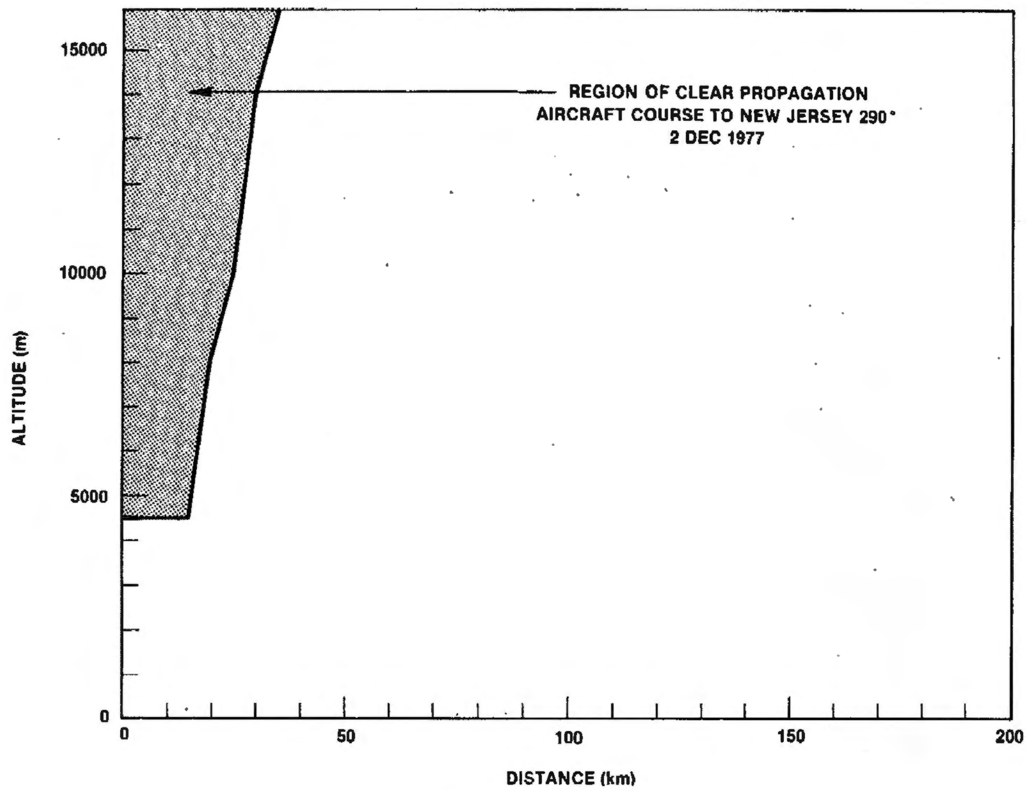
(d)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977

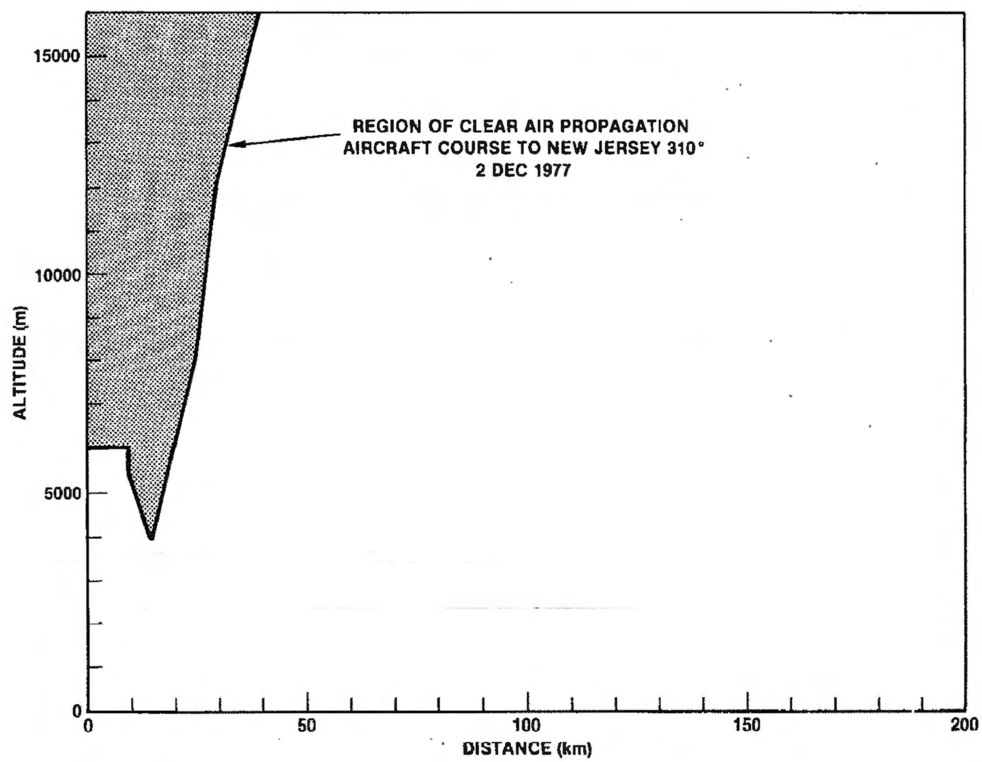


(e)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977

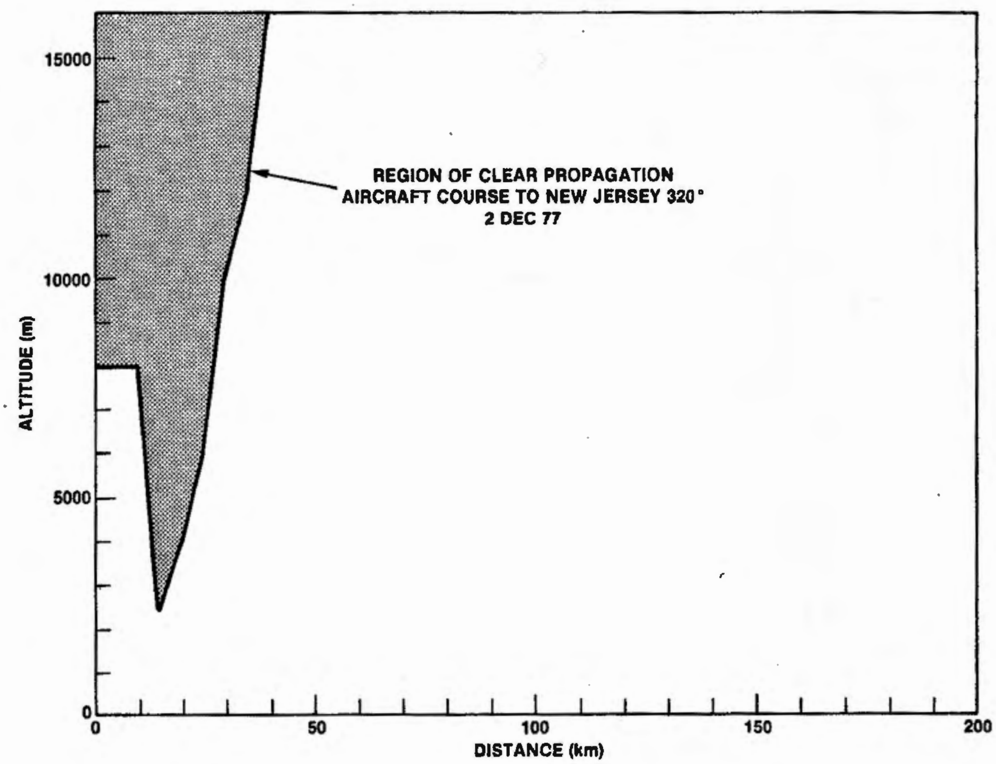


(f)

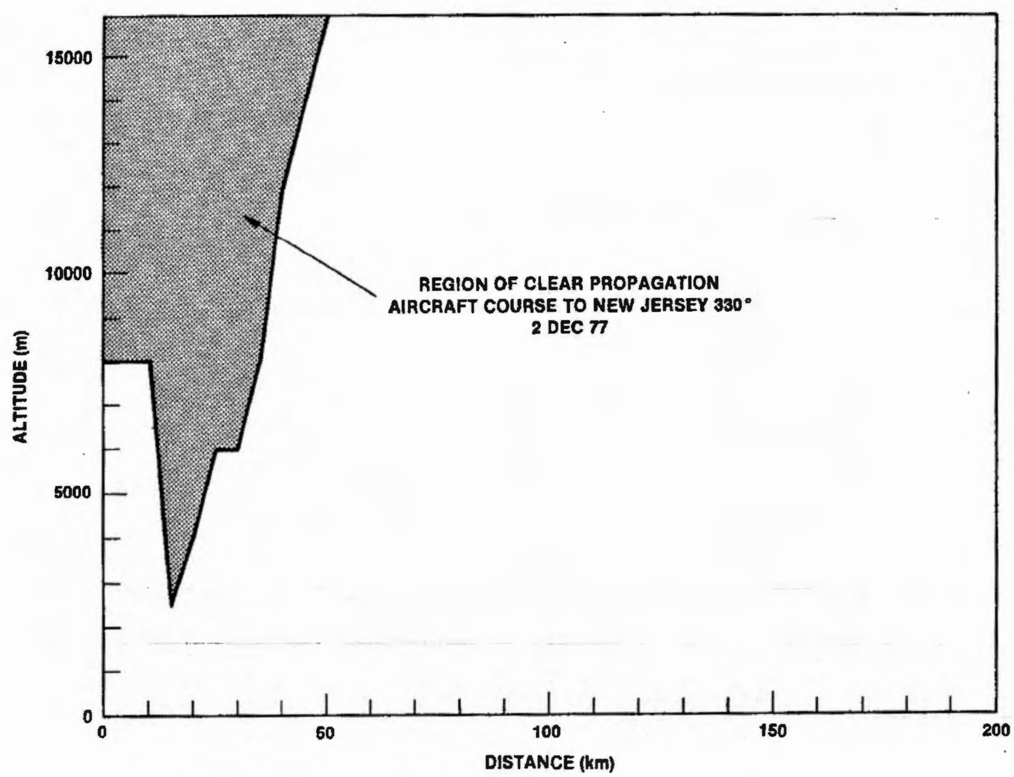


(g)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977

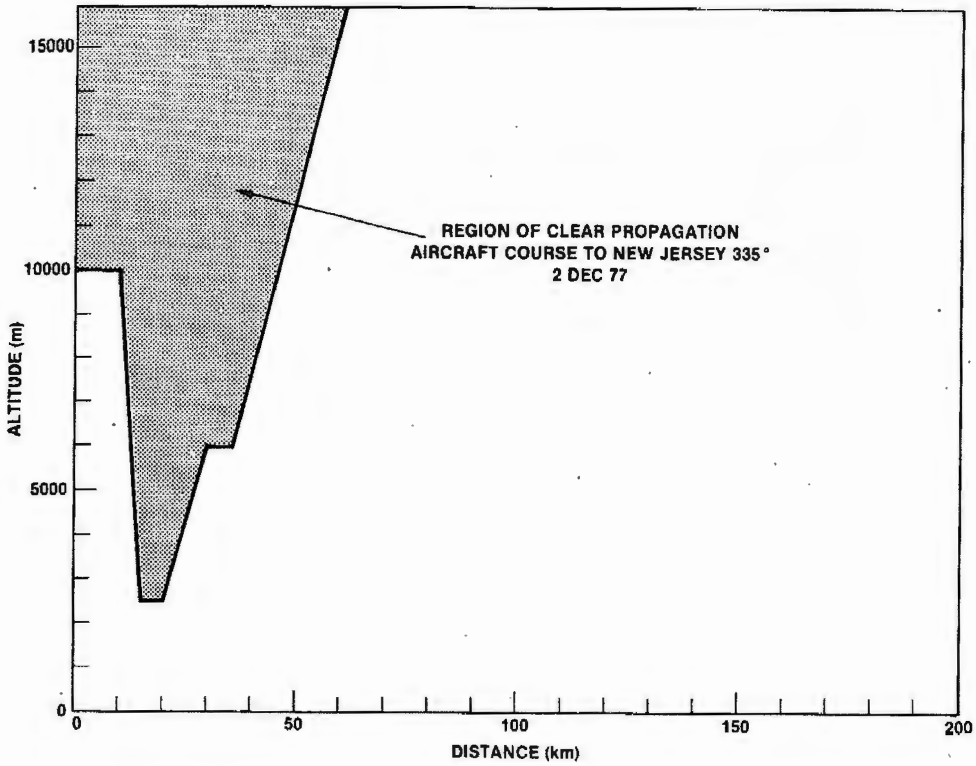


(h)



(i)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977



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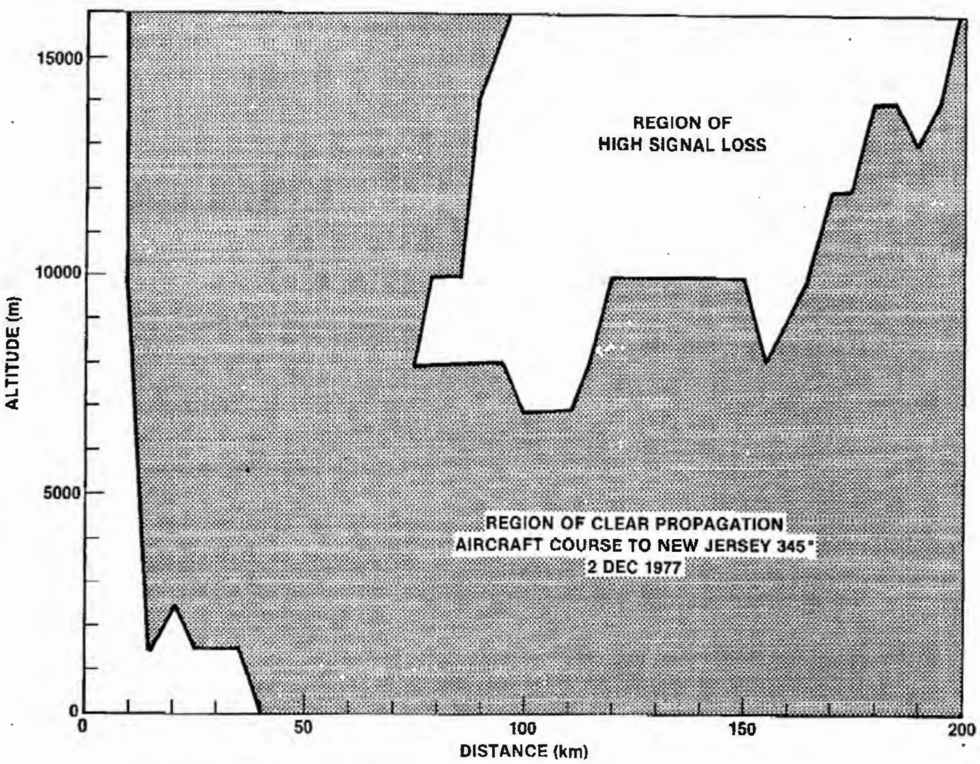
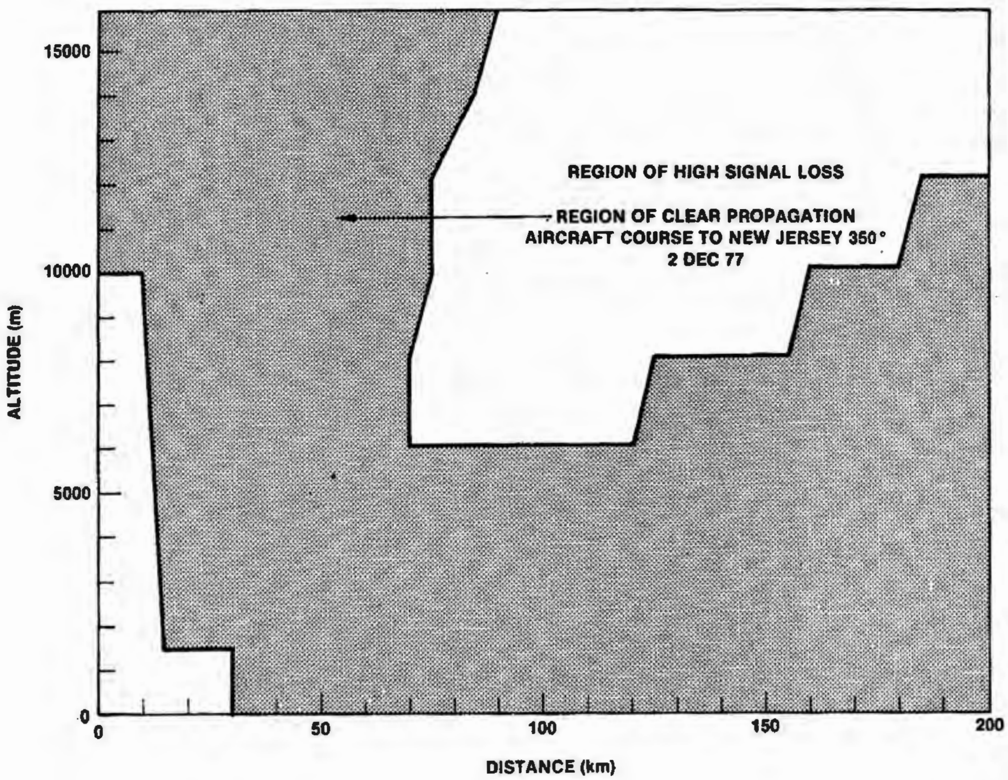
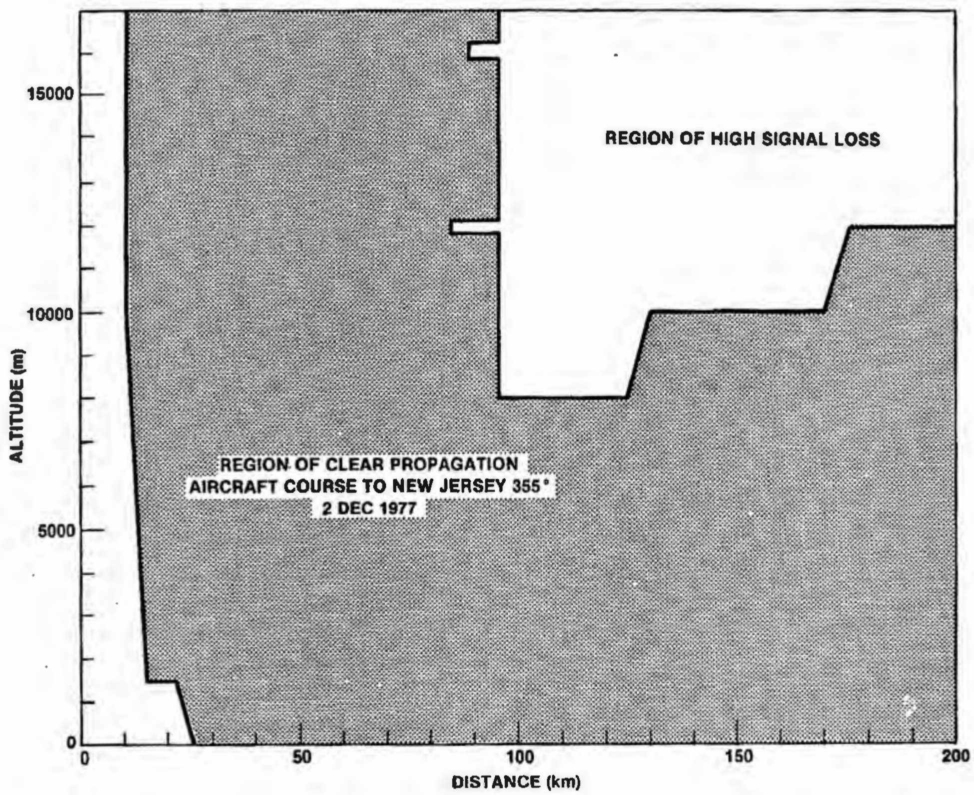


(k)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977

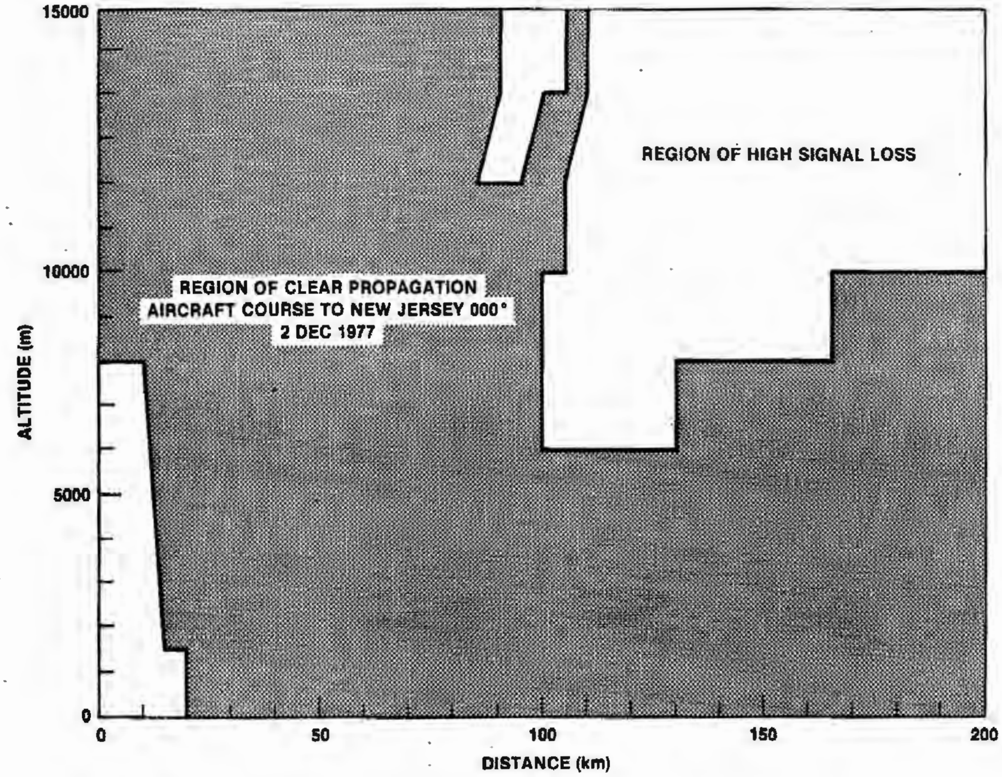


(l)

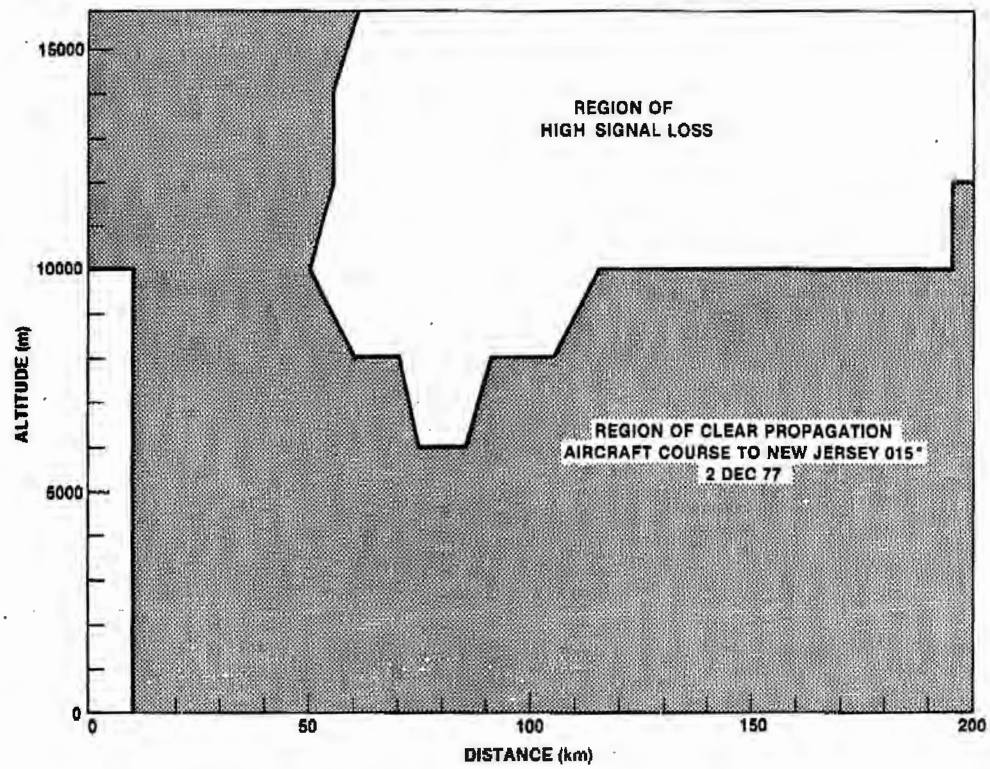


(m)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977



(n)



(o)

Figure 8 (Continued) — Profiles of clear propagation 2 December 1977

Determination of the Position of an Acoustic Source from Signal Arrival Times at Several Receiving Stations

To reduce the number of ray tracings required, initial approximate localizations were made using the signal arrival times at several stations. A discussion of this method follows.

We wish to estimate the position of an acoustic source, given that we know the time of arrival of a signal from the source at a number of receiving stations whose positions are known. We make several assumptions in the absence of better information and in order to simplify the problem:

1. The source and receivers are at sea level.

2. The speed of sound is constant, so there is no ray bending.

3. The earth is spherical. (The errors caused by this assumption are small if the path lengths are relatively short.)

If n stations received the signal, then there are $N = n(n-1)/2$ pairs of stations which received the signal. We denote the stations of each pair as (ϕ_{i1},λ_{i1}), (ϕ_{i2},λ_{i2}) for $i = 1, N$ where ϕ_{ij} is the co-latitude (i.e. $\pi/2$ - latitude of station j of pair i), and λ_{ij} is the longitude of that station. The stations are ordered so that $(\phi_{i1}, \lambda_{i1})$ is closer to the source than $(\phi_{i2}, \lambda_{i2})$. That is, the arrival time at the first station is earlier than the arrival time at the second station. Now for each pair of stations we can calculate the difference in time of arrival: $T_i = t_{i2} - t_{i1}$ where t_{ij} is the time of arrival at station j of pair i. The locus of possible positions of the source, given only the information available from a single pair of receivers, is then given by the equation $D_{i2}(\phi, \lambda) - D_{i1}(\phi, \lambda) = VT_i$ where ϕ is the co-latitude and λ is the longitude of a possible position, $D_{ij}(\phi, \lambda)$ is the distance from (ϕ, λ) to station j of pair i, and V is the speed of sound. This describes a hyperbola with foci at the stations. Since we know that the source is closer to station 1 of a pair, we know that the source is on the branch of the hyperbola around station 1.

We now proceed to perform a graphical solution to the problem by drawing the hyperbola for each station pair and then estimating by eye where the hyperbolas intersect. The hyperbolas are drawn using the following method. Let R be the distance in radians between the two stations and χ be the bearing of station 2 from station 1. Let D_1 and D_2 be the distances in radians for (ϕ, λ) on the hyperbola to stations 1 and 2 respectively. Let θ be the angle such that $\theta + \chi$ is the bearing of (ϕ, λ) from station 1. Then by the law of cosines for spherical triangles $\cos D_2 = \cos R \cos D_1 + \sin R \sin D_1 \cos\theta$. Since, (ϕ, λ) is on the hyperbola,

$$D_2 - D_1 = D \text{ or } D_2 = D_1 + D,$$

where $D = VT/(\text{earth radius})$, so that

$$\cos D_2 = \cos(D_1 + D) = \cos D_1 \cos D - \sin D_1 \sin D$$
$$= \cos R \cos D_1 + \sin R \sin D_1 \cos\theta.$$

Dividing by $\cos D_1$ and collecting terms in D_1 we get

$$Tan D_1 = \frac{\cos D - \cos R}{\sin D + \sin R \cos\theta}.$$

Again, using spherical trigonometry we get

$$\cos\phi = \cos\phi_1 \cos D_1 + \sin\phi_1 \sin D_1 \cos\theta + \chi$$

$$\sin(\lambda - \lambda_1) = \sin D_1 \sin(\theta + \chi)/\sin\phi.$$

We draw the hyperbola by letting θ range from -170 degrees solving for χ and λ, and plotting the result.

There are two points about this process which are worth further consideration. First, it has been tacitly assumed that $D_1 \geqslant 0$, $D_2 \geqslant 0$, and $D \leqslant R$. However, notice that if $D > R$ then $\operatorname{Tan} D_1 < 0$ and therefore $D_1 < 0$. Then the equation $D_2 - D_1 = D$ becomes the equation for an ellipse. It has in fact been found that some of the curves plotted are ellipses. This indicates that the data used in plotting those curves are invalid. Either the arrival times are incorrect or the assumed sound speed is incorrect.

The second point for consideration is the redundancy involved in the above process. Note that for any three stations there are three pairs of stations: $((\phi_{11}, \lambda_{11}), (\phi_{12}, \lambda_{12}))$, $((\phi_{21}, \lambda_{21}), (\phi_{22}, \lambda_{22}))$, $((\phi_{31}, \lambda_{31}), (\phi_{32}, \lambda_{32}))$. But if $(\phi_{11}, \lambda_{11})$ is the closest station and $(\phi_{32}, \lambda_{32})$ is the farthest station, then $(\phi_{31}, \lambda_{31}) = (\phi_{11}, \lambda_{11})$, $(\phi_{12}, \lambda_{12}) = (\phi_{21}, \lambda_{21})$ and $(\phi_{22}, \lambda_{22}) = (\phi_{32}, \lambda_{32})$, so

$$
\begin{aligned}
D_{32}(\phi,\lambda) - D_{31}(\phi,\lambda) &= D_{22}(\phi,\lambda) - D_{11}(\phi,\lambda) \\
&= D_{22}(\phi,\lambda) - D_{12}(\phi,\lambda) + D_{12}(\phi,\lambda) - D_{11}(\phi,\lambda) \\
&= (D_{22}(\phi,\lambda) - D_{21}(\phi,\lambda)) + (D_{12}(\phi,\lambda) - D_{11}(\phi,\lambda)) \\
&= vT_2 + vT_1 \\
&= T_2 + T_1 \\
&= v(t_{12} - t_{11} + t_{22} - t_{21}) \\
&\quad v(t_{32} - t_{31}) \\
&= vT_3.
\end{aligned}
$$

That is the equation for $i = 3$ is the sum of the equations for $i = 1,2$ and therefore adds no information. This explains why the charts drawn show a number of points where three lines cross at a single point. The fact that three lines cross there means no more than if two lines cross.

Chart plotting is done by two programs. The first program, called ACE, calculates the various hyperbolae for an event. The input is a disk file containing station identifiers and times of arrival. It produces a disk file for each pair of stations which contains the station identifiers and positions on the hyperbola. The second program, called PLHYP, reads files produced by ACE and plots them on a Mercator chart.

It is worth mentioning that if we have two equations of the form $D_{i2}(\phi,\lambda) - D_{i1}(\phi,\lambda) = vTi$ then we can, in principle, solve for (ϕ, λ) if v is given. That is we can perform an analytic solution. Similarly, if we have three such equations we can solve for ϕ, λ and v, and if we have more than three equations, we can find ϕ, λ, v such that $\Sigma\, (D_{12}(\phi,\lambda) - D_{i1}(\phi,\lambda) - vT_i)^2$ is minimal.

Discussion

The results of the preliminary analyses can be summarized as follows. Time correlation of citizens' observations in New Jersey and Charleston show that after the initial startling coincidence of reports from both areas at 1500 Z (1000 EST) on 2 December 1977, the time correlation between areas is relatively low. Any correlation which does exist can be attributed to the fact that the pattern of events at each station shows typical manmade distributions of events as a function of time. The events in each location begin at the start of the normal work day, build a second peak in midafternoon, and slacken again at the end of the normal work day. A third smaller peak appears in the early night. The events are largely confined to normal work days with almost no activity on Sundays and holidays. A good time correlation was found between citizens' observations in New Jersey and signals measured by the Lamont-Doherty and Weston observations. Of a total of 183 signals detected by Weston from 28 November 1977 to 16 January 1978 about 85% gave initial localizations in or near warning area W-107 off the coast of New Jersey. While localization could not be made from the Lamont-Doherty data, the apparent directions of arrival of the signals varied by less than 10° and were in agreement with the Weston data. The Baptist College detections agreed with the times of significant citizens' report in the Charleston area and gave directions of signal arrival consistent with the location of military operating areas off the coast near Charleston. All observations are consistent with the conclusion that the events detected both in New Jersey and Charleston were infrasonic when they reached land.

INVESTIGATIONS

Historical Record of Unexplained Noises

There is a sizable body of information in nineteenth-century periodicals concerning unexplained detonations. Most reports are of "ear witness" observations and also contain summaries of other observations and traditions reaching back hundreds of years. The phenomenon most described are the "Barisal Guns." The "Barisal Guns" were heard in the delta of the Ganges and described as "dull sounds, or more or less resembling distant artillery" or "like the firing of big guns heard from a distance ... the report is always double." Boatmen offshore report "these guns are always heard in triplets." An observer on a steamer moored in the channel reported, "Sometimes a single report, at others two, three or more in succession, ... Sometimes the reports would resemble cannon." Another reporter at work outside his tent described sounds as "the distant report of a heavy gun." A surveyor working in the field reported "a heavy gun ... clear and distinct, yet a long way off, followed closely and at irregular intervals by two other discharges." In another report an observer walking on the river bank heard "the booming distinctly, about as loud as heavy cannon would sound on a quiet day about ten miles off. Shortly after ... a heavy boom much nearer. Suddenly ... two quick successive reports more like horse-pistol or musket." The Asiatic Society of Bengal published a summary in 1889 of a committee investigation of these sounds. The summary stated,

"the sounds seemed always to come from the south or southeast.

they were sometimes single and sometimes double, like two cannons fired immediately after each other.

they came sometimes singly at short intervals and sometimes as many as five or six in quick succession, with only a second or two between while at other times a single sound was heard not followed by another at all that day, or not till after a long time.

the sounds were heard indistinctly except in somewhat still weather, hence, they were heard more clearly and distinctly at night than by day.

the sounds when loud and distinct could not be mistaken for any other sound but when indistinct they might not be distinguishable from the sounds of bombs.

the distinctive characteristic of the sounds was the resounding hollowness of them, resembling the sound of a heavy substance falling onto a wooden floor in a large vaulted building, heard from a considerable distance."

Barisal Guns are often related to "Seneca Guns" sounds heard around Lake Seneca in New York. These are described as a "dull boom," or on a clear, still midnight as "dull, far-away, muffled, repeated booming for a few seconds." Another report states the sound an "uncanny mysterious sound, like the report of a far-away cannon." A 1940 report in the *Geneva Gazette* stated, "The sound is usually heard on hot sultry days, though one has heard the ice crack .... More often than not they are heard on afternoons by the lake or on it, when the wind was dying down or had ceased to blow and the surface of the water had become glassy or 'oily'."

An apparently similar phenomenon was reported in the vicinity of Lough Neagh, Ireland. An observer standing in a meadow by the lake described a rumbling noise. He stated "The day was very fine and warm and dead calm .... The noise was like a short distant peal of thunder." Persons sailing on the lake described sounds generally heard in fine weather. Other observers described the sounds as "cannonlike." The sounds have been heard in the winter when the whole of the lake was frozen over and the air was still. Skaters heard the "guns" booming every five or six minutes.

A report of similar sounds was made by a party making an overland trip in the Black Hills in 1810. The statement is "in the most calm and serene weather, and at all times of the day or night, successive reports are now and then heard among these mountains, resembling the discharge of several pieces of artillery." Similar reports were heard by Lewis and Clark in the Rocky Mountains, according to their journal. The sounds were described as like a 6-pounder gun at three miles.

To the extent that detailed descriptions of this class of events are provided, two significant points appear again and again in the narrative. The first point is that calm, still air conditions are associated with these historical sounds. This is contrasted for instance with the weather in New Jersey in December 1977-January 1978 where surface winds typically were 15 mph. The second point is that a majority of the historial observers were outdoors, removed from structures. This is the inverse of the typical observer's location reported during December 1977-January 1978. No detailed description of the December-January events places the observer outdoors, and there are a significant number of cases where persons out of doors did not hear the events heard intensely by persons indoors nearby. The inference is that the December-January events were infrasound (<5 Hz as confirmed by microbarograph measurements), whereas the historical sounds were in the audible region (>20 Hz). Any conclusion that the December-January events are the same kinds of sounds as those reported as "Barisal Guns" or "Seneca Guns" does not appear to be justified by available evidence.

References

Chatham, George N., *East Coast Aerial Explosion, December 30, 1977 Report*, Library of Congress Report, 3 January 1978.

Businger, J.A., *Rabelais' Frozen Words and Other Unidentified Sounds of the Air,* Weather **23** (1968).
Corliss, W. R., *Strange Phenomena* Vol. G-1 (Glen Arm, Maryland: William R. Corliss 1975).

Explosions

Nuclear Detonations

Monitoring Agencies

An NRL investigator met on 31 January 1978 with the Technical Director of the agency responsible for long-range detection of nuclear events. The following facts were provided. No hydroacoustic signals were seen from the area in question, no radioactive debris was identified as coming from this area, no seismic signals from the area were detected and no detections were made from space platforms. As will be discussed below, the frequency of the signals observed at both the Lamont and Weston observatories was at least two orders of magnitude higher than the frequencies which might be expected as a result of the detonation of even a small nuclear device. Based on all evidence, there is no reason to believe that any of the events reported along the east coast of the United States were nuclear explosions.

DNA

Mr. P. Haas, the Deputy Director for Science & Technology of the Defense Nuclear Agency, told NRL investigators that neither the Defense Nuclear Agency nor the Department of Energy carried out any nuclear or high-explosive tests off the east coast of the U.S. during the three-month period beginning 1 December 1977.

The Physics of High Explosive Effects

Introduction

At moderate to large distances from a point explosion, the acoustic parameters are determined by the geometry and by the energy of the explosion, usually expressed as an equivalent weight of TNT. The two most readily accessible parameters are the peak overpressure and dominant frequency of the received signal. Given that, Professor W. Donn of Lamont measured a peak-to-peak pressure of 5 Pa, at an estimated distance of 170 km from the hypothesized explosion, and that the dominant frequencies as observed on the Weston arrays were 2 to 3 Hz we seek to determine what equivalent weight of an isotropic detonation of TNT could account for his observations. Of the two parameters, the dominant frequency turns out to be the more useful because the pressure observed at a sensor depends on the details of the propagation path. The frequency of an infrasonic signal is modified by atmospheric absorption. High-frequency components of an acoustic signal are absorbed more readily than the low-frequency components. If the source receiver distance can be determined, one can correct for the effect of differential atmospheric absorption. In any case all propagation effects cause the dominant frequency detected at a remote receiver to decrease. The dominant frequency observed at a receiver must be lower than the frequency in the vicinity of the explosion. This fact enables one to determine an absolute upper bound on the yield. One can thus show that if the event of 2 December were due to an isotropic chemical detonation, the source would equate to approximately 1 ton of TNT. The observed pressures are consistent with these values.

Frequency Considerations

According to the principle of similarity, explosions in air are characterized by times that scale according to the relationship

$$\frac{t_1}{t_2} = \left[\frac{W_1 p_2}{W_2 p_1}\right]^{1/3} \frac{c_2}{c_1} \tag{1}$$

where W is the weight of an equivalent charge of TNT, p is the ambient pressure, and c is the sound speed. Thus the dominant frequency of an explosion must be given by

$$f_d = \frac{K}{c}\left(\frac{P}{W}\right)^{1/3} \tag{2}$$

Since c is a weak function of altitude relative to $p^{1/3}$, the highest possible frequency for a given charge weight will be obtained near sea level. (This neglects ground proximity effects, which will be discussed later on.) Thus for the purpose of finding an upper bound for W we can consider $p = p_0 = 100$ kPa and $c = c_0 = 337$ m/sec. Thus

$$f_d = \frac{K'}{(W)^{1/3}}. \tag{3}$$

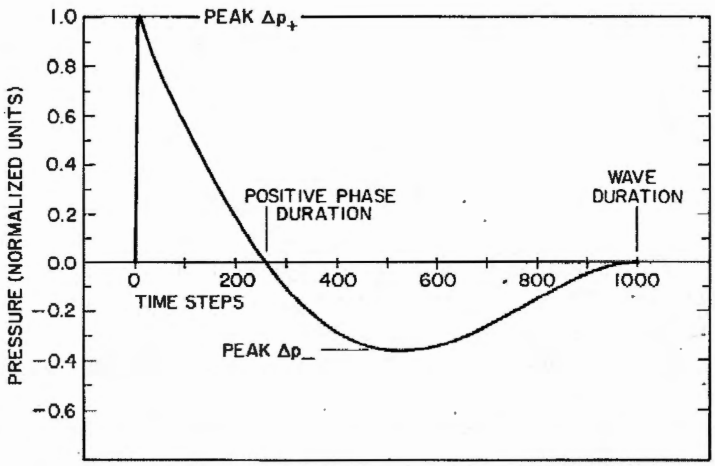


Figure 9 — Pressure-time signature of explosion

The waveform for an explosive signal is shown in Figure 9. The peak positive overpressure is Δp, the time duration of the positive phase is t_+, and the total time duration is τ. (Note, t_+ and τ scale as in equation (1) or for our purposes like $1/f_{dom}$ in equation (3).) Reed has shown that such a waveform is well approximated by

$$p(t) = \Delta p\left(1 - \frac{t}{t_+}\right)\left(1 - \frac{t}{t_+}\right)\left(1 - \frac{t^2}{\tau^2}\right) \tag{4}$$

The curve is normalized using the well-known parameters for a 1-kt nuclear explosion (actually the equivalent of 10^6 lb TNT, since half the energy from a nuclear explosion is dissipated in radiation). At 2.7 km from such an explosion $\Delta p = 3.4$ kPa, $t_+ = 0.375$ sec, and $\tau = 1.375$ sec. The Fourier transform of equation (4) has been evaluated. Using this evaluation and the

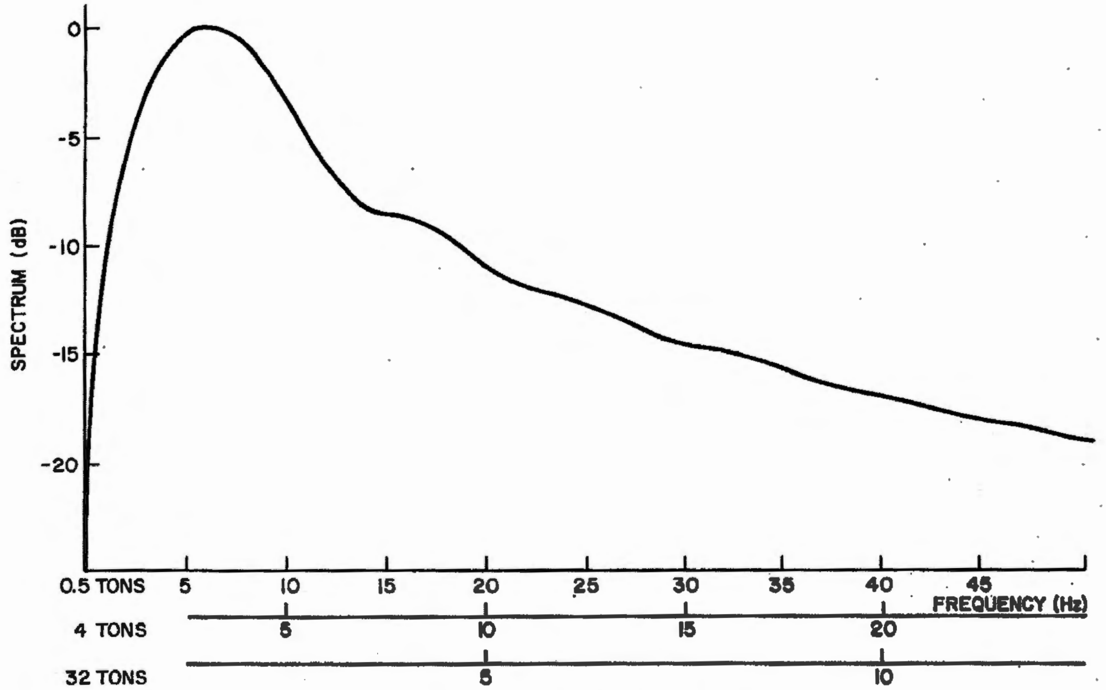


Figure 10 — Spectrum for various change weights

scaling law of equation (3), we obtain the spectrum shown in Figure 10 for charge weights of 0.5, 4, and 32 tons of TNT. The dominant frequency is given by

$$f_{dom} = \frac{25}{4} \left(\frac{1}{2W}\right)^{1/3} \tag{5}$$

where W is the charge weight in tons of TNT. Equation (5) is plotted in Figure 11. It is evident from Figure 11 that 3 Hz corresponds to a charge weight of 5 tons of TNT.

Because of atmospheric absorption effects the equivalent charge size must have been significantly less than 5 tons of TNT.

Atmospheric attenuation is proportional to $f^{1.25}$ at low altitudes and f^2 at very high altitudes. This will tend to decrease the frequency observed at long ranges. As a result of a complex ray tracing computation the 2 December events were determined to have taken place at a distance 170 km from Lamont. At 3 Hz the sea level attenuation is about 5×10^{-7} dB/km while at 5 Hz the attenuation is 7.5×10^{-3} dB/km at a distance of 170 km the loss at 5 Hz is 1.275 dB, which the loss at 3 Hz is only 0.85 dB. Since most of the propagation path was at altitude vice sea level, the differential absorption was probably significantly greater than that computed here. Making reasonable estimates of this effect, it is probable that at the source of the explosion the dominant frequency was 5 Hz vice 3 Hz. Using Figure 11 it would appear to be likely that the equivalent size of isotropic explosion was probably 1 ton of TNT or less. There are additional reasons to believe that even this figure is a serious overestimation of the size of the initial energy release.

Nonlinear propagation effects tend to stretch the pulse. This effect generally is proportional to $[\log(s)]^{1/2}$ where s is the path length of the energy from source to receiver. This will also cause an apparent lower frequency at long ranges.

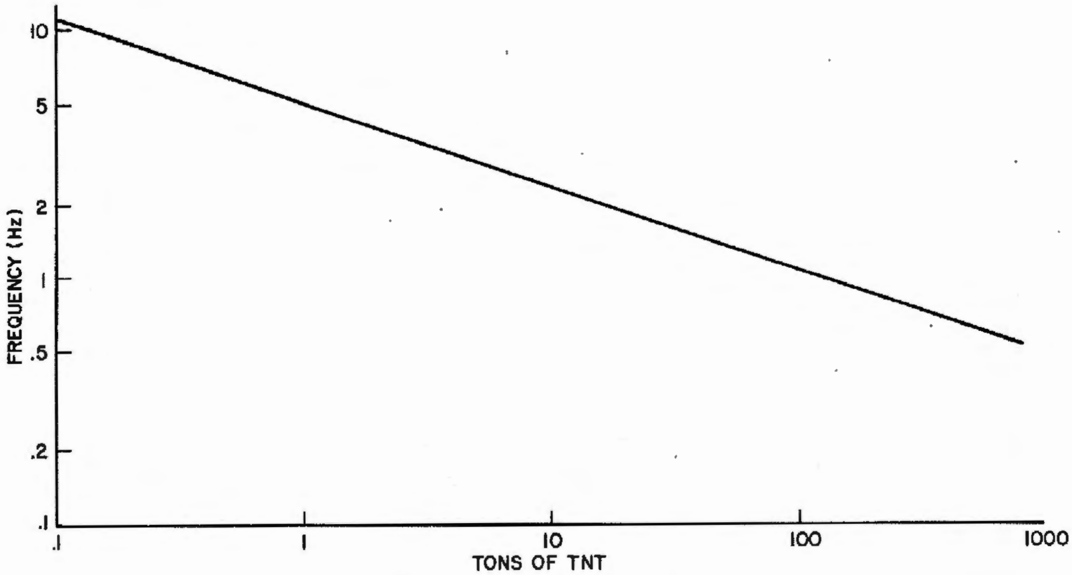


Figure 11 — Frequency vs yield

Amplitude Considerations

Ray tracing computations indicate that strong winds on 2 December led to strong ducting conditions. Losses over a 170 km path of only 88 dB were predicted. This would correspond to a falloff of amplitude with range according to $R^{-1.20}$. This agrees with empirical scaling laws for air explosives which predict that

$$\Delta p = 538 \ (2W)^{0.4} R^{-1.2} \tag{6}$$

for the overpressure in Pa, when W is the charge weight in tons and R is the slant range in kilometers for a free-air burst. Since Prof. Donn's measurements were made at ground level, the surface reflection doubles the observed pressure, so

$$\Delta p^* = 1076 \, (2W)^{0.4} R^{-1.2}. \tag{7}$$

The peak-to-peak value will be from 1.35 to 2 times this value. Hence we may take

$$(\Delta p^*)_{ptp} = 1452 \ (2W)^{0.4} R^{-1.2}. \tag{8}$$

For 1 ton at a range of 170 km, this comes out to $(\Delta p^*)_{ptp} = 4$ Pa, which is about what Donn measured. For comparison, Figure 12 shows measurements made by Reed at several long-range distances from a 1-ton (2-ton "effective") charge of TNT. Donn's measurement is shown on the same scale (to convert to 1 ton, lower all of Reed's data by a factor of $(1/2)^{1/3} = 0.8$).

Thus from amplitude considerations we also find that Donn's measurements are consistent with an equivalent source charge weight of about 1 ton of TNT. An independent calculation made by Dr. Swisdak of NSWC indicates that Donn's measurements, both amplitude and frequency, are consistent with an explosion of from 0.5 to 1 ton of TNT.

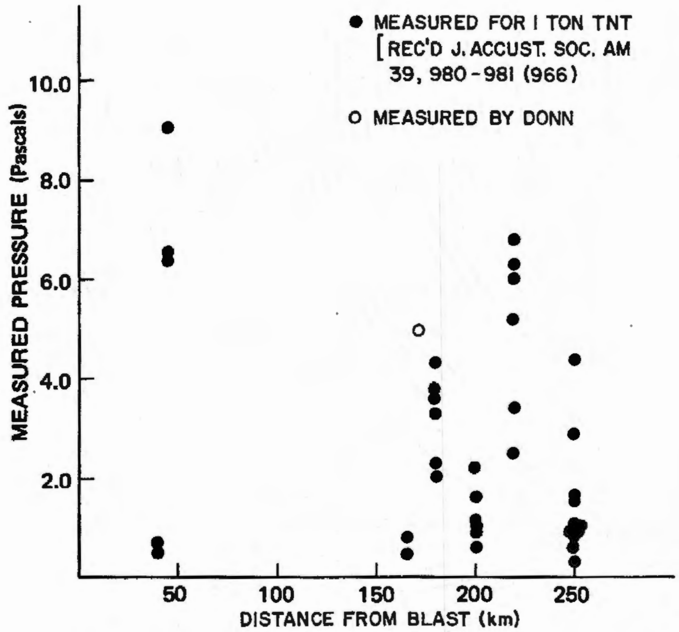


Figure 12 — Pressures measured for various distances

Coupling into the Water

Since an explosion is omnidirectional a certain fraction of the rays will fall within the critical angle for the air-water interface (13.4°) and will refract into the water as shown in Figure 13. Although most of the energy is reflected due to the large impedance mismatch at the air-water interface (71 dB), the *pressure* in the water is twice the pressure in the air. Thus, from equation (6) a 1-ton explosion at 5 km will generate a pressure in the water of 102 Pa with a roughly spherical wavefront. This would be equivalent to a source level of at least 160 dB re 1 μPa. This would be a fairly substantial underwater signal and would have been detected unambiguously by many existing underwater sensors. No such detections were reported. A sonic boom, on the other hand, which has its rays nearly parallel to the surface, is always totally reflected, producing only short-range inhomogeneous waves in the water.

Review of Evidence from Large Atmospheric Explosions

The Defense Nuclear Agency in the past has carried out tests involving up to 500 tons of TNT as a simulation of nuclear explosions. These tests have mainly been near Suffield, Canada, and in Hawaii. A comparison of the frequency content of these large explosions with that of the U.S. east coast acoustic events reveals major differences.

A total of five high-yield ($\geqslant$100 ton), high-explosive bursts are known to have been instrumented with microbarograph experiments at ranges greater than 25 km from ground zero. Two of these were 500-ton events: Prairie Flat (August 9, 1968 at the Defense Research Establishment, Suffield, in Alberta, Canada) and Mixed Company III (November 13, 1972 at Grand Junction, Colorado). Both events were part of the Middle North Series, which also included another 500-ton burst, apparently uninstrumented with microbarographs, known as Event Dial Pack. The three other bursts of interest are 100-ton events and were the second,

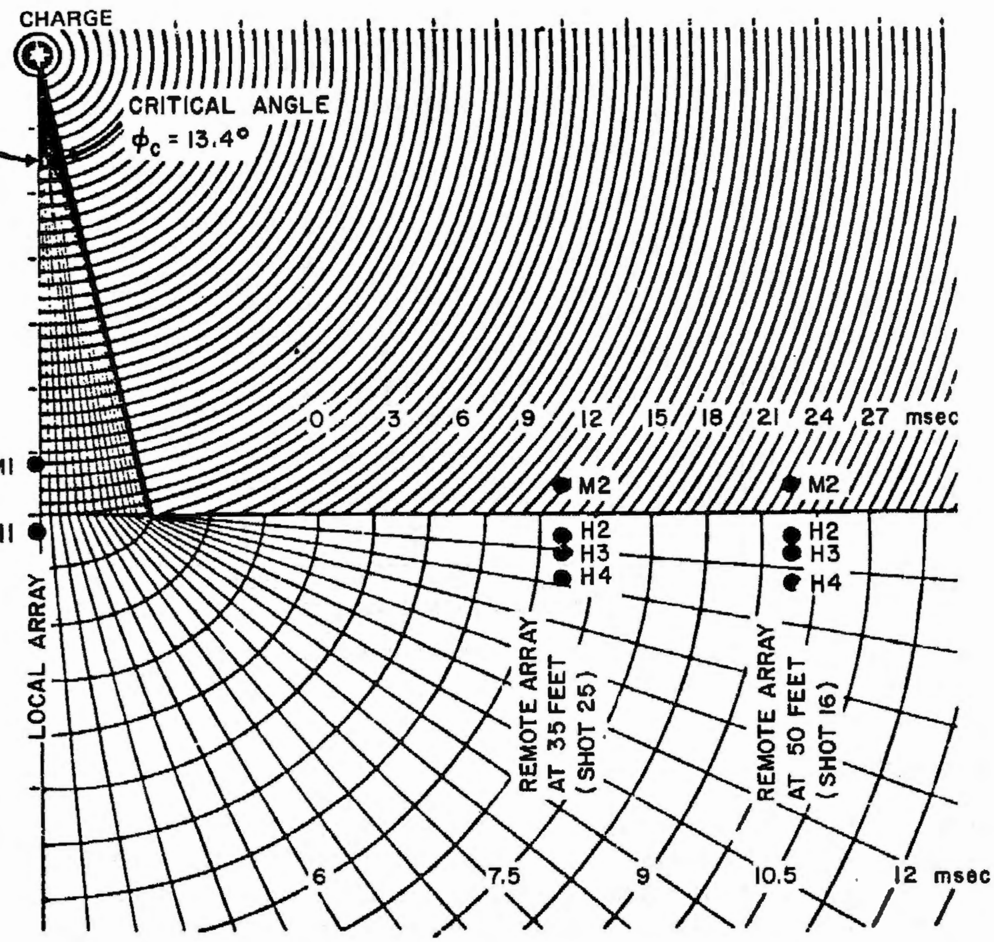


Figure 13 — Locations of sensor for measurements of penetration of sound wave energy into water (from Waters and Glass).

third, and fourth events of Project Middle Gust conducted in 1971/1972 near Ordway, Colorado. Table 3 shows the events to be discussed, together with the distance of the microbarographs from the burst point and peak overpressures. The Prairie Flat event is of special interest since the experimenters were intentionally looking for the ducting and focussing phenomenon to be mentioned below.

Reed [4] gives the following "quasi-acoustic, empirically valid propagation equation" for the far field peak overpressure Δp of a chemical high-explosive surface burst as a function of the distance R from ground zero:

$$\Delta p = 149.3\ W^{0.4}\ R^{-1.2} \left(\frac{P}{1000} \right)^{0.6} ; \quad \Delta p \leqslant 2.55 \times 10^{3}\ \mathrm{Pa}$$

where

Δp = peak overpressure

W = burst yield (kilotons)

Table 3
Overpressures for Large HE Explosions

Event	Yield (tons)	Reference	R (km)	Peak Overpressure 10^2 Pa
Prairie Flat	500	1	192-227	0.15-0.75
Prairie Flat	500	1	644	0.012-0.018
Middle Gust	100	2	7.56-111.9	0.1-0.2 at 11.9 km
Mixed Company	500	3	2.78-26.6	0.87 at 26.6 km
Mixed Company	500	4	4.43-76.75	0.718 at 76.75 km

1 bar $= 10^5$ Pa

1 mb $= 10^2$ Pa

R = distance from ground zero (km)

p = ambient pressure 10^2Pa (mb).

Using the ambient pressure at the Mixed Company III test site (795 mb) and standardizing to a 500-ton event, we get:

$$\Delta_p^{500} = 98.7\ R^{-1.2}.$$

For 100-ton events we should get $(0.2)^{0.4}$ times the above:

$$\Delta_p^{100} = 51.8\ R^{-1.2}.$$

For the large distances R under discussion here, ducting, caused by atmospheric refraction, will cause waves to return to ground level at significant incidence angles, and the measured pressures will be nearly doubled by acoustic reflection. (It should also be noted that an air burst will reduce the measured pressures by approximately 25%.)

Bearing in mind that we are after only a reference pressure for each yield and range, we can create the following reference table of expected overpressure measurements for the ground bursts under consideration.

Range km	Peak Overpressure 10^2 Pa (doubled by reflection)	
	500 tons	100 tons
25	4.15	2.18
75	1.11	0.582
100	0.786	0.412
200	0.342	0.180
644	0.0841	0.0441

Ducting

Ducting effects are seen graphically in the Prairie Flat tests where 3 or 4 distinct arrivals are noted 200 km from ground zero with peak overpressures ranging from 0.15 to 0.74 mb. Compared to our reference value of 0.35 mb, it is seen that it is impossible to realize intensification of more than a factor of two. The Prairie Flat results also show a wavelike variation of peak overpressure with distance similar in appearance to interference fringes.

It should be noted that all of the bursts under consideration here took place in inhabited, even if sparsely so, environments. Because of this, the experimenters were constrained to fire only when the atmospheric temperature and wind profiles were such as to *minimize* ducting, at least over populated areas. It is therefore probable that the results are *not* typical of a random burst, at least with regard to the ducting phenomenon. In spite of the precautions, however, damage claims, for broken windows and even cracked foundations, from residents tens of kilometers away were commonplace.

Prairie Flat Results

The Prairie Flat results [1] are unique from two standpoints: 1) the experimenters computed ahead of time where focussing should occur and an array of 18 microbarographs was set up in this region to look at the interference ring structure; and 2) infrasonic acoustic wave detection apparatus was set up 644 km from ground zero, capable of picking up acoustic waves in the frequency range 0.017 to 2.2 Hz. Measured peak amplitudes range from 15 mb to 75 mb. The experimenters identified four distinct arrivals. The time between arrivals ranged from 1.5 to 3 sec, with significant Fourier components within each wave packet in the 1-2 Hz range, with some energy in the 4-Hz range.

The infrasonic acoustic wave results at $R = 644$ km showed peak amplitudes around 1.2 to 1.8 mb, Calculations done by the experimenters beforehand, which included ducting effects, predicted 13 mb, so the experimental measurements are about an order of magnitude lower than predicted. Calibration of the detectors is in doubt however. Most of the energy resides in frequencies 0.25 Hz or lower at this distance, and that the disturbance lasts for more than 6 minutes.

Mixed Company Results

The only measurement of possible interest for our purposes is that from Delta MB Station, 76.75 km from ground zero [4]. At least two distinct arrivals were seen, with peak overpressures of 37.1 mb and 71.7 mb respectively. Peak energies are in the 2-Hz range, with components as high as 10 Hz.

Middle Gust Results

Again we have only one measurement station [2] in our range of interest, the Limon MB Station, 11.9 km from ground zero. Again we note multiple arrivals and energies in the 2-4 Hz range.

Conclusion

If the events of 2 December 1977 in New Jersey were due to a chemical explosion in the air, the energy release was the equivalent of approximately 1 ton of TNT. The failure of underwater hydroacoustic sensors to detect the acoustic events militates against an interpretation of these events as being caused by explosions vice a sonic boom.

REFERENCES

1. Reed, Jack W., Operation Prairie Flat, Airblast Project LN-106, Microsbarograph Measurements, Final Report: "Distribution of Airblast Amplitudes in the Ozonosphere Sound Rings." Sardin Laboratory Report SC-M-69-33, February 1969.
2. Reed, Jack W. Blast Predictions and Microbarograph Measurements. Project Middle Gust Final Report. Sandia Laboratories Report SLA-73-0484, August 1973.
3. Vortman, L. J. Middle North Series Mixed Company III Event. Project Officers Report — Project LNID5. Intermediate Range Airblast. Sandia Laboratories Report POR-6750, October 1973.
4. Reed, Jack W. Blast Predictions and Microbarograph Measurements, Project LN-106 Project Mixed Company Final Report, Sandia Laboratories Report POR-6603, October 1973.

Military R&D Operations

Army R&D

The possibility that Army R&D activities, especially in the field of fuel-air explosives, could be the cause of the acoustic events was checked through LTC Connell of the Office of the Deputy Chief of Staff for Research, Development and Acquisition, and Mr. Spates, Assistant Director for laboratory activities. Col. Cook of ARADCOM Armament Concepts Office, Picatinny Arsenal, was also contacted. All replies were negative.

Navy R&D

The NRL Director of Research was able, by direct contact with the Assistant Secretary of the Navy for RE&S and with all Navy Laboratory Technical Directors, to determine that Navy R&D activities (other than aircraft) were not the source of the events. The only significant explosive work during this period was seven detonations of 600 kg of PBX off the west coast of Florida during January and February.

Air Force R&D

Mr. C. Porter was Air Force point of contact in the Office of the Deputy Chief of Staff for Research and Development. He had already begun investigation of the events in December and could assure the study team that Air Force R&D activities were not the source of the events.

DARPA

LTC W. Whitaker, Special Military Assistant to the Director, Defense Advanced Research Projects Agency, ruled out DARPA activities as sources of the events.

DNA

Mr. P. Haas, Deputy Director for Science and Technology, DNA, stated that there were no DNA activities that could have caused the events.

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EOD

Discussions with Explosive Ordnance Disposal Detachments and the Joint EOD school revealed that typical EOD operations are usually less than 100 pounds per event, and that events of 1-ton of TNT equivalent were extremely unusual; further, repeated events of this size were unheard of along the east coast of the United States at this time.

Quarry Operations

In the state of New Jersey, the Department of Labor and Industry monitors the transportation and civilian use of high explosives. Mr. T.K. Shea, Chief Mine Safety Engineer, stated that no unusual shipments of high explosives had taken place in the State in the months immediately preceding December 1977. The only major user of explosives in the State are quarry operations. Mr. Shea provided summary sheets of quarry blasts for the months of November and December 1977 (Appendix 4). No correlation was found between quarry blasts and the events under investigation. The operator of the seismic system in Charleston stated that she was familiar with the signature of quarry operations and that quarry operations did not correlate with the acoustic events reported by citizens.

Geophysical Exploration

An NRL representative contacted the U.S. Geological Survey (USGS) and spoke to Dr. John Lees, Conservation Director, Eastern Division, and John Bailey of Dr. Lee's office. USGS issues geophysical survey permits to oil companies within the oil lease areas. Offshore Navigation, Inc., Hanahan, Louisiana was working in the Baltimore Canyon area in December and January 1978. Copies of the navigation charts and logs were requested from Offshore Navigation, Inc. A conversation with Mr. Kelly Robertson and Mr. Marchal ((504) 733-6790) revealed that three other exploration companies may have also been working off the east coast during December and January. The following companies confirmed that they were working off the east coast at that time:

ESSO Seismics, Inc.
3616 Richmond Ave.
Houston, TX (713) 783-8220

Decca Survey Systems
10401 Westoffice Drive
Houston, TX (713) 783-8220

Fairfield Aquatronics Division
3410 Mercer Street
Houston, TX (713) 627-1990

All three companies felt that it would be too expensive to go through all of their navigation logs and charts themselves and requested that NRL send personnel to Houston to work with the required data. They gave us full cooperation.

Because USGS issues exploration permits only to oil companies, and not to exploration companies, a request was sent to many of the exploration companies that are often contracted with by the oil companies to do the actual exploration work. The following companies were contacted by letter:

*Alcoa Marine Corporation
8235 Penn Randall Pl
Upper Marlboro, MD 20870

*Aquatic Exploration Company
4683 First National Bank Building
Dallas, TX 75202

*Decca Survey Systems, Inc.
Kingston Road
Leatherhead, Surrey
England

*Digicon Geophysical Corporation
3701 Kirby Drive
Houston, TX 77006

Dresser Olympic Operations
Dresser Tower
601 Jefferson St.
Houston, TX 77005

*ESSO Seismic, Inc.
3616 Richmond Avenue
P.O. Box 2180
Houston, TX 77001

Geophysical Service Inc.
P.O. Box 5261
Dallas, TX 75222

Gulf Research and
Development Company
P.O. Drawer 2038
Pittsburgh, PA 15230

Mobil Oil Corporation
150 East 42nd St.
New York, NY 10017

Odom Offshore Surveys, Inc.
8174 GSRI Rd.
P.O. Box 927
Baton Rouge, LA 70821

*Petty-Ray Geophysical, Inc.
6909 Southwest Freeway
P.O. Box 36306
Houston, TX 77036

*Seal Company
P.O. Box 1168
Galveston, TX 77550

*Seismic Explorations International S.A.
3616 West Alabama
P.O. Box 22328
Houston, TX 77027

Seismograph Service Ltd.
Box 1590
Tulsa, OK 74102

*Shell Oil Company
One Shell Plaza
P.O. Box 2463
Houston, TX 77001

*State Boat Corporation
3701 Kirby Drive
Houston, TX 77006

*Teledyne Exploration Company
P.O. Box 36269
Houston, TX 77036

*Texas A&M University
Department of Oceanography
College Station, TX 77843

*Tracor Marine, Inc.
Ocean Technology Division
P.O. Box 13114
Port Everglades, FL 33316

University of Delaware
College of Marine Studies
P.O. Box 286
Lewes, DE 19958

*Geophysical Laboratory
Marine Science Institute
University of Texas
700 The Strand
Galveston, TX 77550

*Western Geophysical
8100 Westpark Drive
P.O. Box 2469
Houston, TX 77001

Raytheon Company
Ocean Systems Center
P.O. Box 360
Portsmouth, RI 02871

The companies that have replied to date are marked with asterisks. All replies have been negative.

NRL investigators went to Houston during the week of 30 January 1978. They met with Mr. J.C. Johnson (General Manager) and B.T. Reid (Operations Supervisor) of ESSO Seismics. ESSO had been working off the coasts of South Carolina, Georgia, and Florida in an area called the Georgia Embayment. The seismic equipment used was a "sleeve exploder" (gas) and a 900-joule sparker. Both systems operate below the sea surface and could not have caused the acoustic phenomena under investigation. The following is a list of ESSO's operating areas with the dates and times of operation.

Latitude	Longitude	
32-19N	79-42.5W	
32-10N	79-27W	
31-55N	79-39W	Northern Area
32-04N	79-54W	
Begin 0040Z	12/03/77	
End 0358Z	12/06/77	
31-30N	80-16.5W	
30-57.5N	80-16.5W	
30-28.0N	80-50.0W	Southern Area
30-08.5N	80-20.0W	
30-42.0N	80-00.0W	
Begin 1908Z	12/06/77	
End 1727Z	12/20/77	

NRL representatives spent 1 February 1978 with Mr. Robert J. Hoff of Decca Survey Systems, Inc. Decca had no operations off the east coast during January 1978. Decca uses standard geophysical exploration equipment for their surveys. The basic equipment consists of a 10-kilojoule sparker, side-looking sonars, and echosounders. This equipment could not be responsible for the sonic effects under investigation.

On 2 February 1978, NRL representatives met with Mr. F. Don Bowman, Vice President of Operations for Fairfield Aquatronics Division. Fairfield Aquatronics uses the same type of equipment as does Decca, i.e., 15-kilojoule sparker, side-looking sonar, echosounders. Once again, this equipment could not have been responsible for the sonic events in question. Fairfield has been working in the Baltimore Canyon area during November and December of 1977, and the first week of January 1978.

NRL representatives contacted Mr. C. H. Savit, Senior Vice President of Western Geophysical Co., Box 2469, Houston, TX 77001 ((713) 781-3261). He reported that Western Geophysical had no operations off the east coast during December 1977 and January 1978.

The petroleum exploration community is a small group located in a fairly concentrated area. For this reason, everyone within the community usually knows who is working where and with what vessels, and for which company. For example, each company visited in Houston mentioned that the other two companies were also operating in the area of interest. Therefore, it was concluded that only four seismic exploration companies were operating off the east coast during the period of time under consideration. Those companies are Offshore Navigation, Inc.; Decca Survey Systems, Inc.; ESSO Seismic, Inc.; and Fairfield Aquatronics Division. All of these companies use basically the same exploration equipment and are normally as advanced as the state-of-the-art. None of these companies use explosives of any kind on marine seismic exploration surveys. The crews of the operating survey vessels did not report any unusual acoustic events while they were working in the area. Therefore, it is believed that the exploration operations of the petroleum industry could not have caused the sonic phenomena under study.

An investigation of educational institutions, industrial firms, and government agencies that may have been conducting geophysical operations off the east coast of the United States was conducted. The following is a brief summary of the institutions and people contacted by telephone during this investigation.

University of Miami, Rosenstiel School of Marine and Atmospheric Science, Key Biscayne, FL ((305) 350-7211): A conversation with and inquiries by Ms. Dawn Moreau revealed that neither the Ocean Engineering nor the Marine Geology Departments were involved in any seismic reflection or refraction work during the December-January period.

Florida Institute of Technology, Jensen Beach, FL ((305) 334-4200): Mr. G. G. Greenwood of the Institute said that FIT was not involved in any marine seismic work in December 1977.

Skidway Institute of Oceanography, Savannah, GA ((912) 356-2471): All personnel who would be cognizant of geophysical programs carried out in December and January were at sea and were expected to return on or about 1 March 1978.

University of South Carolina, Columbia, SC ((803) 777-6449): Dr. Pradeep Talwani of the Marine Geophysics Department said that USC did no seismic or explosives work in December. He did say, however, that their seismographic stations received some of the "booms" and that they appear to be similar to sonic booms made by aircraft in most cases. One exception to this was a low-frequency event, in the neighborhood of 2 Hz, noted on 13 January at 1907Z. The duration of the event was approximately 8 seconds. Dr. Talwani further stated that the other acoustic phenomena recorded by USC almost invariably occurred on Thursdays and Fridays and that they are indicative of man-made sources.

Duke University, Durham, NC ((919) 684-2206): Dr. Oren Pilkey, principal investigator for the R/V *Eastward* said that *Eastward* was at sea off the coast of North and South Carolina during the first week in December doing biological experiments. No seismic or explosives work was performed, nor were any unusual acoustic events reported. After that time, *Eastward* was tied up for the remainder of December and into January.

Virginia Institute of Marine Science, Gloucester Point, VA ((804) 642-2111): Dr. John Zeigler of the Earth Science Department said that no geophysical work capable of causing atmospheric or aquatic noise of any type was performed by VIMS.

U.S. Geological Survey, Reston, VA ((703) 860-7564): Mr. Bruce Weetman of the Operations Division said that no USGS-contracted vessels were shooting in early December, and that explosives have not been used in offshore petro-exploration for some time. He said that pneumatic and electrical energy sources used in modern oil exploration could not generate a noise such as that which caused the "booms."

National Oceanic and Atmospheric Agency, Rockville, MD ((301) 443-8322): Capt Williams of the Fleet Operations Office said that NOAA was not involved in any seismic operations at sea. This was basically because NOAA does not have the capability or equipment to do this type of research.

Westinghouse Corp., Annapolis, MD ((301) 765-5606): Mr. Voorhees, Assistant Operations Manager, said that Westinghouse did no work with seismic, pneumatic, and/or explosive devices during the investigative time frame.

Maryland Geological Survey, Baltimore, MD ((301) 235-0771): Mr. Randy Kerhin, a staff geologist, said that the Marland Geological Survey did no seismic work at all during the time frame under investigation.

Delaware Bay Marine Science Center, Lewes, DE ((302) 645-2486): Mr. Rod Layton said that the Center did neither seismic work nor atmospheric sounding during the December-January period.

University of Delaware, College of Marine Studies, Lewes, DE ((302) 645-4320): Mr. Wadsworth Owen, Director of Marine Operations, said that no seismic air gun or sparker work was done in December. They presently have a sparker working on contract to Offshore Navigation, Inc., Harahan, LA 70183. Contact with Offshore Navigation was made at an earlier date and is so noted in an earlier memorandum on the subject.

Princeton University, Princeton, NJ ((609) 452-3000, X-4118): Dr. Robert Phinny of the Marine Geophysics Department said that no field geophysical work, either atmospheric or aquatic, was done by Princeton in December or January.

State University of New York at Stony Brook ((516) 245-6546): A conversation with Mr. Fred Robbins revealed that SUNY/SB was not involved in either seismic, oceanographic or atmospheric work in December 1977.

Rhode Island Marine Services, Inc., Wakefield, RI ((401) 789-3023): Ms. Doris Tasich said that Rhode Island Marine Services did no seismic, acoustic, or explosives work in December 1977.

Lamont-Doherty Geological Observatory, Palisades, NY ((914) 359-1400, X-234): Ms. Betty Batchelder of the Marine Geophysics Section said that no Lamont research was done in the western North Atlantic in early December. R/V *Conrad*, Cruise CO 21, operated from 13 November to 10 December in the Caribbean Sea, using continuous seismic profiling systems. The ship departed Colombia in November and arrived in Barbados on 10 December. No unusual phenomena were reported. R/V *Vema* is in the Indian Ocean.

Naval Underwater Systems Center, New London, CT ((203 442-0771, X-2682): Mr. F. J. Kingbury, Assistant Director for Operations, said that NUSC did not use any seismic sources, nor did they use any explosives at sea during the time frame in question.

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University of Connecticut, Groton, CT ((203) 446-1020): A conversation with Mr. Robert Miller in the Department of Oceanography and Marine Geophysics revealed that the University did only shipboard work in Long Island Sound in December. No seismic work was performed. No unusual acoustical data or phenomena were reported.

Raytheon Corporation, Portsmouth, RI ((401) 847-8000, X-2381): Mr. Robert Brown, Director of Ship Operations, said that the only shipboard work that Raytheon was involved in during December was a buoy-laying operation on Georges Bank for hydrographic purposes. No unusual instances were reported.

University of Rhode Island, School of Oceanography, Kingston, RI ((401) 792-6110): Mr. James Griffin, Director of Technical Facilities, was contacted. He said that Cruise EN 16 of the R/V *Endeavor* was conducted in conjunction with R/V *Vityaz* (USSR) in the Polymode Area (30°-34°N, 68°-72°W). Endeavor departed Narragansett, RI, on 5 December and proceeded to the Polymode Area where it rendezvoused with R/V *Vityaz* on 8 December. The two vessels operated in concert, conducting extensive hydrographic and bathymetric surveys. The ships departed the Polymode Area on 18 December and *Endeavor* returned to Narragansett on 22 December. No seismic profiling of any kind was performed during this period. There was no acoustic work, and no explosives were used. The cruise report (*Endeavor*) indicated that no unusual acoustic phenomena were observed.

Massachusetts Institute of Technology, School of Earth and Planetary Sciences, Cambridge, MA ((617) 253-3380): Ms. Maureen Hayes said that no shipboard work was done by MIT in December. Dr. Ira Dyer confirmed that statement and said that MIT was not engaged in any marine geophysical work in January, either.

Woods Hole Oceanographic Institution, Woods Hole, MA ((716) 548-1400, X-221): Dr. Elizabeth Bunce said that she had the R/V *Atlantic II* in the Kane Fracture Zone (23°50'N, 45°45'W) in October and early November. Dr. Michael Purdy had the ship in November and December and operated in the same area, conducting seismic refraction experiments. Purdy used 50 charges of 256 lb, and 3 charges of 512 lb, all of which were between 13 November and 22 November. Purdy also had the ship in January but did not use any explosives. No unusual acoustic phenomena were observed.

Lincoln Laboratories (MIT) Cambridge, MA ((617) 253-7871): Dr. Joseph D. Phillips said that experiments were using SUS Mk 61 charges between 10 and 17 October 1977. Phillips also indicated that USNS *Redstone* was using SUS charges sometime in October.

Space and Missile Test and Evaluation Center, Detachment No. 1, Patrick AFB, Cocoa Beach, FL ((Autovon-8) 854-5722): A conversation with Major Brown revealed that USNS *Redstone* was in a test support position on 4 and 5 December, centered at approximately 20°N, 55°W. Between 11 and 14 December, the ship was recovering a bottom transponder, and from 17 December to 27 January USNS *Redstone* was in port.

In view of the above investigations and the conversations that transpired, these institutions, universities, corporations, and agencies must be ruled out as the source of the acoustic events in this study.

Methane

Methane burns readily in air, but it is very difficult to detonate. Indeed, published literature shows there is still a debate among experts as to whether successful detonations with methane/air have been obtained, whereas detonations have been obtained with any other fuel/air mixtures.* Although methane has a high heat of combustion, its other flammability properties such as burning rates, ignition energies, autogeneous ignition temperature, quenching distances, etc. show it to be more inert than other hydrocarbons and other fuels, which may explain why it would be difficult to detonate. For background, the following flammability properties of methane/air are compared to other materials:

Methane	210.8 Kcal/mole	13.14 Kcal/gm
TNT (excess air)	820.7 Kcal/mole	3.61 Kcal/gm
Heat of Detonation [2,13]:		
Methane		~5 Kcal/gm
TNT		1.1 Kcal/gm
Limits of Flammability in Air [3]		
	Lower	Upper
Methane	5.0%	15.0%
Propane	2.2	9.5
Hexane (gasoline)	1.1	7.5
Hydrogen	4.0	75.0
Autoignition Temperature [3]		
Methane	-	1004°F
Propane	-	842°F
Hexane	-	437°F
Hydrogen	-	752°F
Maximum Flame Velocity in Air		
Methane (4)	-	33.8 cm/sec
Propane (5)		40.0 cm/sec
Hydrogen [5]		~260.0 cm/sec
Flame Temperatures in Air [5]		
Methane	-	1875°C
Propane -	1925°C	
Hydrogen	-	2045°C
Minimum Ignition Energy (millijoules)		
Methane [4]		0.29
Hydrogen [5]		0.02
Detonation Velocity in Air		
Methane	-	Not available
Propane [6]	-	1900 m/sec 900 m/sec at limits
Hydrogen [5]	-	2100 m/sec

*Most of those were in confined, or weakly confined, devices, such as tubes, tunnels, or balloons. Detonations of completely unrestrained bubbles or clouds would be more difficult, especially of methane.

Although many detonations of fuel/air mixtures have been studied experimentally under controlled conditions, these were on a relatively small scale. However, one truly large scale, but adventitious, detonation of an unconfined gas cloud has been investigated [6]. This was near Port Hudson, MO on 9 December 1970, following a break in a propane pipeline. It was estimated that 750 barrels of liquid propane escaped in 24 minutes. This resulted in a cloud covering about 10 acres, occupying a volume of 1-2 million cubic feet. The detonation was estimated to be equivalent to about 50 tons of TNT, which, based on the heat of combustion of propane, was only a 7.5% yield. However, this is considered high for an unconfined gas/air explosion. Yields in three other gas explosions (styrene, butadiene, vinyl chloride) ranged from 0.3 to 4%. These low yields are attributed to poor mixing with air. This was evidenced in the Port Hudson explosion where there was a considerable firestorm after the detonation, indicating a large quantity of fuel/air mixture that was too "rich" to detonate, which then burned later.

Methane Generation

The natural gases found in sediments and sedimentary rock formations generally contain methane as the major constituent. Other gases may also be present, but with only a few exceptions, methane is by far the most abundant. Smaller amounts of higher hydrocarbons (ethane and propane) are sometimes found, as well as nonhydrocarbon components such as carbon dioxide, nitrogen, and hydrogen sulfide. Occasionally, one of the latter three gases may be found in excess, but this is not normally the case. Hydrogen is not present in natural gas.

Methane occurs worldwide, being found in association with organic-containing sediments at various depths below the earth's surface. When found in shallow aquatic sediments, methane is sometimes known as marsh gas or swamp gas. When found in coal deposits and carbonaceous sedimentary rock, the gas is known more familiarly as fire-damp. All oil fields at whatever depth have methane associated with them. Even in the absence of petroleum, commercial natural gas fields (mostly methane) are found in many parts of the world. In deep sea sediments, it has been shown that methane is "by far the most important gas generated in marine sediments" [1]. Finally, the peculiar geological phenomenon known as "mud volcanoes" should be mentioned [2]. This is the term used to describe an eruption of watery mud caused by escaping methane. Mud volcanoes are generally found in basin areas which contain appreciable depths of sediments. Most often, they occur as a mild upwelling accompanied by gas bubbles; however, on occasion the eruption can be quite violent, with millions of cubic meters of gas being expelled in an explosive manner [3].

Methane is formed during the decomposition of organic matter in the absence of oxygen. Either of two processes may be involved: (a) the microbial degradation of organic matter in the upper sedimentary layers, such as occurs in marine sediments, lake bottoms, and marshed; (b) the non-biological thermal cracking of complex organic compounds in the deeper sediments at elevated temperatures and pressures. In a typical marine sediment, for example, the following sequence of microbial reactions normally takes place in successive layers of the sediment: (a) aerobic oxidation in the upper few centimeters to produce CO_2;* (b) anaerobic sulfate reduction to produce sulfide;† and (c) anaerobic methane production via carbonate reduction. The

*Where the bottom waters are anoxic, such as in the Black Sea, this type of reaction is absent.
†Absent in fresh water sediments.

last reaction accounts for almost all methane found in recent aquatic sediments and in shallow sedimentary rocks. With increasing depth in the sediments, however, the temperature begins to rise, microbial processes become more and more limited, and nonbiogenic thermal reactions at some point begin to produce methane. The crossover depth at which this becomes significant is not at all well known; however, it is safe to say that at depths of 1000 meters or more, the thermochemical production of methane is the dominant process.

Methane-consuming organisms as well as methane producers exist within marine sediments (e.g., there is considerable evidence of co-metabolism of CH_4 by the sulfate reducers), and much of the biogenic methane produced in the upper layers never reaches the sediment-water interface. However, because these upper layers are relatively porous, a considerable fraction of the biogenic gas is still able to migrate upward and escape into the water column. Such areas of escaping gas usually manifest themselves as small bubbling seeps. Except in very shallow waters, most of the gas bubbles dissolve before reaching the surface. The bubbling rates are highly variable. An investigation of gas seeps in the Gulf of Mexico [4] showed bubbling rates varying from sporadic, single-stream bubbles of less than 1 cm^3/min to plumes of bubbles with rates greater than 5×10^4 cm^3/min. Even with increasing depth of sediment, the rate of escape of biogenic methane from the upper layers is generally sufficient to prevent any appreciable trapping of significantly sized gas pockets and buildup of gas pressure.

In deeply buried sediments, the situation may be quite different. Sediment compaction and decrease in pore size of the rock trap the methane, and appreciable subsurface pressures can develop. In most cases, the gas remains stored in the sedimentary rock, being sealed in place by a relatively impermeable cap rock. Occasionally, tectonic processes such as rupture of the rock strata or fault formation will occur, allowing the gas to escape to the surface. If the escape is gradual, as is usually the case, gas seeps at the surfae may be created. If the tectonic process is catastrophic in nature (e.g., an earthquake), the escape of the gas can be sudden, and explosions and fires may occur.

In attempting to assess the significance of methane explosions as a possible cause of the atmospheric phenomena under investigation, two processes which might conceivably release methane into the atmosphere will be considered: (a) microbial generation of methane at marine sewage disposal sites, and (b) periodic venting of methane from the earth's interior. The first possibility arises from the near coincidence between the plotted location of the 2 December explosion and the location of a major sewage disposal site in the New York Bight. The second process has been suggested by Prof. Gold, (Cornell University) and in view of what is known about the worldwide occurrence of methane within the earth, was considered in detail.

Methane from Sewage

The sewage disposal site in question is located within the apex of the New York Bight, just outside the entrance to New York Harbor (about 11 miles south of Long Island and 11 miles east of New Jersey) (Figure 14). This is the dumping area for most of the sewage waste from the New York City area, together with other types of waste such as dredge spoils. There is only one other offshore sewage disposal area along the Atlantic coast. This is located about

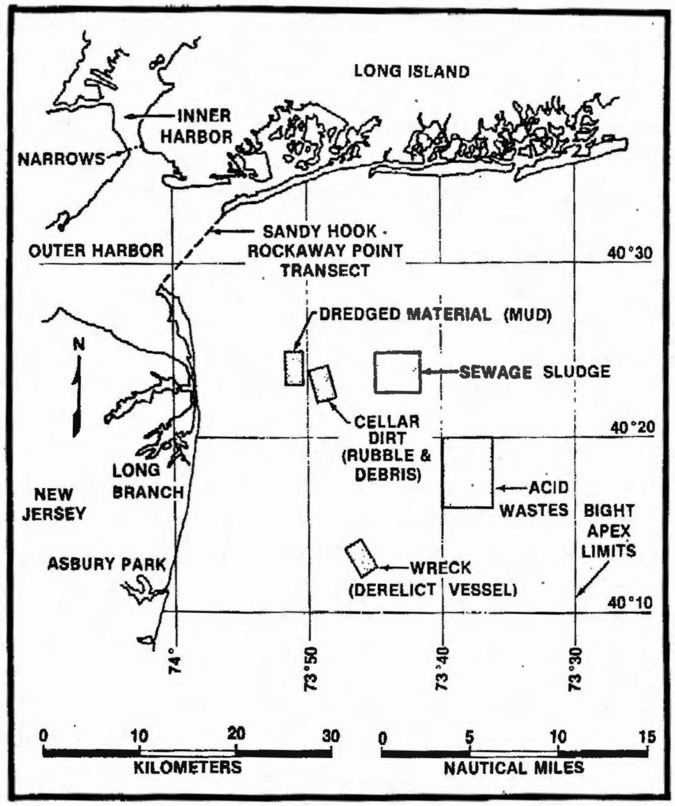

Figure 14 — Sewage dumping areas

10 miles off Cape May, New Jersey, and is used for disposal of sewage sludge from Philadelphia. However, the quantities involved are very much less than in the New York area, and little or no bottom sludge has accumulated. To complete the picture, it should also be mentioned that copious quantities of methane are generated during anaerobic digestion at sewage treatment plants ashore, but this gas is either utilized for heating or disposed of in a controlled manner, and need not be considered further. Similarly, gas generation from sanitary landfills (garbage, etc.) can be disregarded; normally, most os the gas slowly percolates upward through the relatively permeable landfill materials and escapes into the atmosphere at a slow but steady rate.

Within the New York Bight apex, approximately 5 million tons per year of wet sludge are dumped at the designated site under Coast Guard supervision. This material is about 5% solids and 95% water, so that on a dry basis, approximately 250,000 pounds per year of organic-rich solids are barged to sea. If all of this material continued to accumulate in one area over the years, a potential for generating vast quantities of methane would exist. However, an examination of the situation shows that this is not the case. The MESA (Marine Ecosystems Analysis) project of NOAA has been monitoring this area for several years, and the following information taken from their reports [5] is pertinent to the problem at hand.

First, waters within the Bight apex have an active circulation. Second, the bulk density of the sewage sludge averages about 1.014 g/cm^3, somewhat less than seawater. This imparts a slight positive buoyancy to the sludge as dumped, and in view of the dynamics of the circulation system, there is a definite tendency for most of the material to be dispersed and carried away. Third, dissolved oxygen consumption by suspended sludge in the water column is high enough to oxidize a large fraction of the daily input of sludge. All three factors act to prevent any appreciable buildup of sludge in the bottom sediments. This has been confirmed by the sedimentological studies of the MESA investigators, who report no significant accumulation of sludge on the bottom after some 50 years of dumping. The sediments at the site appear to be relatively clean and nonreducing, being a mixture of natural fine sands, natural muds, and sewage-derived material. The only significant change in bottom topography since 1936 has been at the dredge spoil dumpsite nearby, where dumping of the dredged material has caused up to 10 m of shoaling. However, dredge spoil is a rather ill-defined, heterogeneous mixture of sand, silt, topsoil, clay, and shale, with some industrial and municipal waste; the organic content is relatively small, and because of the nature of the material, any methane which may be formed in the interior is not expected to build up to any significant extent.

Unfortunately, analyses for methane were not included in the MESA monitoring. However, the above considerations lead to the conclusion that methane buildup within the sediments in the Bight disposal area is not expected to occur. Some methane may indeed be formed, but without the accumulation and compaction of organic-rich sediments, conditions favorable for the entrapment of large quantities deep within the sediment do not exist. In the absence of such conditions, the storage and sudden release of methane into the atmosphere in sufficiently large quantities to cause an explosion is considered highly unlikely. Similar considerations apply to the Philadelphia sewage disposal site.

Methane Venting from the Earth's Interior [7]

Interest in this possibility stems from a theory of Prof. T. Gold of Cornell University regarding the cause of the atmospheric explosions. His recent studies of terrestrial outgassing phenomena have suggested to him that these explosions may well be of natural origin; that is, they may be caused by the sudden release of a combustible gas (methane) from the earth's interior, followed by the subsequent detonation of the gas-air mixture at some undetermined height in the atmosphere. In support of this, he cites historical evidence of a repetitive pattern of similar events occurring on a global scale and over long periods of time. These events consisted of loud booming noises accompanied by either brief flashes or actual flames coming out of the ground, often associated with major tectonic disturbances such as earthquakes.

The release of methane from deep within the interior of the earth seems to provide the only explanation for such events. However, the sudden release of natural gases in the large quantities required for such events appears to require an initiating event such as naturally occurring tectonic processes or manmade drilling operations. For example, the more violent emissions of methane from the mud volcanoes in the Caucasus, in quantities approaching millions of cubic meters of gas, appear to be clearly related to underground shocks [3]. No such tectonic disturbances were observed along the east coast of the U.S. during the time period in question. Furthermore, it has been calculated that the violent eruptions in the Caucasus responsible for releasing large quantities of gas take place on the average about once in a little more than a year. Although this is probably one of the most active areas in the world with respect to gas emissions, this frequency of events cannot account for the reported frequency of atmospheric explosions over a period of a few months. Smaller quantities of gas are of course released more often under quieter conditions. In the Caucasus, the amounts involved range from a few cubic meters to several thousand cubic meters over a period of 24 hours, but this type of release, like the natural gas seeps observed in the Gulf of Mexico [4], can hardly account for the atmospheric explosions in question.

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Along the east coast of the U.S., cores taken from the Continental Shelf and Continental Slope during the Deep Sea Drilling Project, and other sediment cores obtained during routine survey operations of the U.S. Geological Survey, have revealed in some cases the presence of methane [6]. For the deeper cores, in a few cases reduction in pressure as the core was brought to the surface caused expansions of the sediment and the formation of gas gaps along the length of the core. Although this indicates the presence of gas at depth in these sediments, in no case was any sudden release of gas ever noted. *In situ* observations revealed in some cases small bubbles rising from the sediments, but nothing more.

In general, gas released underwater emerges from the water column in extended plumes made up of smaller bubbles. A recent well blowout in the Gulf of Mexico which was investigated by a team of Texas A&M scientists [7] showed that even at an estimated seep rate of 10,000 m^3/day, passage of the gas through the sediments and the water column resulted in a plume of gas about 75 m across and consisting of bubbles from 1 to 5 cm^3 in volume. Emergence of methane into the atmosphere in this state, rather than as a single large bubble, leads to more rapid dilution and less probability of ignition. For example, one of the standard operating procedures in oil drilling operations in the Gulf of Mexico has been the periodic underwater venting of waste gases (some ethane and propane, but largely methane). At the high pressures involved, a single underwater flare is visible at the sea surface as a boiling turbulent area of whitecap water covering areas of several hundred square meters. In spite of the large quantities of gas involved, accidental ignition does not seem to occur. In fact, in only one case in a number of tests was it possible to get ignition by purposely towing an open flame through the boiling area [8].

In summary, the absence of any recorded tectonic disturbances along the east coast during the period in question makes it unlikely that sudden releases of large quantities of methane from deep within the earth could have occurred. The relative frequency of the atmospheric explosions, compared to the much less frequent emissions of large amounts of methane in gas-rich regions, makes it even less probable that methane could be the cause.

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Mixing and Dispersion

If one is to assume that methane was the source of the explosions heard off the east coast, one must consider the sources, mixing and dispersions of clouds of this gas. Possible sources have already been discussed thoroughly. Since this discussion essentially excludes biogenic sources from sewage, this leaves venting from the earth's interior, as postulated by Prof. Gold [7]. Assuming that a large bubble is suddenly "belched" from the earth and that it is essentially pure methane, being lighter than air ($d = 0.55$), it would start to rise quickly, especially so if, as Gold postulates, it is hot. If a source of ignition were immediately available, this bubble would burn quickly at the edges where the concentration in air would be "right," between 5 and 15%. The flame front would progress at an initial speed of about 30 cm/sec, which would be accelerated by the expansion of hot gases behind the flame front and also affected by geometry, composition, aerodynamic effects, etc. The main bulk would be too rich to burn immediately. A diffusion, or candle-type flame would result (similar in type to the burning of the Hindenburg at Lakehurst, N.J.), which would be much slower than the flames of premixed methane/air, (which gives the 33.8-cm/sec figure determined experimentally in Bunsen burners and tubes).

If the bubble were not ignited immediately, as it rose it would start mixing with air quickly by entrainment. L. Ruhnke [8] states that such mixing causes about a 50% dilution (average) for each height equal to the bubble diameter. Thus, a bubble of pure methane (100%) would be diluted to below its lower flammability limit at a height about 5 times its diameter.* To give a concrete example using this simple model, a bubble 1 mile in diameter would no longer be flammable just a little over 5 miles up. However, a large bubble rising in this fashion would generate its own thunderstorm (as a thunderhead does), so that ignition at its edges would occur from its own lightning [8].

If one assumes a sudden "spill" of methane being "borne down" by the wind, the following values are given by CHRIS for an "instantaneous" release [9].

Quantity (tons)	Max. dist. downwind over which gas may ignite (nautical miles)	Max. width of cloud that is flammable (feet)
10	0.5	250
100	1.5	650
1000	4.3	1700

Again it is seen that mixing with air is very rapid.*

Ignition

Although somewhat more difficult to ignite than most fuels, the minimum ignition energy for methane is still very low (0.29 millijoules), if delivered in the form of a spark. Over a fairly wide range of concentration, the energy required is still very low. Thus, almost any ignition source would be sufficient to ignite a cloud if the methane concentration is between 5 and 15% at the ignition source. Below 5% it is too "lean" to ignite and above 15% it is too "rich" to ignite. On the other hand, if a discrete ignition source were absent, and assuming the methane

*This is an obvious oversimplification. It is based on studies of jets. As the bubble rose it would grow by air entrainment and change of pressure, and mixing to establish a homogeneous concentration would not be immediate. Pockets of concentrations higher than the average would still remain.
Although these figures are as given in the charts in the reference, one must assume that buoyancy is excluded because values given for propane, which is denser than air ($d. = 1.5$) are essentially the same as for methane ($d. = 0.55$). Since CHRIS is designed for safety in a very practical sense large spills of methane would usually be cold (cryogenic and cooling by evaporation and expansion) and thus clouds would hug the ground.

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is coming out of the surface hot, as Gold postulates [7], it would have to be at a temperature of about 1000°F to ignite itself. Such temperatures are very unlikely, especially if the methane is released under water because of the cooling effect and the partial inerting of the methane/air mix by the steam generated.

Ignition energy required to give a detonation would be very high. The values quoted earlier are for deflagration only. For a point source of ignition, Bull et al. [10] estimate that about 22 kg of tetryl would be required to cause a detonation. This value is based on extrapolation of ignition energies to give detonations of methane in oxygen-enriched atmospheres. The 22 kg is not a measured value. Kogarko [11] in Russia claimed to have gotten a detonation of methane in air with only 70 g of explosive as an initiator. This was later discredited by several investigators, such as Bull [10], on the grounds that the path length in the experiment was too short to eliminate the effects of the explosive itself. Experiments sponsored by the U.S. Coast Guard with C. D. Lind [12] showed that in methane/air mixtures ignited with 2 kg of Composition B in a 5-m radius hemisphere, there was actually a flame-front deceleration within the mixtures, i.e., the initial detonations degenerated to deflagrations.

Character of the Explosion

In view of the above, it must be concluded that it would require unusual circumstances for a released bubble of methane to detonate. For a sustained detonation to occur, the methane/air mixture must be very close [13-15] to stoichiometric (9.487% in air), and this specific mixture must occupy a large volume. Gerstein [16] estimates that a volume between 10 and 100 ft in diameter "might" give a detonation, that between 100 and 1000 ft a detonation would be probable, and that > 1000 ft it would be likely. This is due to decreases in curvature, i.e., a flat wavefront is necessary to sustain detonation [15,16]. It is recognized by Gerstein and others [14] that these volumes are "guesstimates" at best, since no hard data are available.

If one assumes a 100-ft-diam. bubble* of methane at stoichiometric concentration, this would contain about 900 kg of methane. Based on heats of explosion of methane and of TNT, and a yield of 100%, this would release energy equivalent to about 4500 kg of TNT. This quantity would generate a frequency near the 2 to 3 Hz observed by Donn for the 2 December 1977 events. If the yield is about 5%, which might be high, it would require 20 times more methane in the bubble, but the equivalence should remain about the same.

Atmospheric turbulence would be expected to cause inhomogeneity in composition which would decrease the likelihood of detonation markedly [13].

If a detonation in a methane cloud were to be initiated, then, by analogy, wavefront velocities would be expected to be very high, approaching 2000 m/sec, and considerable noise would be generated. If, on the other hand only deflagration occurred, again it would take unusual circumstances of bubble shape, concentration, ignition source, and aerodynamics to generate a very large noise, considering normal flame-front velocities. It cannot be dismissed completely, however, if one has a very large cloud, in which a flame front being distorted by hot gases and burning irregularly might accelerate well beyond normal.* Whether this could be enough to explain the 2 December 1977 events is not known, but it certainly must be considered as very unlikely.

*As the minimum required for detonation.

Discussion of Methane as Cause of Events

Explanation of the noises heard and recorded on the east coast as being due to methane explosions must be considered as extremely unlikely, even assuming a recurring source of the gas.* It is too difficult to explain these noises based on deflagration alone, and for detonation to occur, too many conditions have to be "just right." Methane is not a fuel that leads to easy detonation. On the other hand, higher hydrocarbons (gasoline for example), or methane mixed with hydrogen or higher hydrocarbons will detonate much more easily.

Also, higher hydrocarbons could appear on the ocean surface off the east coast from rusting through the tanks containing such hydrocarbons in tankers sunk off the east coast. The Coast Guard has a record of 27 tankers sunk or damaged off the east coast by enemy action during the early months of World War II, from December 1941 to June 1942 [18]. But the probability of repeated recurrence of releases of liquid fuel, coupled with the need to establish clouds† in the proper concentration ranges and adventitious ignition sources at the right moments is much too remote to be considered further. This is also true of adventitious explosions from explosives in sunken ships.

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*MacDonald at the MITRE meeting on 3 February 1978 stated that there are geological faults along the east coast.
†Such clouds would tend to "stay low" because such hydrocarbons are heavier than air.

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Antipodal Effect

One hypothesized source of the atmospheric sonic events that have taken place off the east coast of the United States is that the actual event may have taken place on the opposite side of the earth. The acoustic energy would then transit around the earth, as a normal air acoustic wave, or as a Franz wave [1] or creeping wave [2], and through focussing could produce substantial intensity at a spot 180° opposite (i.e., the antipode) from the original phenomenon. The antipodal point diametrically opposite to the east coast of the United States is several hundred miles southwest of Australia.

Therefore, the Australian Embassy was queried as to whether Australia had detonated any large explosives coincidental with the events of 2, 15, and 21 December 1977, that the Laboratory is investigating. It was reported that a 620 lb detonation took place in the great Australian Bight (south of Australia) on 12 December 1977. It was also reported that a seismic exploration vessel (oil) was shooting with a 4,500 cu-in. air gun off the northwest coast of Australia. Because no detonations had taken place on any of the dates of the events queried, and the only known substantial sources of energy release were not detected in the U.S. (nor were they at the east coast antipode), it is concluded that antipodal acoustic phenomena are not responsible for the atmospheric events being investigated. A further confirming factor is that when sound travels over such long distances as are postulated here, the higher frequencies are attenuated, leaving only frequencies well below 1 Hz, whereas the predominant energy of the signals detected in the U.S. lies well above 1 Hz.

Aircraft Operations

Infrasound from supersonic aircraft was considered a likely explanation of the December 1977-January 1978 acoustic events as soon as the frequency of sound was determined. The fact that the source was above the surface of the ocean but below 25 km made it even more likely. The cultural pattern reflected by all reports — citizen observer, microbarograph and seismic stations — strengthened the case further.

Effect Maneuvers on Sonic Booms

The following section discusses the mechanisms by which various acoustic phenomena can be generated by aircraft in normal supersonic flights.

The geometry of the sonic boom is illustrated in Figure 15. As the aircraft traverses the distance from A to B at some supersonic velocity v it generates a shock wave. The shock front, in a homogeneous isotropic atmosphere, would be a cone whose apex is at the nose of the aircraft and has a half-angle given by

$$\mu = \sin^{-1}\left(\frac{1}{M}\right)$$

where c is the speed of sound and $M = vk$ is the Mach number. The rays originating from the point A also would form a cone with half-angle given by

$$\theta_0 = \cos^{-1}\left(\frac{1}{M}\right).$$

At Mach 1.1, $\mu = 65.38°$, at Mach 2 $\mu = 30°$, at Mach 2.5 $\mu = 23.58°$.

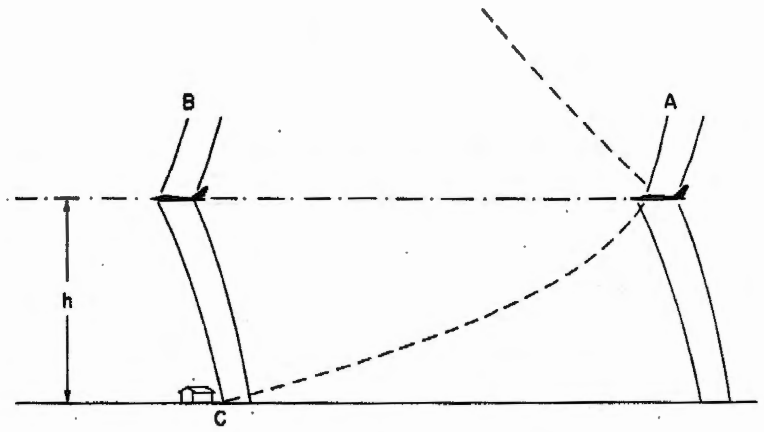

Figure 15 — Generation of sonic boom

In a realistic atmosphere, however, the sound speed decreases linearly with altitude up to about 11 km, after which, in the absence of winds, it becomes more or less constant. As a result, the rays, rather than being straight lines, are arcs of circles and the wavefronts are curved along the ray

$$\frac{\cos\theta}{c(z)} = \text{const} = \frac{\cos\theta_0}{c(h)} = \frac{1}{v}$$

where h is the altitude of the plane. Thus, when $c(z) = v$, θ is zero and the ray turns upward. Hence, if the aircraft speed v is less than the sound speed at ground level, $c(0)$, the sonic boom will not reach the ground. We define the plane's Mach number by

$$M = \frac{v}{c(h)}.$$

For altitudes above the tropopause, sonic booms will reach the ground only if $M \geqslant 1.15$. For lower altitudes this critical Mach number will be lower. As one gets further and further from the ground track, the angle that the ray makes with the horizontal gets smaller and smaller. Thus, if one gets sufficiently far from the ground track, the ray will no longer hit the ground and the so-called lateral cutoff occurs. The higher the plane and the larger the Mach number the wider the lateral spread of the sonic boom on the ground. Figure 16 shows typical data for lateral spread. For most cases involving fighter aircraft, we would expect to find sonic booms up to 15 miles off the ground track. Note that the cutoff is quite sharp but until one reaches the cutoff the decrease in pressure is fairly slow. For high altitudes and Mach numbers, the sonic boom may extend 20 to 30 miles from ground track. Returning to Figure 15, we note that, for a plane at 11 km flying near the cut-off Mach number of 1.15, the shock wave which hits the house located at C was generated when the plane was 25 miles away (though the plane was only about 3 miles past the house when the boom was heard). It is important to note that the boom would be heard at C even if the plane had gone subsonic (or even turned around) after passing point A, 25 miles away. If there were a temperature inversion or wind shear causing the sound speed gradient to be decreased, the critical Mach number could be lowered and the 25-mile distance increased. Also, if there were a strong tailwind above the aircraft, the upward-going ray indicated by the dashed line could be refracted down to the ground at a distance of over 100 miles from the point of generation. We will discuss this possibility in somewhat more detail later on.

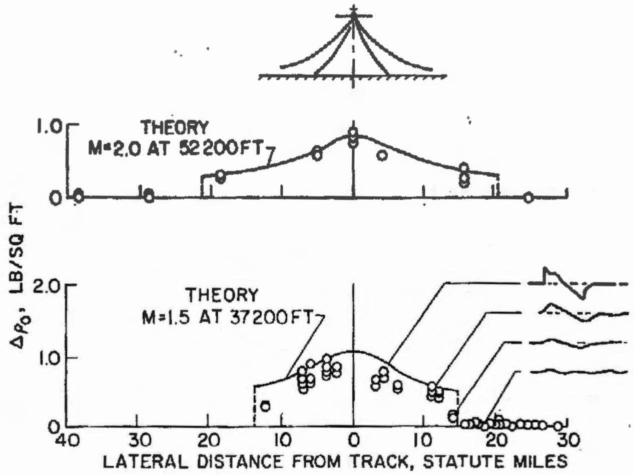

Figure 16 — Lateral-spread patterns

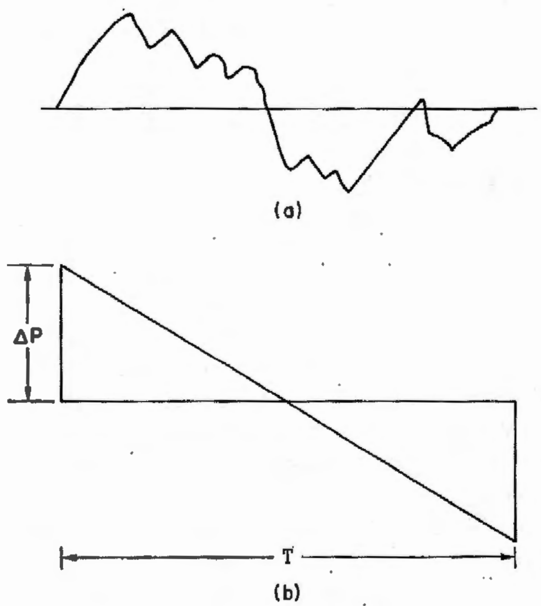

Figure 17 — Development of N-wave

As the plane passes through the air it must displace it, and thus in some sense the plane is a volume source of sound. In addition, the lifting surfaces provide dipole-like force terms. The detailed shape of the wave near the plane is thus a complicated (but well understood) function of the geometry and aerodynamics of the plane. Though in the near field the waveform may be quite complex (as in Figure 17a), nonlinear propagation eventually transforms it into a simple *N* wave as shown in Figure 17b. This comes about because the amplitude dependence of the propagation speed causes negative slopes to decrease, positive slopes to increase and eventually shock, and larger shocks to overtake and swallow up smaller shocks. The *N*-wave once formed slowly spreads and decreases in amplitude (over and above geometrical spreading loss) due to the acoustic wave behind the shock front overtaking the shock. The plane in some sense acts like a phased line array generating a conical wavefront at the Mach angle. Since the wavefront is conical (not spherical) the spreading loss is cylindrical rather than spherical; i.e., the wave decays as $s^{-1/2}$ rather than s^{-1} where s is the length of the ray. For cylindrical waves the nonlinear losses vary as $s^{-1/4}$, so overall the wave decays as $s^{-3/4}$. To be specific, for unaccelerated flight

$$\Delta p_2 = P_0 K_B K_R \frac{d}{l^{1/4}} \frac{M^{3/4}}{(M^2 - 1)^{1/4}} \frac{\exp\left[-\frac{g\gamma h}{2c(0)c(h)} \right]}{s^{3/4}}$$

where P_0 is the pressure at ground level, K_B is the body shape factor, d is the maximum diameter of the equivalent body of revolution, l is the length of the plane, g is the acceleration due to gravity, and γ is the ratio of specific heats. The geometry and aerodynamics of the plane are contained in K_B and d.

Since the shock at the front of the *N*-wave originates at the front of the plane and the shock at the rear originates at the tail of the plane, the duration of the *N*-wave is naturally closely related to the length of the plane. (For most fighters T is about 0.1 and one may hear one or two bangs.) The pressure spectrum of an *N*-wave given by

$$P(\omega) = \frac{\Delta P}{(2\pi)^{1/2} T} j_1 \; (\pi f T),$$

where j_1 is a spherical Bessel function, is shown for $T = 0.1$ sec in Figure 18. The dominant frequency is given by

$$f_{max} = \frac{2}{3T}$$

which is 6.7 Hz for $T = 0.1$. For Concorde f_{max} would be about 2.2 Hz.

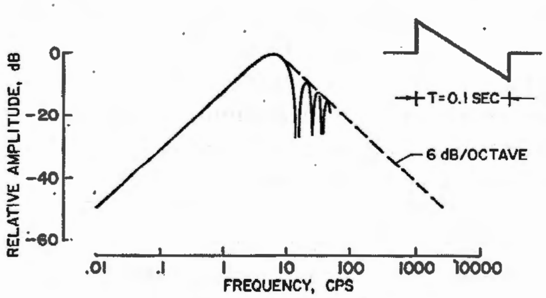

Figure 18 — Spectra of N-waves

For fighter aircraft operating in the 6- to 12-km altitude range, the expected shock amplitude along the ground track would be from 50 to 100 Pa (1 to 2 psf). Figure 19, a table taken from a paper by Von Gierke, indicates that such levels would cause probable to significant public reaction and rare minor damage. The focussing effects discussed in the next section could, over a limited region, increase these numbers by a factor of from 2 to 5, putting them in the "Incipient Damage" regime.

The pressure waveform near a TNT explosion is not appreciably different from that of a sonic boom. Moreover, as it propagates it will look more and more like an *N*-wave. In fact, TNT explosions are often used to simulate supersonic booms and vice versa. It is therefore

Estimates and observations of the effects of exposure to sonic booms of different peak pressures.

Peak Overpressure (lb/sq ft)	(dyn/cm^2)		Predicted and/or Measured Effects
0–1	0–478		No damage to ground structures. No significant public reaction day or night.
1.0–1.5	478–717	Sonic booms from normal operational altitudes: typical community	Very rare minor damage to ground structures. Probable public reaction.
1.5–2.0	717–957	exposures (seldom above 2 lb/ft sq)	Rare minor damage to ground structures; significant public reaction particularly at night.
2.0–5.0	957–2393		Incipient damage to structures.
20–144	9.57 $\times 10^3$ 6.8 $\times 10^4$	Measured sonic booms from aircraft flying at supersonic speeds at minimum altitude; experienced by humans without injury.	
720	3.44 $\times 10^5$	Estimated threshold for eardrum rupture (maximum overpressure).	
2160	1.033X10	Estimated threshold for lung damage (maximum overpressure).	

aRefs. 2, 4, 5, 7.

Figure 19 — Effects of sonic booms

difficult to distinguish between long-range reception of a sonic boom and long-range reception of an explosive signature.

When aircraft perform certain maneuvers such as acceleration at supersonic speeds, pushovers, or turns, focussing of the sonic boom may occur on the ground. Pressure increases of a factor of from 2 to 5 have been measured for linear acceleration and pushovers and increases of up to a factor of 9 have been measured near the "super focus" associated with a turn. The localized areas subjected to the superbooms are indicated by the shaded areas in Figure 20. The thickness of the shaded exposure areas is only about 100 m, but the length may be 10 or 20 miles. It is important to note that the superboom area is fixed on the ground; it does not move with the plane. Thus it is not unlikely to have widely spread reports of "very loud" booms, whereas individuals located very near to the reported superbooms hear little or nothing. The situation for linear acceleration is illustrated in Figure 21. As the plane accelerates the rays get steeper and steeper. A caustic is formed by the "envelope" of these rays. Along the caustic the wavefront has a cusp and the sound intensity is very high. To the left of point A (the point where the caustic intersects the ground) no sonic boom is heard, but a rumbling may be heard as the cusp passes overhead. At point A a superboom is heard. Between points A and B two booms are heard. The second arrival, having passed through the caustic undergoing a $\pi/2$ phase shift, tends to be *U* shaped rather than an *N*-wave. Beyond point B (where the second arrival is tangent to the ground), a single ordinary *N*-wave is observed. Every supersonic flight must create at least one superboom as the plane accelerates to speed. This is important, since a pilot who accidentally goes supersonic must always create not just a boom but a superboom, and multiple booms as well.

A second kind of focussing and defocussing due to atmospheric inhomogeneity has been described by Pierce and Maglieri. This causes spatial variations in the pulse shape and amplitude but is probably of little importance here.

The events of 2 December 1977 can be explained on the basis of military supersonic aircraft operating in warning zone 107 with a general heading of 330° to 350°. On 2 December 1977 and F-14 with an experimental reconnaissance pod was operating in W-108 at Mach 1.6 from 0930 to 1700 Z (1200 EST). The flight profile was from 1700 meters to 10,000 meters in a NW/SE orientation. There were five F-106's out of Atlantic City operating in W-107 along a

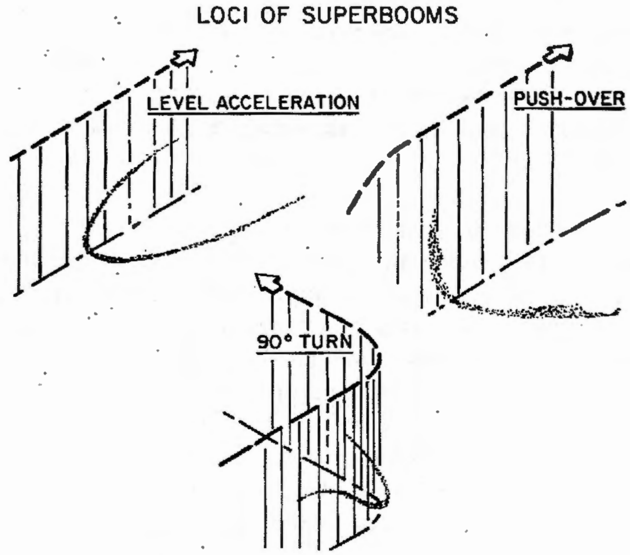

Figure 20 — Loci of super booms

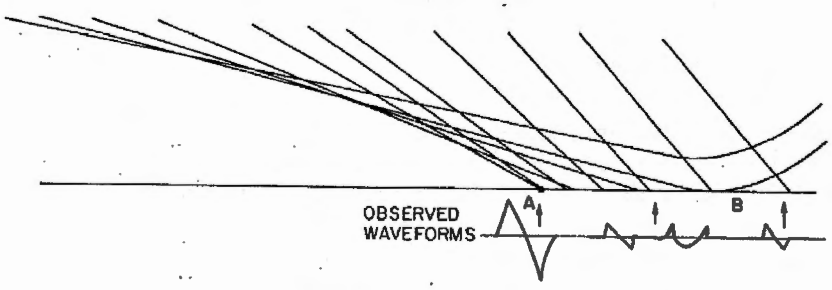

Figure 21 — Effect of linear acceleration

330°, 150° bearing at the time of the 2030 Z (EST) event. Four F-106's left Atlantic City supposedly at 1500 Z (1000 EST) for similar operations, but they could not have been responsible for the 1004 event recorded at Lamont. Four F-15's from Langley AFB were reported in W-107/108 during the period in question, and judged to have been the cause of the 1500 Z event on 2 December 1977.

With any of these aircraft there may have been a focus due to acceleration or pushover involved which would explain the multiple booms heard and the general severity of the event at certain locations. We need not consider any focussing to explain the event at Lamont. There are many possible north to northwesterly aircraft flight paths which would put Asbury Park and Long Branch within about 10 km of the extrapolated ground track with Lamont within 30 or 40 km of it. The cutoff could not have been very far beyond Long Branch and still have the plane within the warning zone, so Long Island and New York City would not be involved. If the ground track were to the east of Asbury Park, one would not expect anything to be observed anywhere more than about 20 km west of Asbury Park.

A hypothesized situation for the 2 December event is as follows. An F-106 over the ocean creates a sonic boom with a principal frequency. It is received at Asbury Park 45 km away as a loud building-shaking boom with a nominal (unfocussed) pressure of 75 Pa. (The sound heard within a building would persist much longer due to the response of the building, rattling of china and windows, etc.) The question is, could we reasonably expect the upward-going signal to produce the 5 Pa peak-to-peak signal measured for 30 to 40 seconds by the Lamont microbaragraph.

In a ray tracing computation of energy and travel time dispersion, the existence of a time dispersive predicted low loss path between Lamont and the source. Because the source of the energy for the 2 December event was comparatively low (2500 meters) and because of the extraordinarily high winds at higher altitudes (approximately 130 knots at 5000 meters) most of the energy radiated from the source was refracted downward and trapped within the duct that existed below 5000 meters. Because of the strong focussing effect of this duct, very little energy lost which was propagating from the event in the direction of Asbury Park and Lamont. Computer computations predicted a propagation loss of only 88 db between Lamont and the location of the event at 39°30'N, 74°10'W. Without the ducting caused by the high winds, the expected propagation loss for a 170 km path would be about 105 db or 17 db greater. Put in conventional ratios, because of the focussing effects of the high winds and the low altitude of the aircraft generating the superboom, the signal received at Lamont was about 50 times larger than it would have been if no ducting existed. Interestingly the ray tracing computations predicted that the signal at Lamont would only be about 13 db lower (i.e. a factor of 15) at Asbury Park than at Lamont. Since the signal received at Lamont was 5 Pa, it is likely that the signal at Asbury Park was as high as 75 Pa. Certainly, the response of citizens who noticed the event would correlate with this value.

Each individual ray path between the source of the event and the receivers at Lamont and the Weston Observatories, follows a least time path called a Fermat Path. Since each ray spends a different amount of time at each altitude and velocity value, the time of transmission will vary. This effect is well understood in seismology and underwater acoustics. Different multipaths have different travel times. The time interval between the receipt of the first and last signal from an acoustic event is known at the travel time dispersion. The ray tracing computation for the 2 December event predicted a travel time dispersion of between 30 and 35 seconds which agreed with the observed length of the signal. The duration of the signal observed at Lamont depended on propagation not on the duration of the superboom. Similar ray tracing computations were successful in predicting the duration of signals at each of the receivers of the Weston array.

Concordes

The paths of Concordes serving New York (JFK) and Washington D.C. (Dulles) were examined, together with actual times of arrival and departure at JFK and Dulles for days when significant events occurred. These are shown as Figure 22 and Tables 4 and 5. No correlation was found between Concorde operations and reported acoustic events in New Jersey and Charleston. After the investigation was well under-way reports of acoustic events, were received from Nova Scotia. In the hope that data on these events would help clarify the U.S. events a list of times and places of observation was obtained. These are shown in Table 6. The reported events for January were plotted as a function of time of day (Figure 22) and the pattern was typical of manmade events. Since Concorde passes near Nova Scotia when serving U.S., the

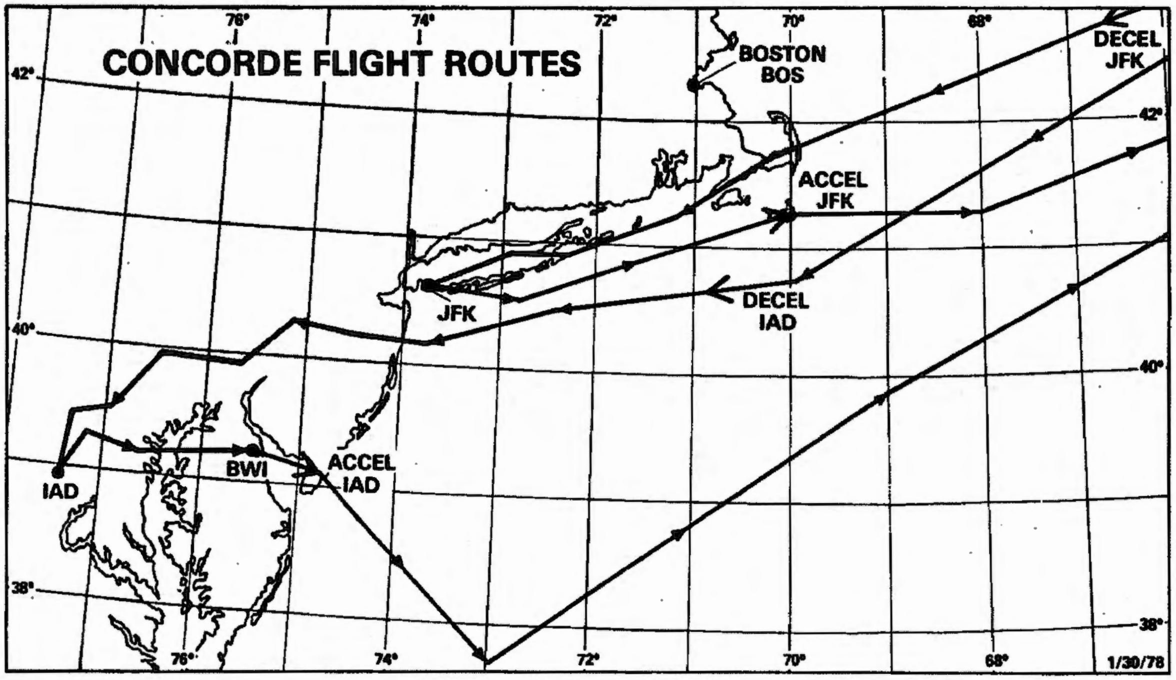

Figure 22 — Concorde routes to JFK and Dulles

UNCLASSIFIED

Table 4
John F. Kennedy International
Airport

Dec. 2	AF	ARR	08:42
	AF	DEP	10:38
Dec. 20	BA	DEP	08:40
	AF	ARR	08:59
	BA	ARR	10:13
	AF	DEP	10:55
Dec. 21	AF	ARR	10:48*
	AF	DEP	14:27P*
	AF	ARR	14:53
	BA	DEP	12:28
	BA	ARR	02:27P
Dec. 22	AF	ARR	08:48
	AF	DEP	10:49
	BA	ARR	12:31
Dec. 23	AF	ARR	8:50
	AF	DEP	10:35
	BA	ARR	11:48
Dec. 24	AF	ARR	08:39
	BA	ARR	10:03
	AF	DEP	10:44
	BA	DEP	12:25
Jan. 12	AF	ARR	08:42
	AF	DEP	10:36
	BA	DEP	12:28
Jan. 16	AF	ARR	08:47
	BA	ARR	10:20
	AF	DEP	10:37
	BA	DEP	12:37

*Diverted to Newark

Table 5
Concorde Operations
Dulles International Airport

Dec. 2	AF	ARR	019:16 EST
	AF	DEP	210:26
	BA	DEP	012:40
	BA	ARR	017:04
Dec. 20	BA	DEP	012:48
	AF	DEP	13:25
Dec. 21	AF	ARR	018:08
	BA	ARR	012:22*
	BA	DEP	013:39*
Dec. 22	AF	DEP	013:13
Dec. 23	AF	ARR	017:55
Jan. 12	AF	DEP	013:15 ± 10
Jan. 16	AF	DEP	013:08
	BA	ARR	012:12

Table 6
Reports of Acoustic Events – Nova Scotia
for Month of January

DATE	TIME (EST)	COMMENTS	
1 Jan	8:10 AM		Cape Sable light station
Sun	11:20 AM		Cape Sable light station
2 Jan	8:15 AM		Cape Sable light station
Mon	11:20 AM		Cape Sable light station
3 Jan	8:10 AM		Cape Sable light station
Tues	9:40 AM		Cape Sable light station
	11:20 AM		Cape Sable light station
4 Jan	11:30 AM		Cape Sable light station
Wed			
5 Jan	3:05 PM		Cape Sable light station
Thurs			
6 Jan	11:35 AM	light	one Cape Sable light
Fri			
7 Jan	8:15 AM	heavy	one Cape Sable light station
Sat	3:10 PM	moderate	Cape Sable light station
	12:30 PM	light	one Clarks Harbor
8 Jan	8:05 AM	moderate	Cape Sable light station
Sun	9:50 AM	moderate	Cape Sable light station
9 Jan	Nothing	moderate	Cape Sable light
Mon			
10 Jan	8:00 AM	medium heavy	Cape Sable light
Tues	9:25 AM	light	Cape Sable light
11 Jan	9:50 AM	light	Cape Sable light
Wed			
12 Jan	Nothing		
Thurs			
13 Jan	8:00 AM	heavy	Northeast Harbor
Fri	8:05 AM	heavy	Barrington
	9:20 AM	medium	Cape Sable light
14 Jan	8:03 AM	heavy	Stone Island (uic Cape Sable)
Sat			
15 Jan	7:55 AM	heavy	Cape Sable light
Sun	7:55 AM	heavy	Barrington
	9:28	heavy	Cape Sable light
	9:28 AM	heavy	Barrington
	9:28 AM	heavy	Northeast Harbor

Table 6 (Continued)
Reports of Acoustic Events – Nova Scotia
for Month of January

DATE	TIME (EST)	COMMENTS	
16 Jan Mon	8:05 AM	light	Cape Sable light
17 Jan Tues	11:30 AM	light	Cape Sable light
18 Jan Wed	10:45 AM	medium heavy	Lower Woods Harbor
19 Jan Thurs	8:30 AM	light	Cape Sable light
	8:45 AM	light	Northeast Harbor
	9:35 AM	light	Cape Sable light
20 Jan Fri	3:35 PM	heavy	Port Saxon
21 Jan Sat	1:00 PM	light	Cape Sable light
	1:30 PM	light	Cape Sable light
22 Jan Sun	7:25 AM	heavy	Clarks Harbor
	9:20 AM	light	Cape Sable light
	11:50 AM	2 heavy ones	Port Saxon
	1:00 PM	heavy	Port La Tour
	1:30 PM	light	Clarks Harbor
	1:30 PM	heavy	Barrington
	1:32 PM	heavy	Port Saxon
	1:33 PM	light	Cape Sable light
	1:33 PM	heavy	Clarks Harbor
23 Jan Mon	9:50 AM	very heavy	Fishing boat Browns Bank
	11:30 AM	light	Barrington
	11:35 AM	medium heavy	Ingomar
	11:36 AM	heavy	Port Saxon
	11:37 AM	light	Port La Tour
	11:40 AM	light	Village Dale
	1:30 PM	heavy	Fishing boat 35 mi S of Cape Negro Island
	3:20 PM	heavy	Port Saxon
	3:22 PM	light	Ingomar
	4:50 PM	very heavy	Fishing boat Browns Bank
24 Jan Tues	8:06 AM	medium	Cape Sable
	9:30 AM	light	Cape Sable
	11:30 AM	moderate	Village Dale
	11:35 AM	light	Northeast Harbor
	11:37 AM	light	Port Nature

Table 6 (Continued)
Reports of Acoustic Events – Nova Scotia
for Month of January

DATE	TIME (EST)	COMMENTS	
25 Jan Wed	7:13 AM	light	Ingomar
	8:05 AM	light	Cape Sable
	9:25 AM	light	Cape Sable
	11:25 AM	light	Cape Sable
	11:35 AM	light	Village Dale
	11;35 AM	light	Shag Harbor
	2:00 PM (approx)	heavy	Baccaro
	3:00 PM (approx)	light	Village Dale
26 Jan Thurs	2:45 PM	light	Ingomar
27 Jan Fri	8AM-9PM	22 different calls over 20 mile area	
28 Jan Sat	8:00 AM (approx)	light	Cape Sable light
	8:09 AM	light	Stoney Island
	9:00 AM	light	Barrington
	9:45 AM	light	Bear Point
	1:30 PM	heavy	Barrington
29 Jan Sun	8:00 AM (approx)	heavy	Baccaro
	8:03 AM	light	Stoney Island
	8:05 AM	heavy	Barrington
	8:05 AM	heavy	Lower Clark Harbor
	8:05 AM	medium	Cape Sable light
	9:30 AM	heavy	Shibbourne Township
	9:40 AM	heavy	Cape Sable light
	9:40 AM	heavy	Doctors Cove
	9:45 AM	light	Stony Island
	11:40 AM	light	Stony Island
	11:40 AM	heavy	Barrington
	11:40 AM	heavy	Baccaro
	11:45 AM	heavy	Barrington
	1:30 PM	heavy	Northeast Harbor
	1:30 PM	heavy	Doctors Cove
30 Jan	8:00 AM (approx)	heavy	Baccaro
	8:00 AM (approx)	heavy	Centervill (Cape Sable Island)
	8:05 AM	medium	Cape Sable Island
	8:05 AM	medium	Baccaro
	8:05 AM	light	Ingomar
	8:05 AM	heavy	Clarks Harbor
	8:07 AM	medium	Lower Clarks Harbor
	10:15 AM	heavy	Cape Sable Island
	10:15 AM	moderate	Baccaro
	10:18 AM	heavy Lower	Clarks Harbor
	10:18 AM	heavy	Ingomar

Table 6 (Continued)
Reports of Acoustic Events -- Nova Scotia
for Month of January

DATE	TIME (EST)	COMMENTS	
	10:18 AM	heavy	Shag Harbor
	10:25 AM	very heavy	East Baccaro
	10:30 AM	heavy	Centerville
	11:43 AM	light	Cape Sable Island
	11:45 AM	heavy	Baccaro
	11:48 AM	heavy	Ingomar
	11:50 AM	heavy	Village Dale
	11:50 AM	heavy	Clarks Port
	1:45 PM	light	Cape Sable Island
	1:52 PM	heavy	Ingomar
	1:53 PM	medium	Clyde River
	1:53 PM	medium	Village Dale
	1:53 PM	light	Doctors Cove
31 Jan Tues	9:05 AM	heavy	Clarks Harbor
	9:08 AM	heavy	Baccaro
	9:09 AM	medium	Lower Clarks Harbor
	9:12 AM	heavy	Barrington
	9:12 AM	heavy	East Baccaro
	9:12 AM	heavy	Ingomar
	9:13 AM	very heavy	Cape Sable light
	9:15 AM	heavy	Stony Island
	9:25 AM	very heavy	Cape Sable light
	9:25 AM	heavy	Baccaro
	9:26 AM	heavy	Barrington
	9:26 AM	medium	Lower Clarks Harbor
	9:28 AM	heavy	East Baccaro
	9:30 AM	medium	Clarks Harbor
	10:25 AM	moderate	East Baccaro
	11:55 AM	heavy	Port Saxon
	12:34 PM	heavy	Cape Sable light
	12:35 PM	heavy	Clyde River
	1:37 PM	heavy	Shibbourne Township
	1:59 PM	heavy	Shibbourne Township
	2:00 PM (approx)	medium	Stony Island
	4:30 PM	light	Stony Island
1 Feb Wed	9:10 AM	light	Shibbourne Township
	9:15 AM	light	Barrington
	9:15 AM	light	Clyde River

scheduled arrival and departure times for Concorde at New York (JFK) and Washington (Dulles) were also plotted and compared to the Nova Scotia pattern. As can be seen, in Figure 23 excellent correlations can be obtained for travel time corrections of 38 minutes before arrival and 60 minutes after departure. At this point in the analysis NRL informed the Federal Aviation Administration of our correlation and provided them with our data. The original purpose for NRL investigators to look at the Nova Scotia data was to see if there was a common geophysical phenomenon producing the effects all along the east coast from Nova Scotia to Charleston. When it become apparent that this was not the case and in view of our charter and time constraints, the NRL staff left the Nova Scotia problem to the Canadian government and concentrated on the New Jersey and Charleston events. It has been suggested later that the Nova Scotia events may be correlated with the times that Concordes make a turn to adjust their course near Nova Scotia. As pointed out in the previous section on maneuvers, turns will produce an especially intense boom. Persons concerned with reducing the Nova Scotia complaints may find it useful to look at these times in more detail.

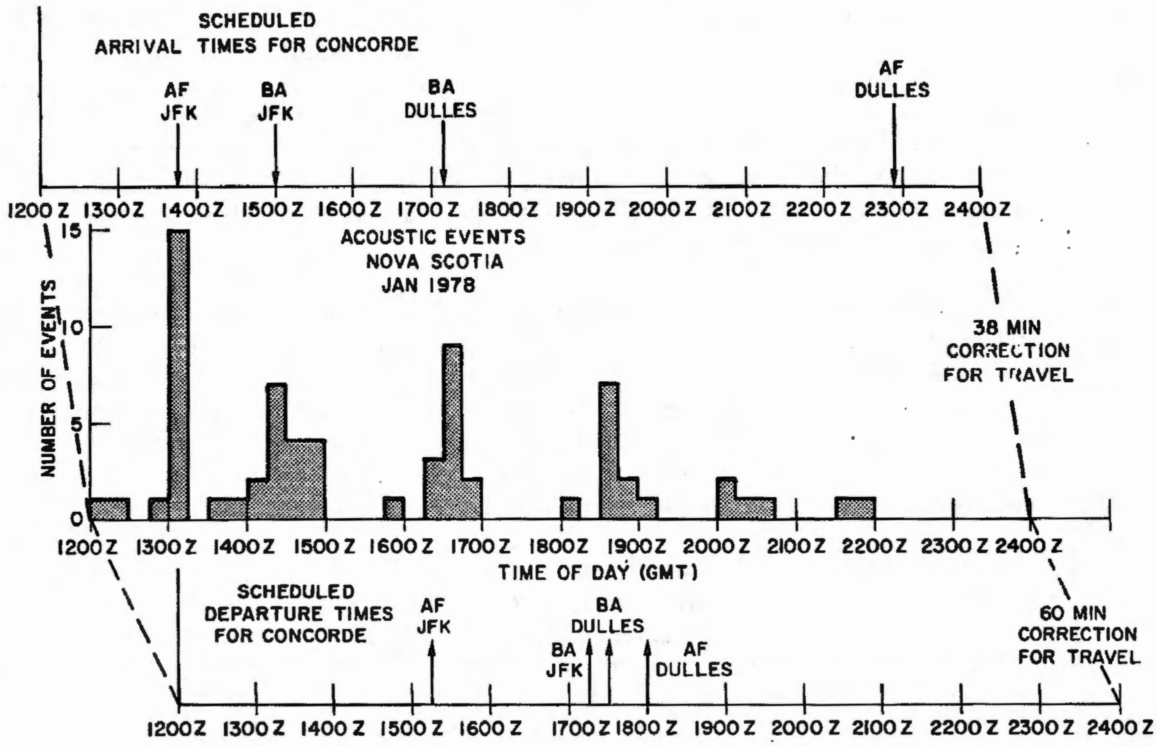

Figure 23 — Nova Scotia events according to time of day

Military Supersonic Aircraft

At the outset of the investigation the designated Air Force R&D point of contact queried the data bank in which reports of supersonic flights are maintained. He received a negative response for the days of interest up to that time (6 January).

Interviews with military pilots established that they do not maintain precise records of their periods of supersonic flight. In crossing from the subsonic to the supersonic regime, pilots' attention is directed to the control of their aircraft and the requirements of their mission. Because of the possible error in establishing the precise time of transition to supersonic flight, the entry of data into the data base is often overlooked.

As more data were accumulated and the cultural pattern became stronger and most of the natural and manmade sources were rejected, it became necessary to review military aircraft operations. Recognizing the problems that stand in the way of 100% reporting of supersonic flight, the question presented to Air Force, Navy, Marine and NASA airfields was rephrased. Organizations controlling the offshore warning areas where supersonic flight is permitted were asked if aircraft capable of supersonic flight were in the adjacent warning areas at the times when convincing citizens' reports and measured acoustic events coincided. This query produced answers which showed that up to the time of the query (12 January 1978) there were military aircraft capable of supersonic flight in warning areas adjacent to New Jersey and Charleston during events that resembled the acoustic events first reported on 2 December 1977. Table 7 summarizes military flight operations of supersonic capable aircraft in contiguous warning areas. These areas are shown in Figure 24.

The correlation was particularly impressive in the Charleston area. In the period 2 December 1977 through 12 January 1978, 20 events were reported. On 17 of these events F-4 or F-15 aircraft were operating in the Standard Operating Areas south of Charleston. Of the seven events where supersonic aircraft were not found aloft, four events were not detected on the seismograph, two of the reports which did not correlate with the presence of aircraft capable of supersonic flight, were from a single observer located about 25 miles inland. One such event was observed on the seismograph but not reported by citizens. Considering that no attempt was made in this analysis to throw out possible errors in observation time by citizens, this is believed to be a convincing correlation.

After the heavily reported 12 January event in the Charleston area, interviews with pilots showed that their training plan involved intercept exercises in supersonic flight with courses radial to the VORTAC beacon at Charleston. Supersonic flight in these areas is an authorized and routine procedure. Since the range to the nearest coast is 42 km, supersonic booms are not usually a concern to residents. A ray tracing based on the atmospheric conditions at Charleston on 2 December 1977, however, show that on that day supersonic booms should be heard as far away as 100 km from sources at all altitudes above 5000 meters (Figure 8).

In the New Jersey area in the period from 2 December to 16 January there were 6 events reported by creditable observers which were also confirmed on scientific instrumentation. For this group of events many of the observers reported only approximate times, so event times were taken from the earliest sensor recording of the event, and corrected for signal travel time from the source to the receiver. On all six such events an F-14 or several F-106 aircraft were operating in the warning areas W-107 and W-108 off the coast of New Jersey. There were a number of cases where scientific instrumentation alone recorded similar signals and F-106 were known to be operating in the warning areas. However, in the absence of citizens' observations, these were not considered in the correlation. Conversations with pilots who operated in the warning areas off the coast of New Jersey indicate that high speed runs frequently occur on radials toward the VORTAC near Atlantic City. It has not been possible to determine how many of these runs were supersonic or on what days they were supersonic. Computer-generated ray traces based on 2 December 1977 atmospheric conditions indicate that good acoustic propagation conditions existed from the extreme southwest part of warning area W-107 (Figure 8). Based on the pattern of observations the 2 December events in New Jersey might have been caused by aircraft passing south to north just off the New Jersey coast. A supersonic aircraft flying at about a 2500-meter altitude, and making a sharp turn and/or climb to enter the warning area from a point midway between Atlantic City and Toms River, New Jersey could have caused the events as reported and measured.

Table 7a
W-107 Military Air Ops (New Jersey)

Date	Time	No. & Type Acft		Organization	Assoc. Opareas
Dec. 2	1004-1210	5	F-106	119th Ftr Int Sqdn	
	1427-1634	5	"	Atlantic City, NJ	
4	1301-1459	7	"	"	W-108
6	1422-1646	3	"	"	
7	1434-1628	3	"	"	
	2013-2402	6	"	"	W-108
8	1433-1620	2	"	"	
	2000-2204	6	"	"	W-108, W-386
9	1750-2035	3	"	"	
10	0957-1217	5	"	"	W-108, W-386
	1437-1622	2	"	"	W-108, W-386
13	1007-1216	3	"	"	
	1826-2043	3	"	"	W-108, W-386
15	1005-1147	2	"	"	
	1426-1631	3	"	"	
	1830-2030	2	"	"	
20	1003-1207	4	"	"	W-108
	1431-1642	4	"	"	
21	1428-1632	6	"	"	
	1845-2017	2	"	"	
22	0955-1200	5	"	"	W-108, W-386
	1438-1644	4	"	"	W-108, W-386
	1845-2047	2	"	"	
23	1431-1607	2	"	"	
26	1945-2045	2	"	"	
27	1000-1202	3	"	"	
28	1306-1523	4	"	"	W-108
30	1018-1221	2	"	"	
Jan. 4	1030-1238	4	F-106	"	W-108, W-386
	1427-1623	4	"	"	W-108, W-386
5	1002-1206	3	"	"	W-386
	1444-1638	4	"	"	W-386
	1834-2034	2	"	"	W-108
6	0958-1200	4	"	"	W-108, W-386
	1428-1625	4	"	"	W-108
	1833-2056	2	"	"	
7	1434-1630	4	"	"	W-386
11	1010-1214	4	"	"	W-108
	1429-1634	4	"	"	
12	1424-1615	4	"	"	W-108, W-386
	1841-2045	2	"	"	
14	1440-1547	4	"	"	W-108, W-386

Table 7a (Continued)

W-134/W-132/W-157 Military Air Ops (South Carolina)
Marine Corps Air Stations, Beaufort, SC

Date	Time	No. & Type Acft	Organization	Area
Dec. 2	0915-1015	2 F-4, 1 F-15	VMFA-115, 1st TFW	SOA-1
	0915-1030	2 F-4	VMFA-122	SOA-2
	0930-1030	1 F-4, 2 F-15	VMFA-115, st TFW	SOA-3
Dec. 15	0800-0920	3 F-4	VMFA-333	SOA-2
	0930-1110	3 F-4	VMFA-333	SOA-3
	1000-1202	4 F-4	VMFA-122	SOA-2
Dec. 20	1300-1430	2 F-4	VMFA-333	SOA-2
Dec. 22	0800-0930	4 F-4	VMFA-333	SOA-2
	0810-0910	3 F-4	VMFA-115	SOA-1
	0925-1045	4 F-4	VMFA-333	SOA-2
	0930-1045	2 F-4	VMFA-115	SOA-1
Jan. 4	0800-0915	1 F-4	VMFA-115	SOA-1
	0910-1045	2 F-4	VMFA-333	SOA-2
	0921-1035	2 F-4	VMFA-451	SOA-2
	1000-1100	2 F-4	VMFA-115	SOA-1
Jan. 5	0730-0830	1 F-4, 1 TA-4	VMFA-115	SOA-2
	0730-0851	4 F-4	VMFA-333	SOA-3
	0800-0950	3 F-4	VMFA-312	SOA-1
	0900-1000	1 F-4, 1 TA-4	VMFA-115	SOA-2
	0905-1031	4 F-4	VMFA-333	SOA-3
	1010-1210	2 F-4	VMFA-312	SOA-1
Jan. 6	0850-1005	3 F-4	VMFA-122	SOA-3
	0900-1000	2 F-4	VMFA-333	SOA-1
	0900-1030	2 F-4	VMFA-312	SOA-3
Jan. 12	1330-1455	2 F-4	VMFA-115	SOA-1

Table 7a (Continued)

W-108 Militry Air Ops (Delaware/Maryland)

Date	Time	No & Type Acft		Organization	Assoc. OPAREAS
Dec. 2	0930-1200	1		F-14	NATC, PAXRIV
	0945-1015	3	F-15	1st TFW	AR-612
	1427-1634	5	F-106	119th FIS	W-107
Dec. 15	1005-1147	2	F-106	119th FIS	W-107
Dec. 20	1003-1207	4	F-106	119th FIS	W-107
	1431-1642	4	F-106	119th FIS	W-107
Dec. 21	1300-1330	3	F-155	1st TFW	AR-612
	1345-1415	3	F-15	1st TFW	AR-612
	1845-2017	2	F-106	119th FIS	W-107
Dec. 22	0955-1200	5	F-106	119th FIS	W-107, W-386
	1438-1644	4	F-106	119th FIS	W-107, W-386
	1845-2047	2	F-106	119th FIS	W-107
Dec. 27	1715-1745	4	F-15	1st TFW	AR-612
	1800-1830	4	F-15	1st TFW	AR-612
Dec. 28	1306-1523	4	F-106	119th FIS	W-107
	1715-1745	4	F-15	1st TFW	AR-612
	1815-1845	4	F-15	1st TFW	AR-612
Jan. 4	1030-1238	4	F-106	119th FIS	W-107
	1300-1330	4	F-15	1st TFW	AR-612
	1400-1430	2	F-15	1st TFW	AR-612
	1427-1623	4	F-106	119th FIS	W-107, W-386
Jan. 5	1000-1030	3	F-15	1st TFW	AR-612
	1444-1638	4	F-106	119th FIS	W-107, W-386
	1834-2034	2	F-106	119th FIS	W-107
Jan. 10	1000-1030	3	F-15	1st TFW	AR-612
	1045-1115	3	F-15	1st TFW	AR-612
Jan. 12	1000-1030	2	F-15	1st TFW	AR-612
	1045-1115	2	F-15	1st TFW	AR-612
	1424-1615	4	F-106	119th FIS	W-107, W-386

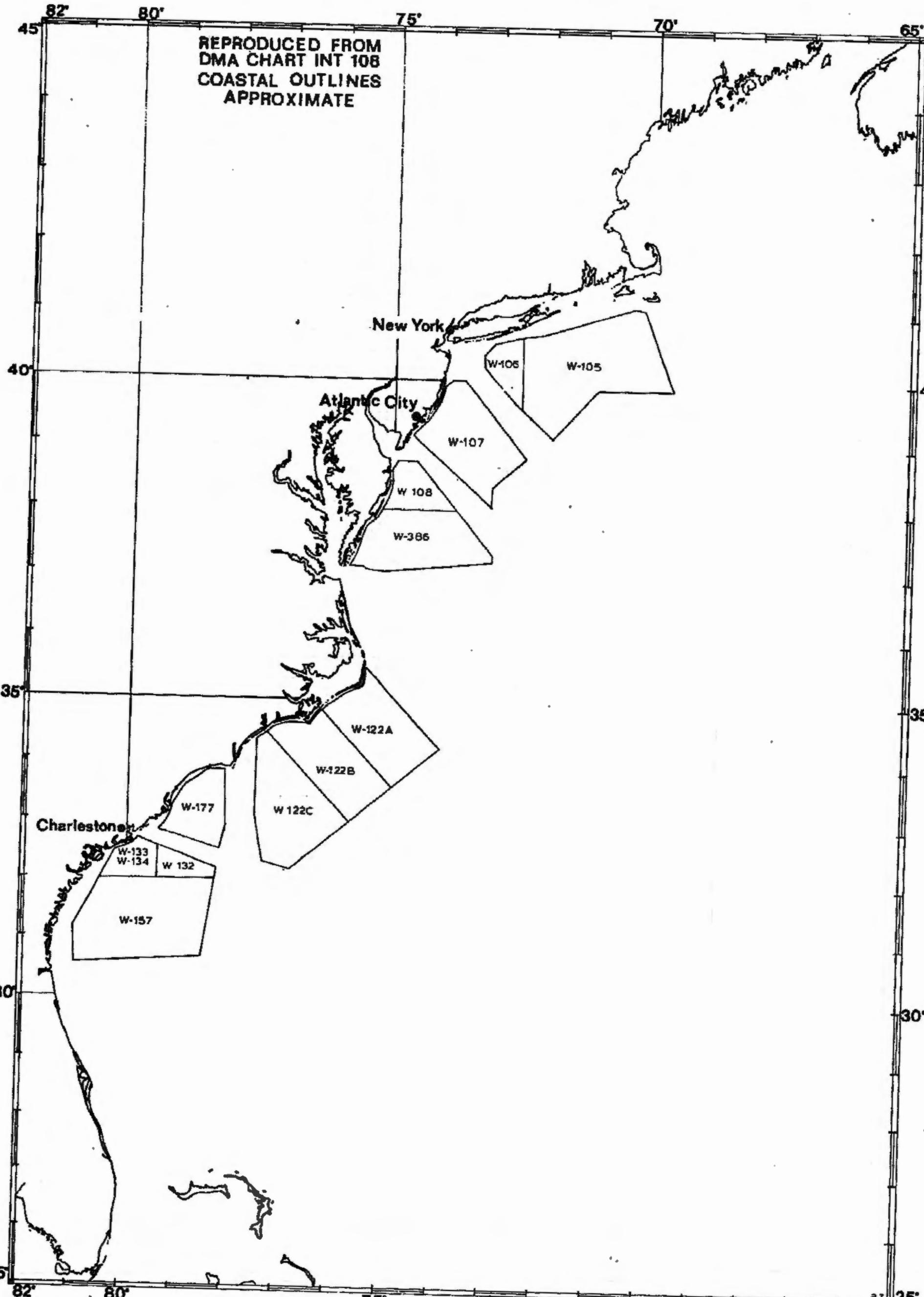

Figure 24a — Location of warning areas

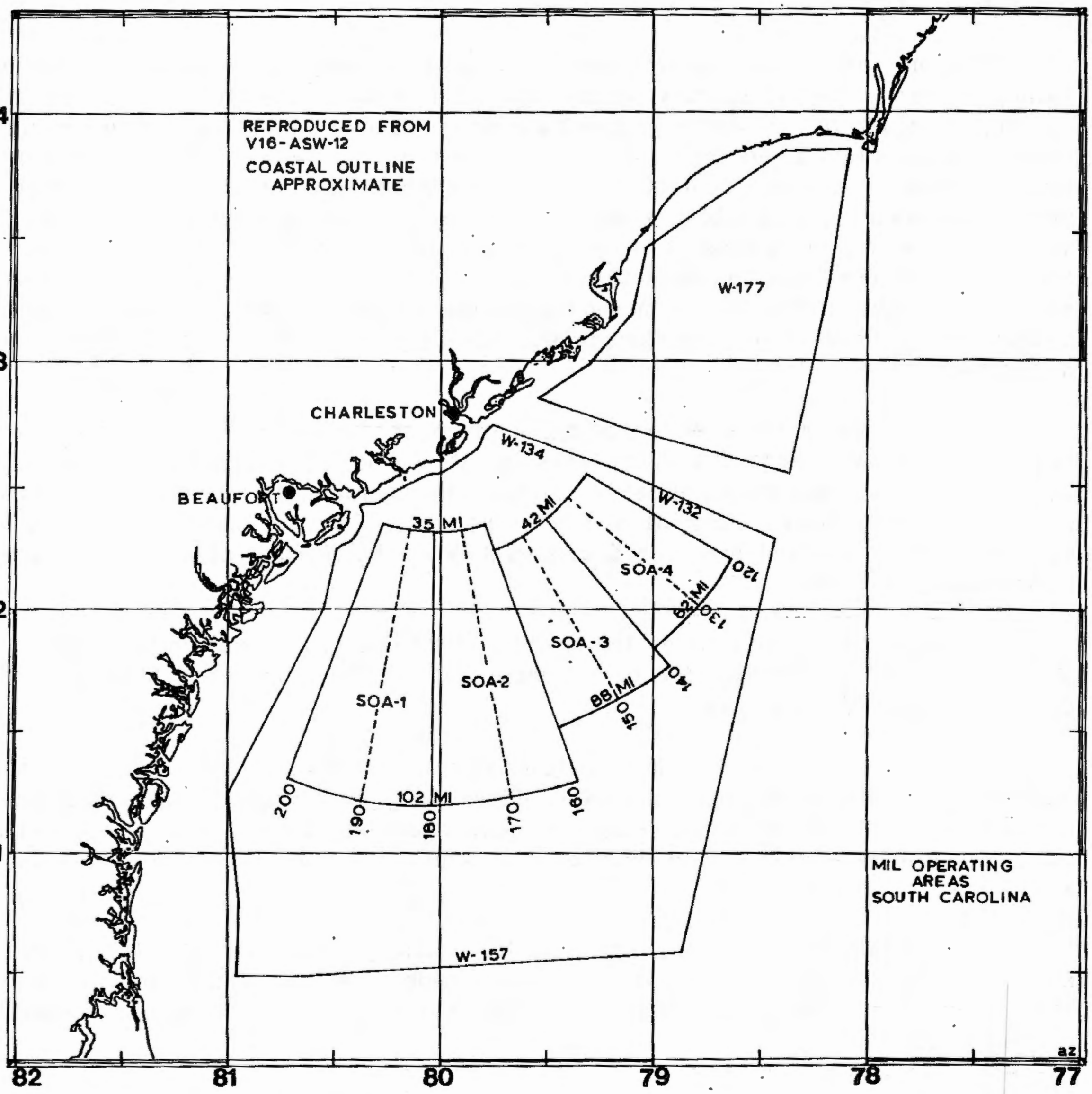

Figure 24b — Location of standard operating areas

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Space Phenomena

Meteorites

Major Meteor Showers

There are two types of meteor input to the earth's atmosphere — shower meteors and sporadic meteors. Shower meteors occupy their orbit as either a stream or a swarm. The stream more or less fills the entire orbit with a constant number density where as the swarm is clumped so as to have a very high number density at one point and zero density at most other spots. A meteor swarm may be likened to an orbiting gravel pit. Stream shower meteors yield meteor showers on an annual basis when the earth's orbit crosses the orbit of the stream. The swarm yields only periodic showers. However, it is estimated that 66% of all meteors observed optically and 95% observed by radio techniques are sporadic. It is also noted that the frequency of events is greater than average after midnight where the observer is in the unsheltered hemisphere. For a similar reason, the seasonal dependence peaks in the autumn in the northern hemisphere.

During December, there are two groups of stream shower meteors. These are the Geminids and the Ursids. According to the American Meteor Society, the Geminids series is the strongest annual meteor shower visible all night on the morning of 14 December. It was an excellent display from local midnight for 3 hours with rates of over 70/hour. December 13 was as strong as the Perseids shower with December 9-12 also being active days. The shower was nearly over on December 15.

The Ursids which occurred on the morning of 22 December were a north circumpolar shower with few observations due to inclement weather. The north was favored for this display with rates of 10-15/hour.

The only meteor showers in January occur with a sharp intense peak on the morning of 3 January. This was the Quadrantids shower. Since the peak is sharp, the display is good only over a hemisphere with the northern latitudes heavily favored. Recent rates have been above 30/hr in sourthern Florida to near 70/hr in the north. The Quadrantids peak around 2 or 3 a.m.

We conclude that, with exception of a few chance coincidences of solar-geophysical events with the sonic disturbances, that there is no evidence in hand to suggest an association between the two. This is visually obvious upon inspection of the various charts provided herein.

This report made mention of only the stream meteor showers. During the largest shower, there were no sonic events recorded. There *were* sonic events recorded during the Ursids (December 1977) and the Quadrantids (January 3). Howeber since these showers are hemispherical in nature and very sharply peaked, it is regarded coincidental that there were reports of sonic events at these times. Meteor showers are probably not the explanation for our sonic events. It is also noted that shower meteors are only a small percentage of the total meteoric input to the earth, with sporadic meteors being the greatest contributors. In addition, sporadic meteors are random. Since the sonic events are discrete and localized and the sporadic meteors are random, there appears to be no logical connection between the two.

The unusual signals detected at the Lamont-Doherty Observatory on 2 December 1977 were compared with sonic signals received from a fuel tank explosion in 1970 at Linden, New Jersey. In addition, an analysis was made of the frequency content of the received signals. Based on the comparisons an isotropic source equivalence of between 1 and 10 tons of TNT would be required. If the sources of the 2 December 1977 events were not isotropic radiators, considerably less energy would be required. The major frequency component of the observed signal appeared to be about 3 Hz. Using well-known relationships between frequency and charge size, an upper limit for the equivalent isotropic source would be about 1 ton TNT. The detonation of 1 ton of TNT equates to an energy release of 4.6×10^{16} ergs. For the sake of discussion, three possible source levels will be considered, — 10^{16}, 10^{17}, and 10^{18} ergs.

Some meteors, called detonating bolides, do cause sonic booms. A recent event (8 March 1976), which occurred over China, is chronicled in the current issue of *Scientific American* (February 1978, p. 84). The accompanying fireball was seen for hundreds of miles, and many pieces were later found. However, not all meteors in the lower atmosphere leave such traces. The huge meteor which fell in 1908 near Tunguska, Siberia, left nothing behind, but caused one of the most spectacular sound events ever recorded. The boom knocked over yurts, stampeded reindeer, broke windows 65 km away, and was recorded by seismometers around the world. A more typical fall was over Treysa in central Germany in 1916, sounds from which were heard by numerous observers within a radius of 100 km.

Frequency of Occurrence

Detonating bolides are rare, there being less than 100 events so far documented. To obtain an upper limit on the rate of occurrence, we will make estimates based on the energy required, that all of the energy of the incoming object is converted to low-frequency sound. The available energy is $1/2\ mv^2$, where m is the mass of the meteor and v is its incoming velocity. Although there is no intrinsic upper limit of the velocity, no object from outside the solar system has ever been observed near the earth. Thus we assume the object is part of the solar system, in which case the maximum velocity it can have at the distance of the earth from the sun is 42 km/sec. If the direction is just right, the velocity of the earth, 30 km/sec, will add to this, giving a maximum possible entry velocity of 72 km/sec. (The earth's gravitational attraction has a negligible effect.) An object of just under 4 kg will release 10^{17} ergs at this, the highest physically possible velocity. A mass of 40 kg will be required to release 10^{18} ergs. However, high-velocity objects lose energy rapidly, and seldom penetrate below an altitude of 20 km, above which they cannot be heard. Most fireballs are, in fact, moving quite slowly in "catch-up" orbits, and enter at velocities of typically 20 km/sec or less (the free-fall velocity would be about 11 km/sec). In this case the energy requirement sets the mass at a minimum of 16 kg for 10^{16} ergs, 160 kg for 10^{17} ergs, and 1600 kg for 10^{18} ergs.

Various data indicate that the flux of particles at the earth with mass greater than M kg is about $4 \times 10^{-5} M^{-1.2}$/sec. Thus the flux has been computed for the three energy releases required for 11.0 km/sec meteors and is shown in Table 8.

Estimating the Probability

Assuming independent events (justification of which is discussed later), the probability of two events being in the same area in the interval Δt is

$$P = \phi \Delta t\ Al/AE.$$

Table 8
Meteorite Flux

Energy	Required Mass	Frequency	Number of meteors per year
10^{16}	16 kg	1.4×10^{-6}sec	44.2
10^{17}	160 kg	9.1×10^{-8}	2.9
10^{18}	160 kg	5.7×10^{-9}	.18

Here ϕ is the flux per day over the earth, AE is the projected area of the earth, and Δt is the time between impacts. In the case of the 2 December New Jersey events $\Delta t \simeq 6$ hours or 0.25 day. Based on ray tracing calculations, both events occurred within an impact area AI that may be taken as a circle of about 10-km radius. Therefore, since the radius of the earth is 6372 km $AI/AE = (10)^2/(6372)^2$ or 2.5×10^{-6}. We can now compute the probability of two meteors landing within 6 hours of each other within a circle of 10 km radius for different required energies of interest. This is shown in Table 9.

Table 9
Probability of Two Meteors

Energy	Flux per day	Flux per six hour period	Probability of occurrence
10^{16}	1.2×10^{-1}	3.0×10^{-2}	8×10^{-8}
10^{17}	7.9×10^{-3}	2.0×10^{-3}	5×10^{-9}
10^{18}	4.9×10^{-4}	1.2×10^{-4}	3×10^{-10}

These probabilities are extremely small ranging from one such event every 34,000 years for the most probable event to one per 10 million years for the least probable event.

Correlated Events

The probability might be expected to be higher if the two events are related; i.e., pieces of the same object. We consider two cases:

1. High-velocity object. In this case the earth's field has negligible effect, anu the earth can be regarded as a target for a shotgun burst. We require that two objects be separated by 10^6 km (i.e., 6 hours) along the earth's orbit around the sun, yet be separated by only 10^4 km transverse to the orbit. Given this, the second object must hit a patch that is only 10^{-3} of the available target. This would appear to be highly improbable.

2. Low-velocity object. In this case the earth's field dominates the objects entering hyperbolic orbits, the projection of which lies along a great circle. Since New Jersey is at a high latitude, it does not lie along the same great circle over a 6 hour interval; in fact in this case a correlated event is specifically precluded.

Sound Observed from Past Meteorites

A starkly simplified procedure has been constructed by Revelle [1] to estimate the infrasound generated by high-velocity meteors entering the atmosphere at low angles to the horizontal. The basic model is a line source of blast waves created by hypersonic flow. The key input parameters are

1. Distance of meteor track to the observer on the ground

2. The fundamental period of the received time signal of overpressure at the ground station, measured at the instant of maximum amplitude

3. The measured overpressure (= acoustic signal) level at the ground station

4. The adiabatic (low amplitude) speed of sound.

From these parameters and from a simplified theory of nonlinear propagation in an isothermal atmosphere, one can *predict* the physical size of the meteor, its energy, etc. Alternatively, one can use the theory to *predict* received signal characteristics, distribution in space, etc., by assuming a meteor size, velocity, mass, etc., and choosing a specific source-observer geometry.

The generation of acoustic signals by meteors entering the earth's atmosphere from outer space is difficult to model mathematically. While existing models serve well to provide estimates, they all fall in the category of rough approximation. A convenient starting point is to consider the track of the meteor to be a *line source of blast waves* caused by supersonic flow. Accordingly, to form an estimate of the pressure level of sound radiated to a distant point it will be first required to calculate the energy E_o deposited by the meteor along its track. From this estimate one can tentatively assign a conversion efficiency of deposited energy into sound, and then arrive at an estimate of the sound level to be expected.

Assume the meteor is spherical, radius r_m, traveling with speed V through a resistive medium which exerts a drug force $\frac{1}{2}\rho V^2 C_D A$ on it. The symbol ρ is the mass density of the air, A is the projected area $(= \pi V_m^2)$, and C_D is the drag coefficient. One identifies this drag force with E_o, the deposited energy. Ordinarily all parameters in this formula for drag must be estimated. Assume the flow past the meteor is hypersonic. This allows C_D to be near unity. The speed V is troublesome to estimate. It will certainly have a history of values as the meteor interacts with the atmosphere. Experience shows that the entry speeds V_E likely to cause infrasound lie in the range of some 10 to 70 km/s. After entry the speed V itself will clearly be a function of altitude z. Formulas for $V(z)$ can be derived directly by solving the equations of motion of hypersonic flight. It is found that several curves $V(z)$ vs z are possible by selecting different values of the point where dV/dt (i.e. the acceleration) passes through its first zero. Direct observation of $V(z)$ by radar leads, of course, to a best estimate of V. Lacking this, one often resorts to charts of $V(z)$ vs z based on selected values of meteor mass density ρm, meteor radius r_m, and ambient pressure P_E^* at point of entry into the atmosphere (see Figure 1) of ReVelle [1]. At all events a value for V can be calculated from data or inferred as a reasonable estimate.

The problem of estimating r_m is also difficult. From classical theory of line blasts one can show that the diameter of the meteor is directly given as the ratio of the "shock radius" R_o, which divides the strong shock region from the weak shock region, and the Mach number $M = V/c$ (c being the speed of sound in linear theory),

$$d_m \simeq \frac{R_0}{M}.$$

Thus a crucial problem is the estimation of R_o. ReVelle [1] shows that R_o can be obtained by use of two experimentally determined parameters, namely T_g, the period (in seconds) of the fundamental frequency at the maximum amplitude of the received signal at the ground station, and $R_{z\rightarrow t}$, the distance from the center of the meteor at any instant to the transition radius which separates the region of weak shock from the region of small-amplitude linear propagation. A series of plausible arguments leads ReVelle to the assumption that $R_{z\rightarrow t}$ 1/2 of the total (radial) distance $R_{z\rightarrow g}$ for the meteor center to the observer on the ground. This last distance is then a *key* input parameter, presumably obtainable by measurement or inference. However obtained, it must be available before calculation can proceed.

Assuming then that $R_{z\rightarrow t}$ and T_g are on hand, one can calculate R_o. The calculation of R_o provides a reference distance, or scale, by which distances in the geometrical description of meteor and ground can be incorporated in the theory. From it one immediately estimates the diameter *dm* of the meteor. Values of *dm* likely to cause infrasound to begin at 1 cm and go up to 10 meters, or more. Meteors of *dm* = > 10 meters are considered large. When the size of the meteor is estimated, one can immediately find the deposition energy E_o, provided the mass density of the atmosphere at the altitude of entry is known. A model of the atmosphere is useful here. ReVelle [1] adopts an isothermal atmosphere, which permits calculation of the mass density at any altitude. Drag forces E_o so calculated have been listed by him for several observed meteors. They show a range of energy deposition from 2.8×10^{11} to 1.3×10^{3} ergs per centimeter of track.

In a similar way the total kinetic energy of the meteor upon entry can be estimated, $E = 1/2\ m\ V^2$. The mass density ρ_m of the meteor must be estimated to begin with. This is a matter of experience and inference. Densities from 0.3 to 7.7 g/cm^3 have been used in calculations. In a compilation of *E*'s for several observed meteors ReVelle comes up with a range from 3.5×10^{17} to 2.9×10^{21} ergs.

The calculation of blast wave pressure level, and acoustic pressure level, is severely complicated by the nonlinear physical processes associated with blast waves, and by the complexities of propagation in an inhomogeneous stratified medium. First, consider the nonlinearity problem. In blast theory (similar to explosion theory) the finite amplitude pressure wave near the center of the source propagates according to strong shock wave theory. In this shock region the speed of propagation exceeds the speed of sound by a large fraction, and the rate of falloff of pressure is much faster than inverse radial distance. Strong shock continues outward to a radial distance of about R_o. Beyond R_o a region of weak shock takes over. The characteristics of weak shock propagation are welldocumented in the literature, but few attempts have been made to apply it to an inhomogeneous stratified medium, such as the atmosphere. The weak shock region is terminated by a somewhat arbitrary boundary, namely the radial distance $R = R_{z\rightarrow t}$ (in ReVelle's notation). Beyond this boundary the pressure wave propagates according to linear acoustic theory. In all cases the observed pressure signal is acoustic, meaning that the amplitude is very much smaller than the ambient pressure. Whatever the region, whether strong shock, weak shock, or linear, the theory requires inclusion of some mechanism of viscous dissipation. ReVelle accounts for dissipation by introducing a dissipation parameter D_{ws} for the weak shock region (equation 28) and D_L for the linear region (equation 31).

Consider the problem of propagation in an inhomogeneous medium such as the atmosphere. A direct attack on this is too involved for the task on hand. Instead, ReVelle chooses his model to be an *isothermal atmosphere* in which geometric acoustic propagation is assured to be valid. This simplification has the one virtue of permitting a calculation of the propagation of excess pressure levels (called overpressures) in a straightforward way, but it obviously omits all consideration of amplification of pressure level by such phenomena of stratified media as skip-zone convergence, caustics, etc.

At all events the calculation of overpressure levels at all radial distances from the meteor is now made tractable. To begin, ReVelle takes the well-known formula of weak shock theory which gives overpressure (see equation (11)) and modifies it in two ways: he introduces a correction for the change in atmosphere density with altitude based on his assumption of an isothermal atmosphere, and he introduces dissipation factors D_{ws} and D_L as needed to account for viscous losses. The final formulas appear as equation (33) of his paper, together with the explanatory notes. These formulas allow one to *predict* the overpressure at ground receiving stations based on a few assumed parameters of meteor geometry. Naturally, it would be desirable to compare these predictions with measured overpressure. ReVelle lists the measured overpressures of five meteors in his Table I. Since by calculation one can associate with each measurement a radial range of the ground station to the meteor $(R_{z \to g})$ one has available a valuable set of data to serve as a guide for comparison (Table 10):

Table 10

Range vs Measured Overpressure

Range (km)	Overpressure (dyne/cm^2)
1705	4.00
0793	1.10
0147	0.25
2497	1.25
0360	2.30

Received overpressure level is an excellent diagnostic. An equally useful diagnostic is the frequency content of the received signal, obtainable from its time record. Spectrum analysis is of course direct and simple. But caution is needed in interpreting the results. The reason is this: Nonlinearity in shock wave propagation alters the frequency content of the overpressure wave along its path. However, one can trace these alterations of spectrum by use of a reasonable model of shock propagation. With such a model it proves valuable to estimate the fundamental frequency in the shock wave spectrum at a range of 10 R_o. This is given by equation (15) of ReVelle's paper, which shows that $fm \gtrsim R_o^{-1}$. A physical event is revealed, namely that the fundamental frequency of the spectrum depends on the expansion and contraction of a cylinder of radius R_o coaxial with the meteor track. As the wave propagates beyond R_o its fundamental period *increases* so that on the ground one predicts a lower fundamental in the received spectrum. This prediction is made by equation (34) of ReVelle. Applying both equations one finds for the Revelstoke meteor a fundamental of 0.2 cycle/sec at a range of 10 R_o, and 0.06 cycle/sec at a range of 1705 km. A list of dominant frequencies measured at ground stations for five meteors has been compiled by ReVelle (Table 11). One can associate with them a meteor to receiver range, and a meteor mass.

The dominant frequency of the 2 December events was approximately 3 Hz and the observed overpressure at a range of about 175 km was 2.5 Pa. This set of parameters would have been compatible with a meteor of about 16 kg.

Table 11
Range Vs Mass

Mass (g)	Range (km)	Fundamental (Ground) Frequency (cps)
4×10^9	1705	0.060
10^6	0793	0.400
10^8	0147	0.250
10^{11}	2497	0.018
10^9	0360	0.080

Conclusions

While a meteor could in principle have generated the observed acoustic signals, we have found that the probability of two meteors landing within a circle of radius of 10 km within six hours is an event of extremely low probability. Thus meteors are an extremely unlikely explanation for the observed acoustic effects.

General References:

1. ReVelle, D.O., 1976, "The Radiation of Infrasound By Meteors," J. Geophys. Res. **81** (7): 1217.
2. Millman, P.R., and McKinley, D.W.R., 1963, in *The Moon, Meteorites, and Comets* B.M. Middlehurst and G.R. Kuiper, ed., University of Chicago Press, Chicago) pp 674-773.
3. McKingley, D.W. R., 1961, *Meteor Science and Engineering* (McGraw-Hill, New York).
4. Heide, F., 1964, *Meteorites,* E. Anders and E.R. DuFresne, trans. (University of Chicago Press, Chicago).

Launch of Missiles on U.S. East Coast

Acoustic measurements made along the east coast of the U.S. over ten years ago established the fact that large missile launches from Cape Kennedy such as the Saturn series created significant infrasound measured routinely as far north as Fort Monmouth, N.J. The record of launches by NASA, Air Force, and Navy at Cape Kennedy and associated ranges and at Wallops Island was obtained and is shown as Table 12. There is no correlation between the acoustic events of December 1977 and January 1978 and any missile launches from these locations.

National agencies whose task it is to detect reentry of missiles and satellites found no correlation between the December –January events and reentry bodies.

Large Bodies in Low Orbit

The measurement of missile launches mentioned before also established that the upper altitude for generation of acoustic signals that reached the ground was about 160 km (90 miles). Above this altitude no signals from missiles or satellites have ever been detected.

Table 12

East Coast Missile Launches in December 1977-January 1978

Date	June (EST)	Missile	Launch Area
1 Dec	1330	Super Loki	Wallops Island
2 Dec	1434	Taurus Orion	Wallops Island
5 Dec	0908	TRIDENT	Cape Kennedy
7 Dec	1033	Super Loki	Wallops Islands
7 Dec	1045	Super Loki	Wallops Islands
7 Dec	1104	Super Loki	Wallops Island
7 Dec	1121	Super Loki	Wallops Island
7 Dec	1154	Super Loki	Wallops Island
11 Dec	1745	Not Identified	Cape Kennedy
14 Dec	0700-0730	Cruise Missile	Grand Turk
14 Dec	1057	Super Loki	Wallops Island
14 Dec	1120	Super Loki	Wallops Island
14 Dec	1212	Super Loki	Wallops Island
14 Dec	1947	Thor Delta	Cape Kennedy
15 Dec	0959	Super Loki	Wallops Island
15 Dec	1036	Super Loki	Wallops Island
15 Dec	1156	Super Loki	Wallops Island
21 Dec	1014	Super Loki	Wallops Island
4 Jan	1029	Super Loki	Wallops Island
5 Jan	0001	Nike Apache	Wallops Island
6 Jan	1030	Super Loki	Wallops Island
6 Jan	1915	Atlas Centaur	Cape Kennedy
9 Jan	1038	Super Loki	Wallops Island
11 Jan	1037	Super Loki	Wallops Island
11 Jan	1055	Super Loki	Wallops Island
18 Jan	1035	Super Loki	Wallops Island
18 Jan	1052	Super Loki	Wallops Island
18 Jan	1521	TRIDENT	Cape Kennedy
25 Jan	1033	Super Loki	Wallops Island
26 Jan	1236	Thor Delta	Cape Kennedy

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There is no way for a satellite at 160 km to sustain itself in orbit at that altitude, and it fails rapidly in the course of one or two orbits because of atmospheric drag. Thus there is no mechanism by which a satellite low enough to produce sound on the surface of the earth could sustain itself long enough to repeat the process over the period in question.

Solar-Geophysical Background

Although it is unlikely that various solar-geophysical activities (i.e., magnetic events, ionospheric disturbances, auroral activity, and x-ray activity) are able to stimulate acoustic vibrations in the atmosphere of the nature and order of magnitude reported, this section is included for completeness and to discount that possibility. This section draws upon data obtained from NRL (in-house SOLRAD-HI data, NOAA (the SELDADS data base), the Naval Observatory (VLF disturbances), and the Air Weather Service (AFGWC/SESS data base). Table 13 summarizes the types of data utilized.

Data Presentation

The x-ray photometer plots contained here are current versions of the quick-look software developed by Uffelman and Wagner [1] as part of the SOLRAD HI SOLOLS data processing system. SOLRAD HI ultraviolet data are also available, but since it was uneventful during the entire December-January time period, it was not of sufficient interest to include in this report. The other graphs—exclusive of the VLF propagation data and the event logs, and the A-index—were developed as part of the SEDAC (Space Environment Data Analysis Center) software capability. Extensive use was made of Air Force and NOAA data resources, however, as indicated in Table 13.

Figures 25-51 exhibit SOLRAD HI x-ray photometer data for 1-3 December, 14-16 December, 19-31 December, 2-7 January, and 9-11 January. These are periods surrounding and including reports of sonic events (see Table 2). Unfortunately, due to the skeletonized nature of the SOLRAD data arising from the failure of the SOLRAD 11A spacecraft, not all flare information is available in Figures 25-51. However, tabulations of GOES 1-8 A x-ray events have been obtained from the NOAA SELDADS data base along with magnetic events and SIDs. This information is certained in Tables 14 and 15 and the times indicated are Greenwich Mean Time (GMT). These events are also exhibited in Figures 52 and 53 for December and January, respectively. The x-ray flare class notations B, C, M, and X indicate the maximum flux density ϕ in MKS units. These are

$$B: \phi < 10^{-6} \text{ Joules m}^{-2} \text{ sec}^{-1}$$

$$C: 10^{-6} \leqslant \phi < 10^{-5} \text{ Joules m}^{-2} \text{ sec}^{-1}$$

$$M: 10^{-5} \leqslant \phi\ 10^{-4} \text{ Joules m}^{-2} \text{ sec}^{-1}$$

$$X: \phi \geqslant 10^{-4} \text{ Joules m}^{-2} \text{ sec}^{-1}.$$

Sudden ionospheric disturbances (SIDs) and magnetic events are also plotted in Figures 52 and 53.

Magnetic activity indices from Fredericksburg, Va. for December and January are provided in Figures 45-46 (A_{FR}) and Figures 54-55 (K_{FR}).

The A index, which can range from 0 to 400, is provided on a daily basis, while the K index, ranging between 0 and 9, is given once every 3 hours. An A index above 30 is considered a magnetically disturbed day.

Table 13
Geophysical Data Sources

DATA TYPE	SOURCE
Solar x-ray photometers (SOLRAD HI) 0.5 - 3A 1 - 8A 2 - 10A 8 - 16A 44 - 60A	NRL
Solar Events X-ray events Sudden Ionospheric Disturbances (SID's)	NOAA
Magnetic Events (Worldwide)	NOAA
Magnetic Activity (Fredericksburg, Va) A Index K Index	NOAA
Total Electron Content (TEC) of the Ionosphere Goose Bay, Labrador Sagamore Hill, Mass. Cape Kennedy, Fla. Ramey AFB, P.R.	AFGWC/NOAA
Critical Frequency of the F2 maximum (f_oF2) Goose Bay, Labrador Wallops Island, Va. Cape Kennedy, Fla.	AFGWC/NOAA
HF Skip Distance Factor, (M3000) (related to height of the F2 maximum) Goose Bay, Labrador Wallops Island, Va. Cape Kennedy, Fla.	AFGWC/NOAA
Propagation Disturbances at VLF (East Coast Daytime)	Naval Observatory

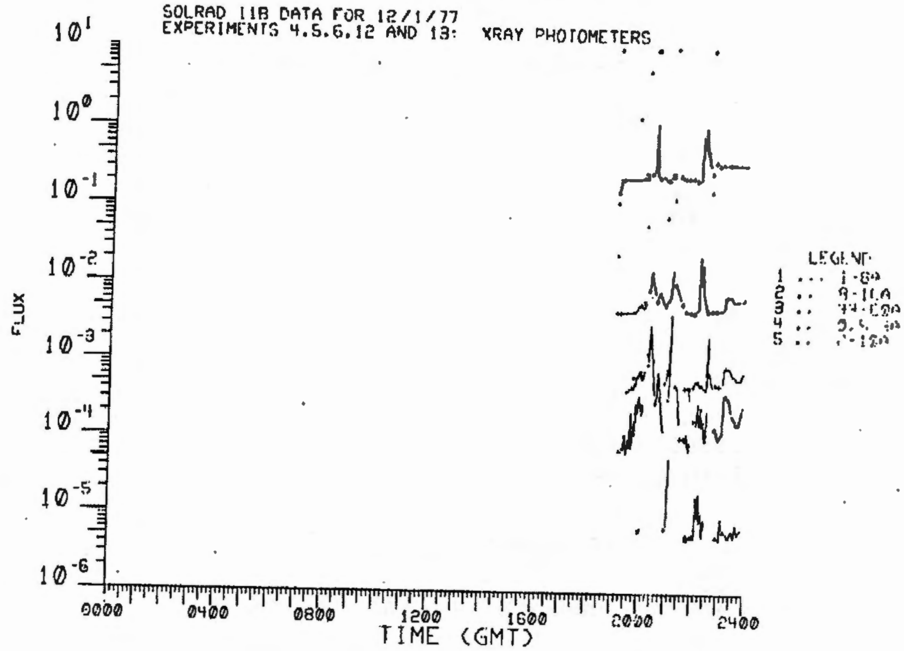


Figure 25

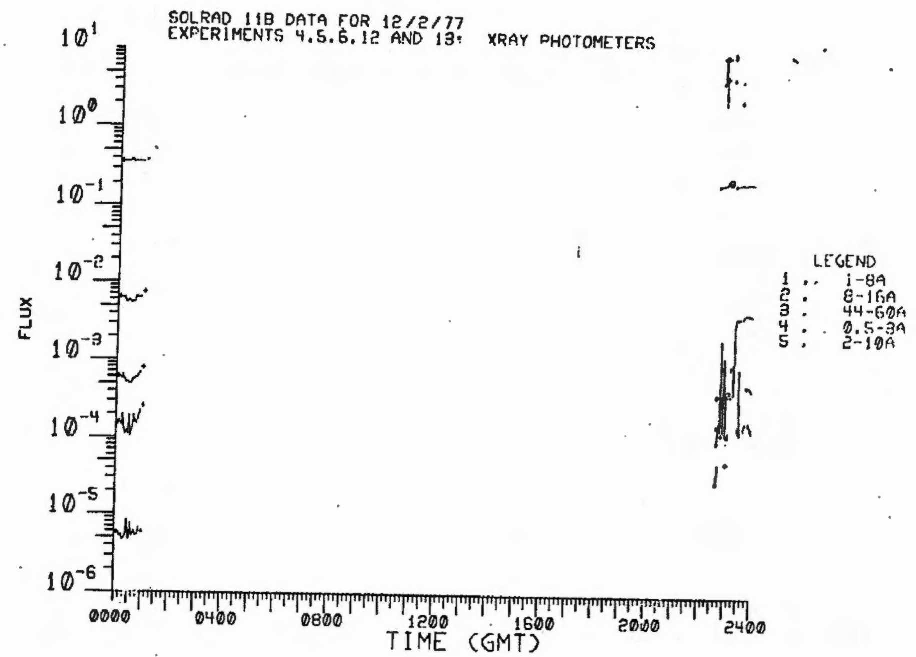


Figure 26

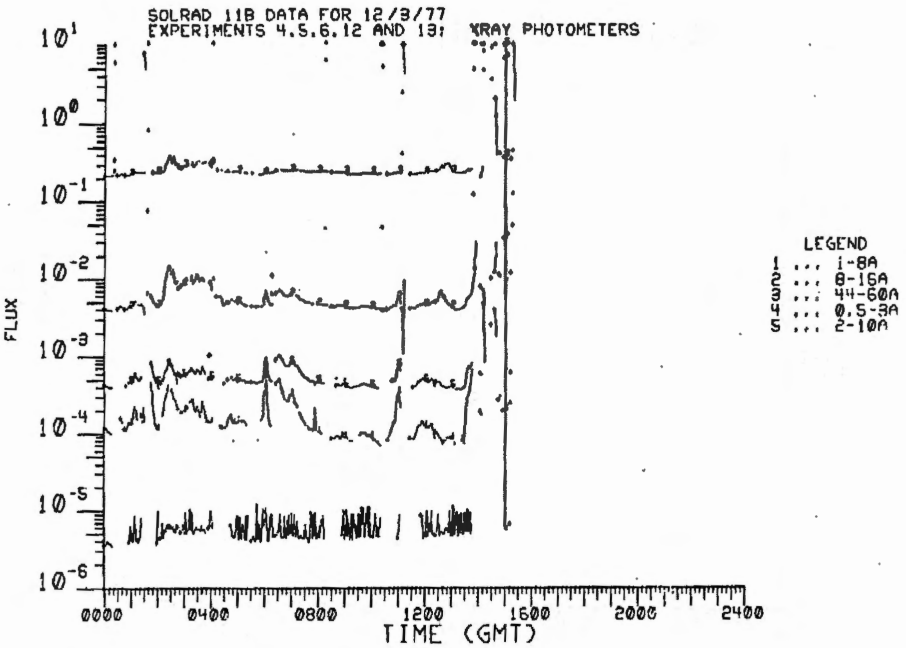


Figure 27

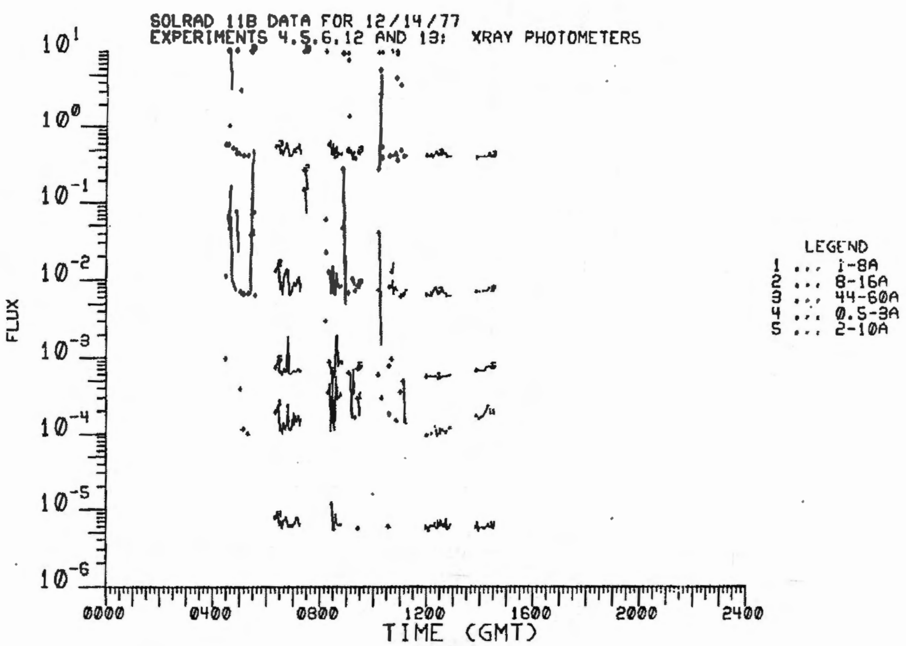


Figure 28

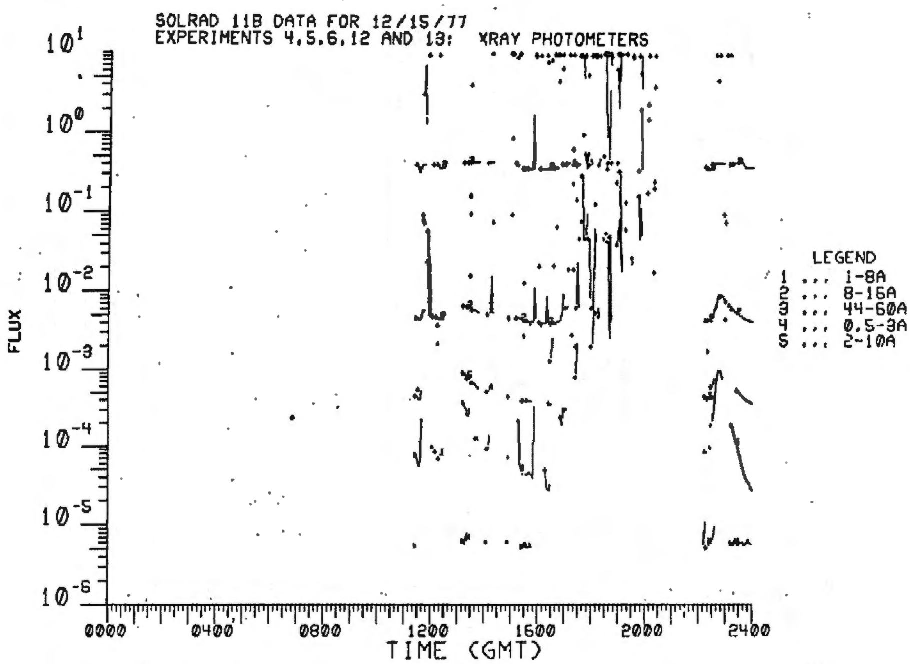


Figure 29

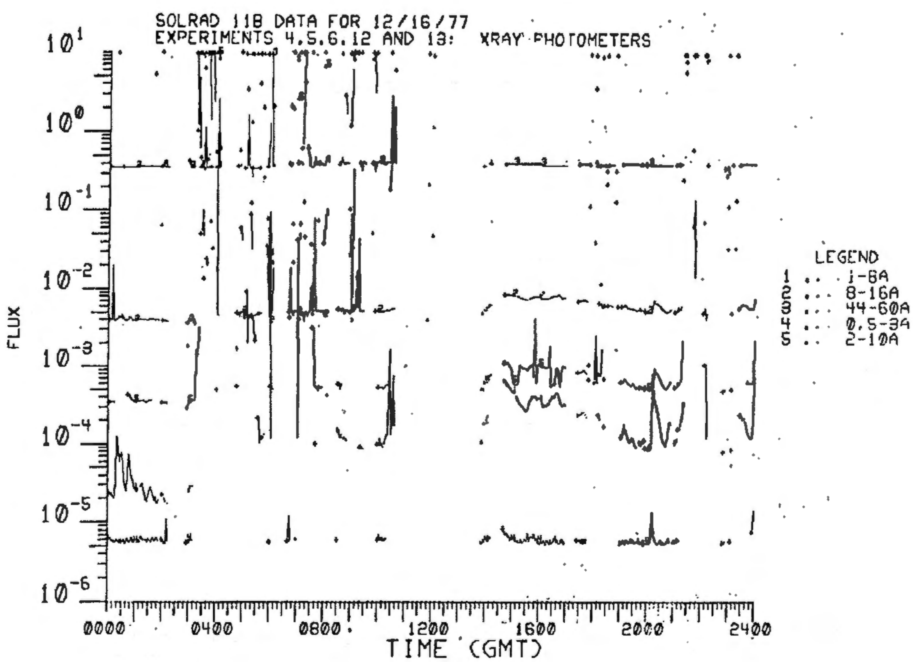


Figure 30

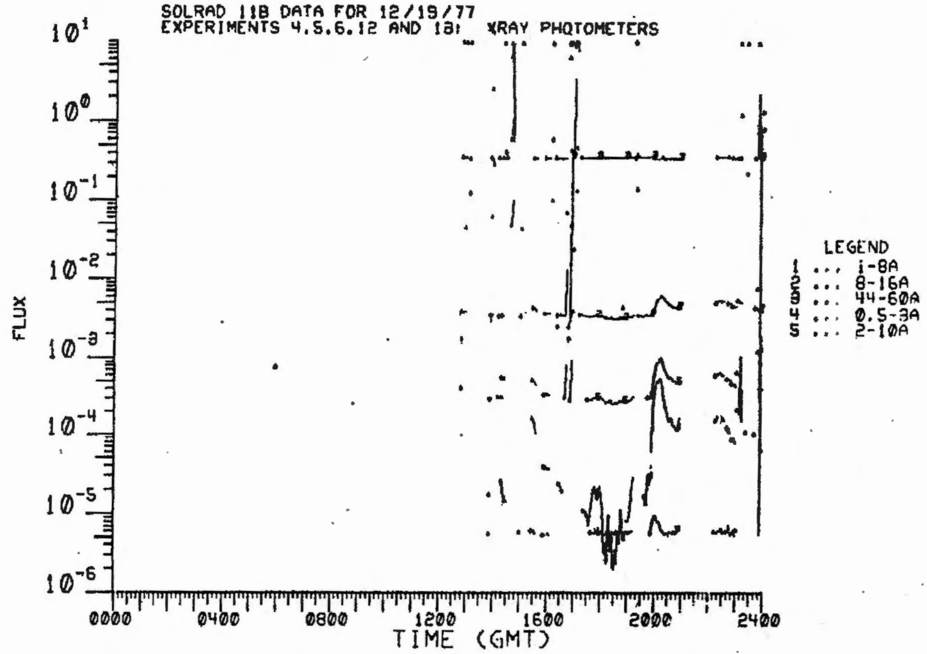


Figure 31

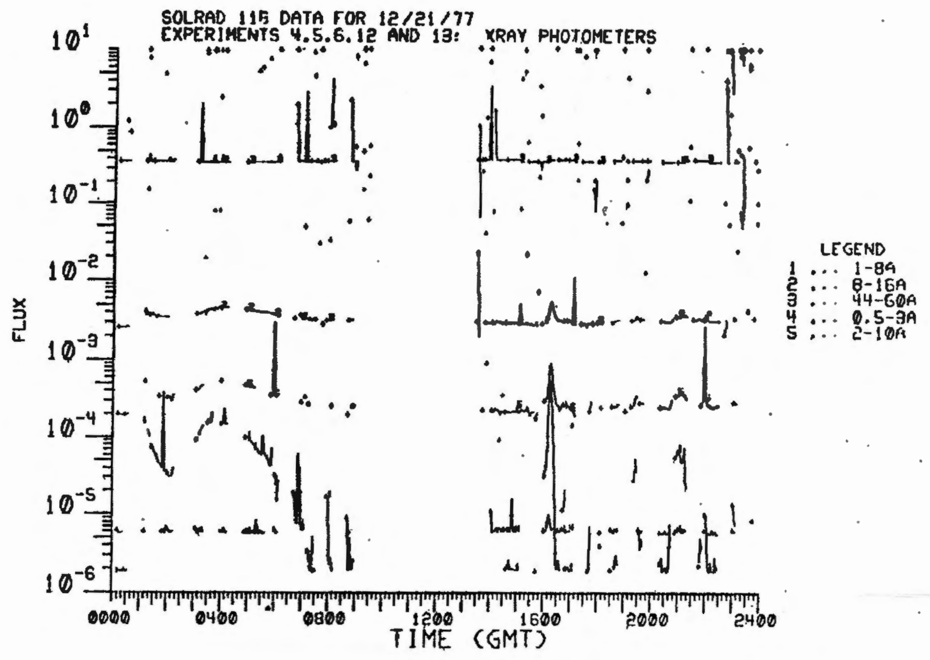


Figure 32

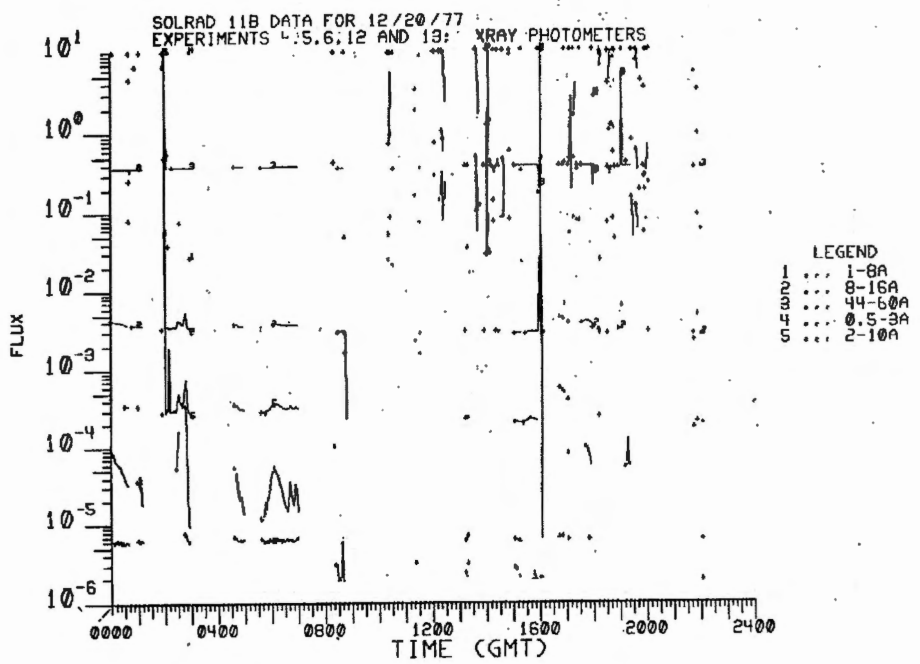


Figure 33

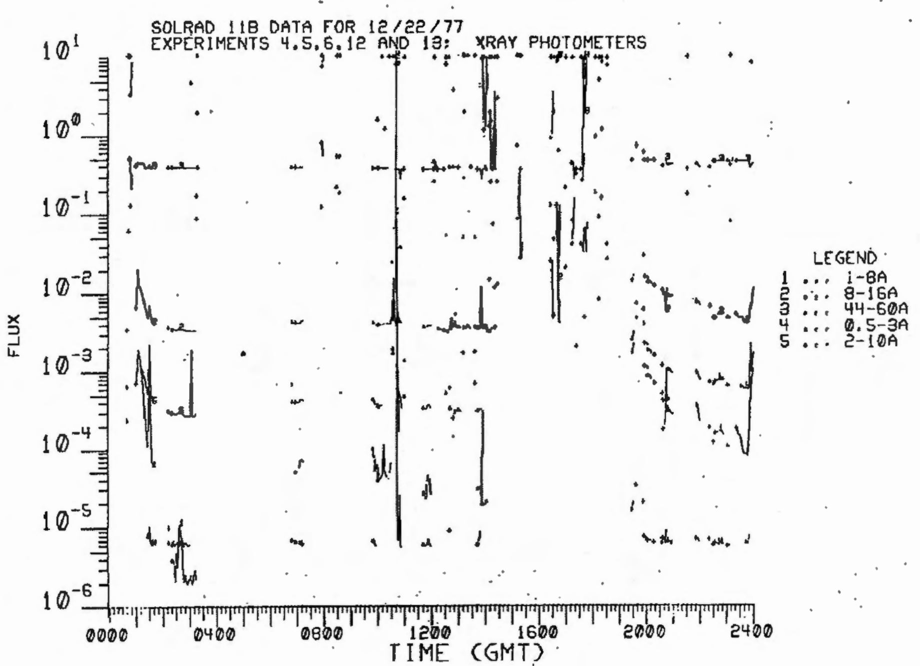


Figure 34

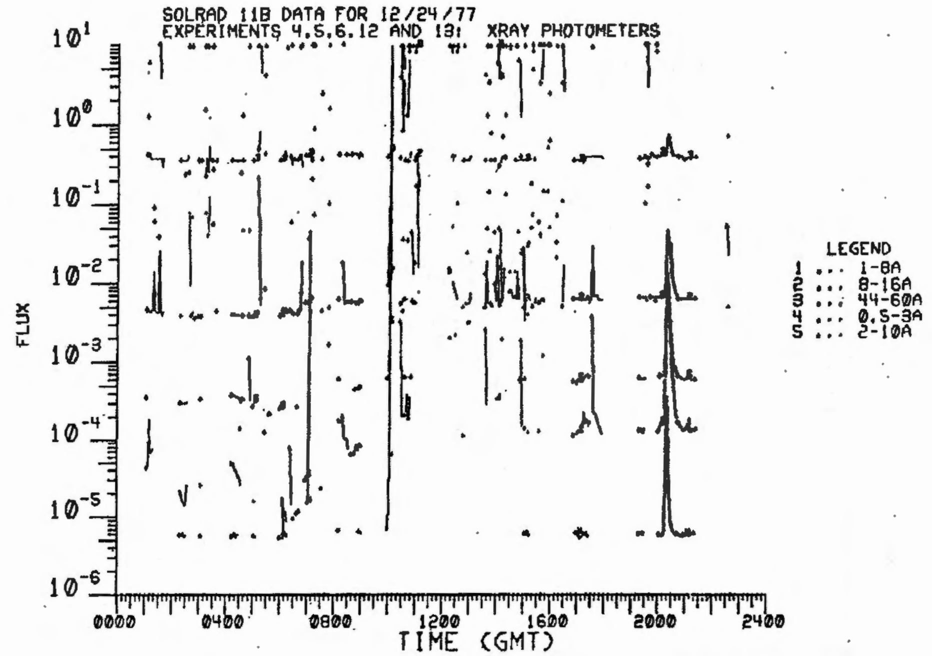


Figure 35

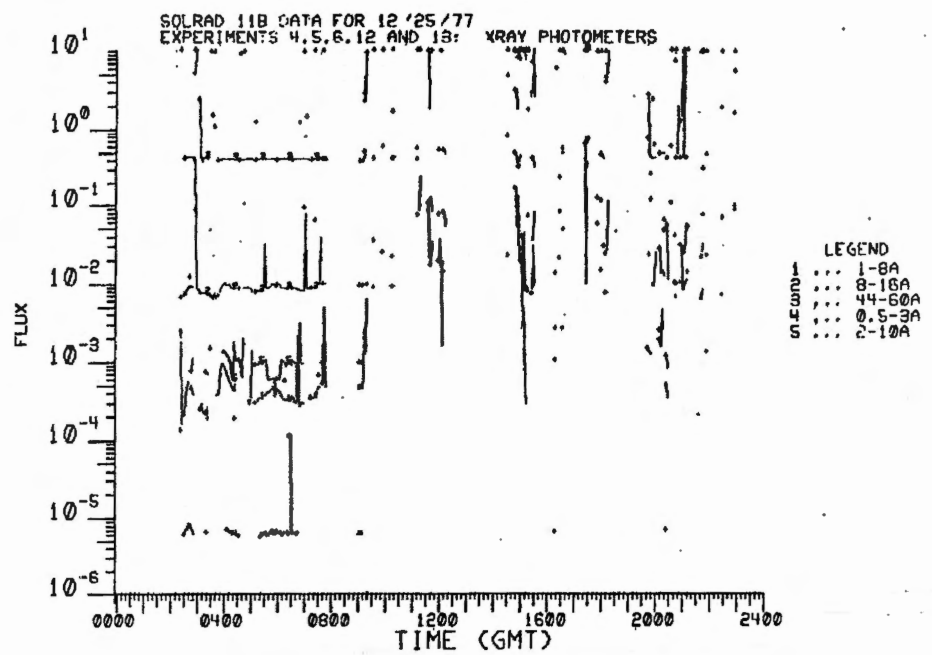


Figure 36

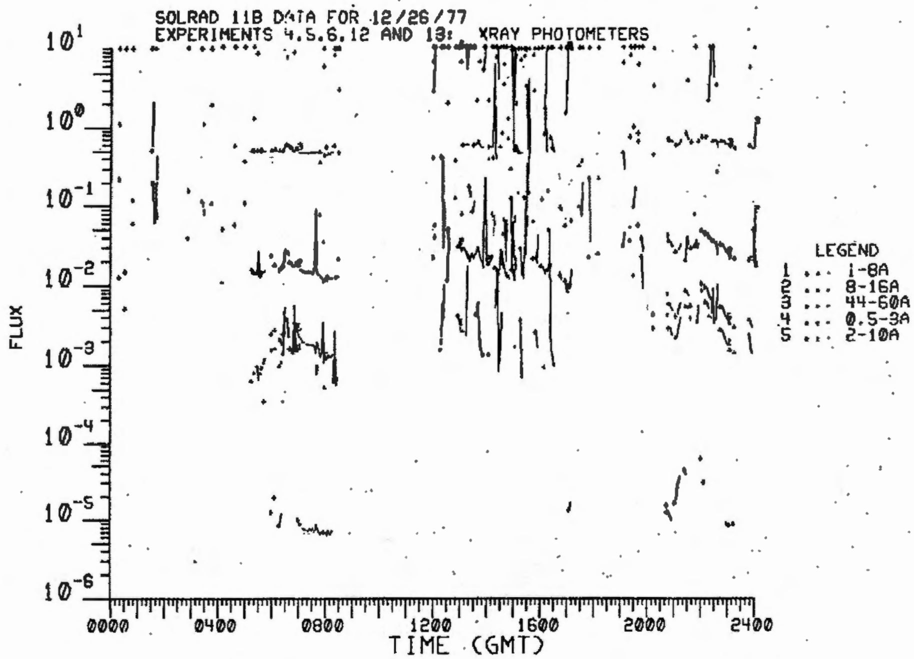


Figure 37

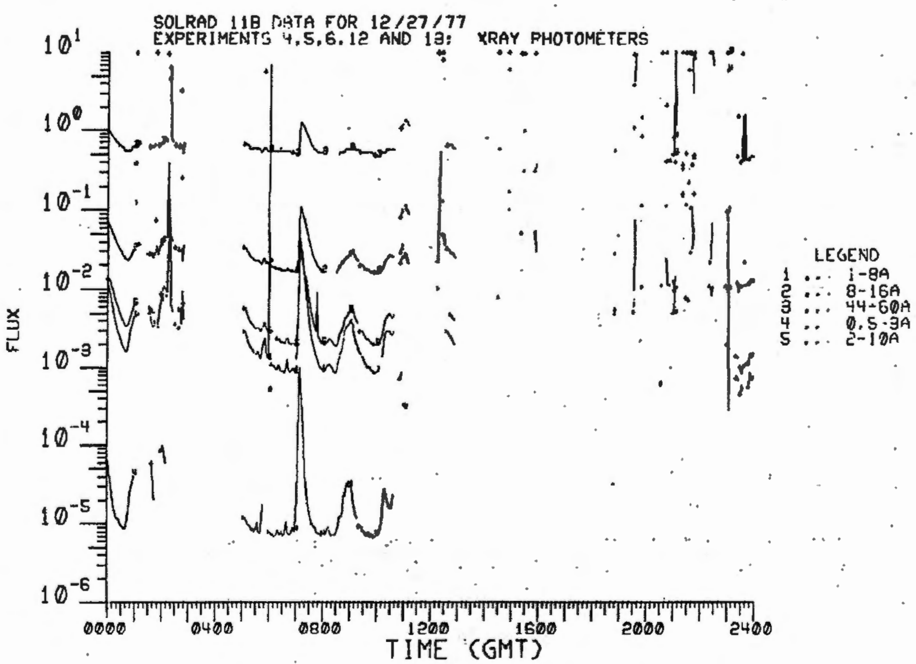


Figure 38

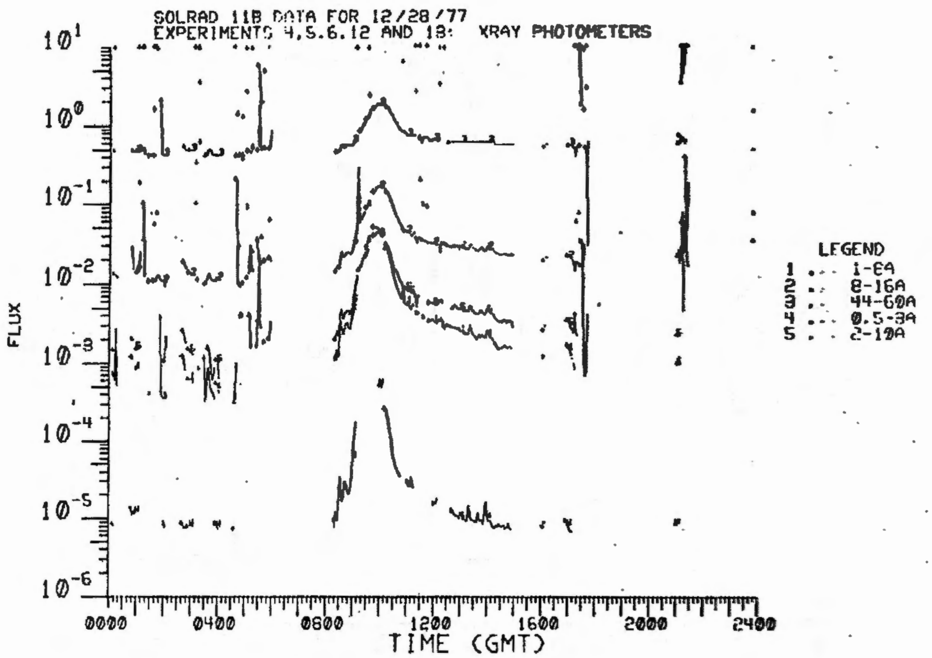


Figure 39

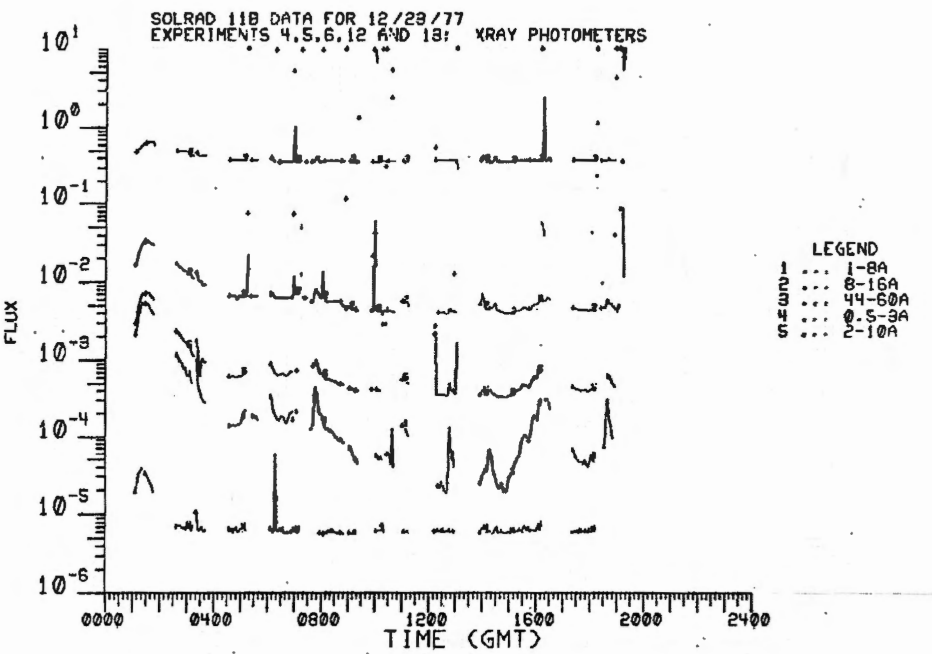


Figure 40

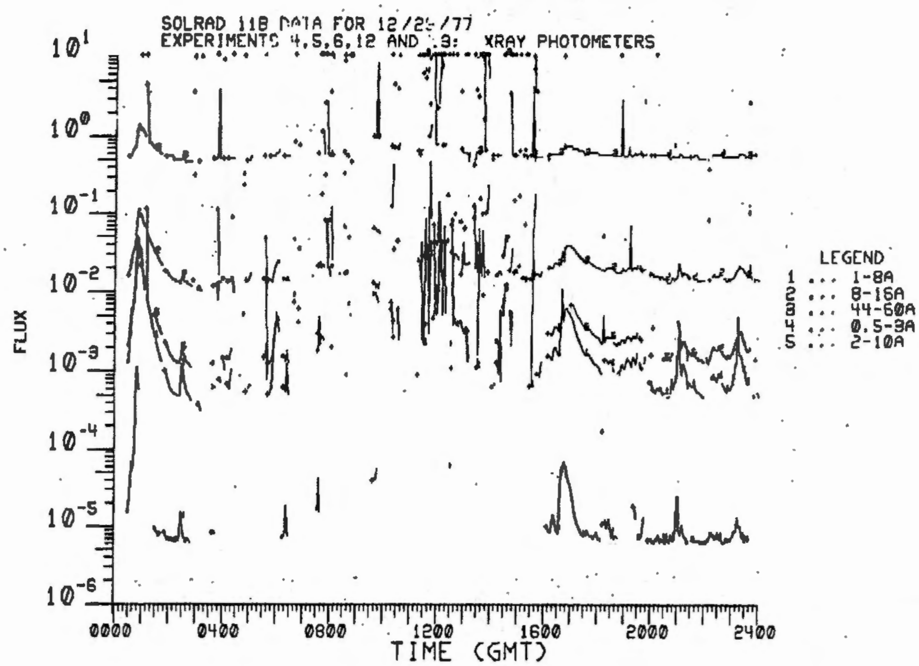


Figure 41

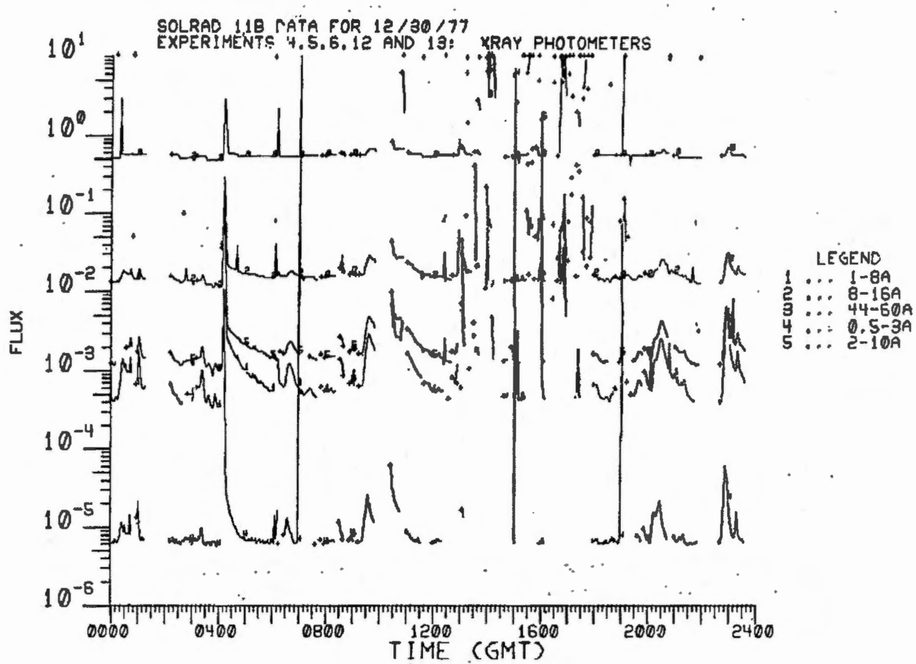


Figure 42

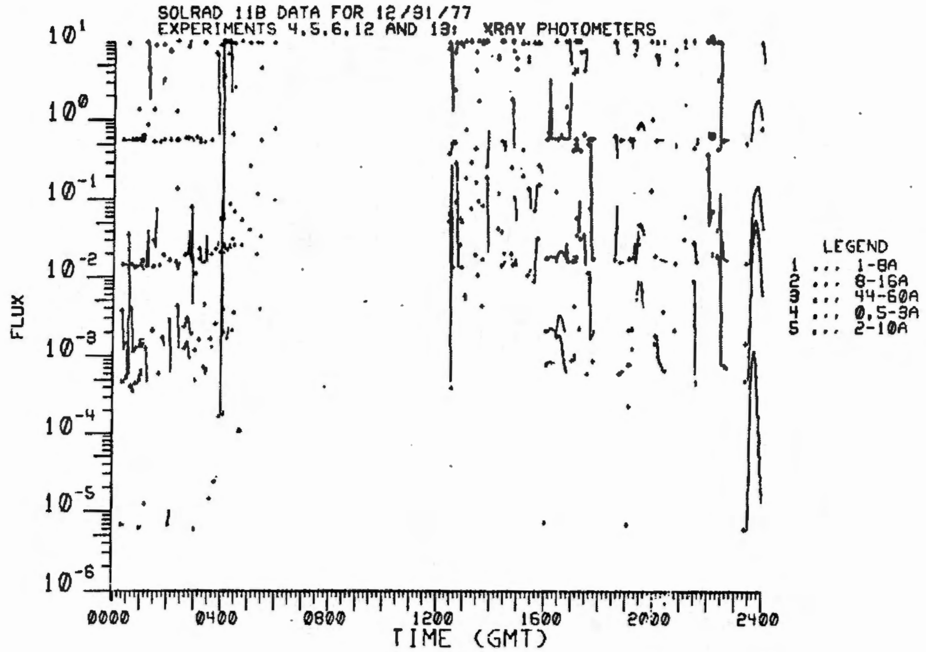


Figure 43

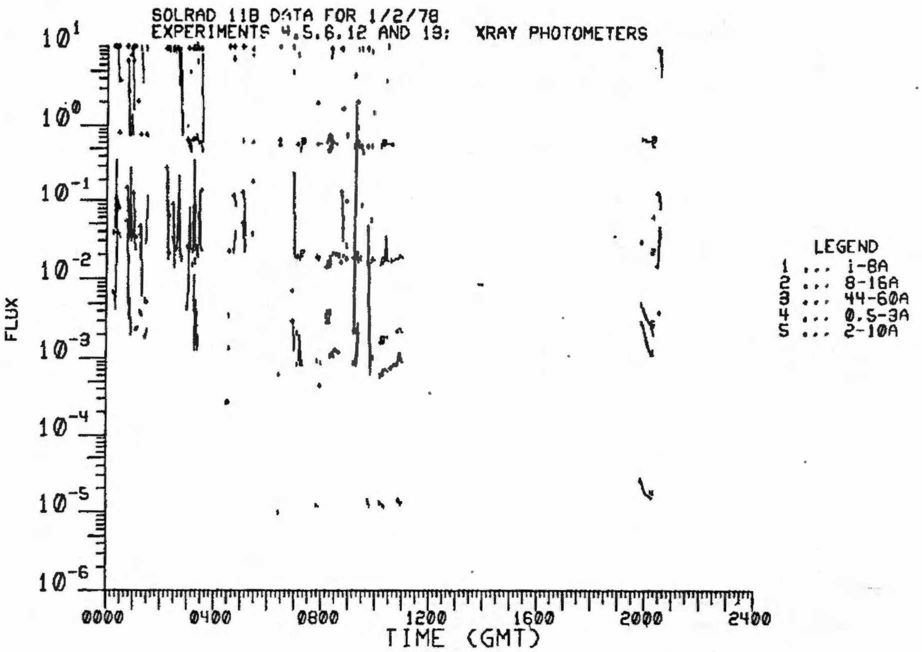


Figure 44

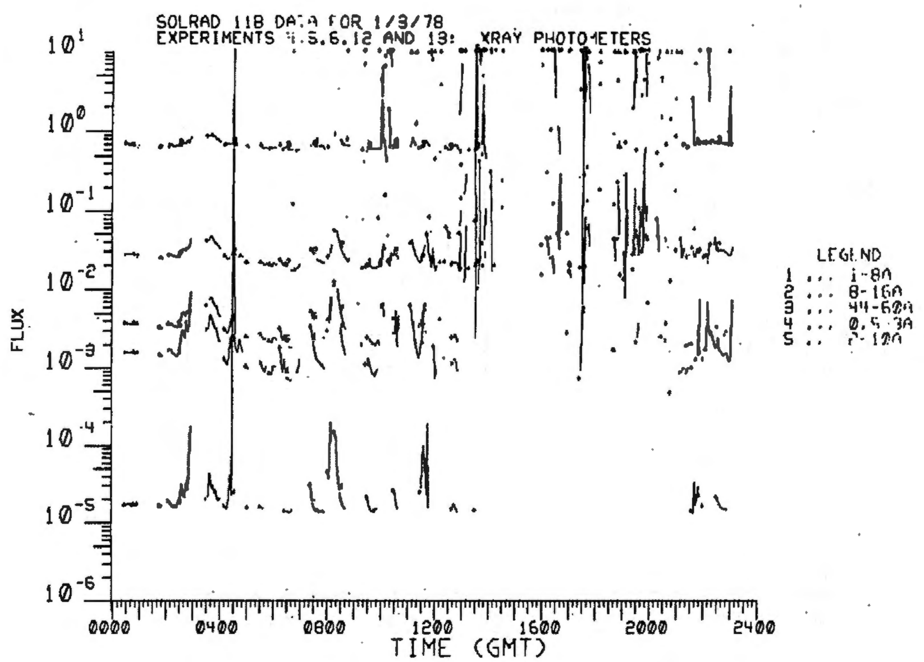


Figure 45

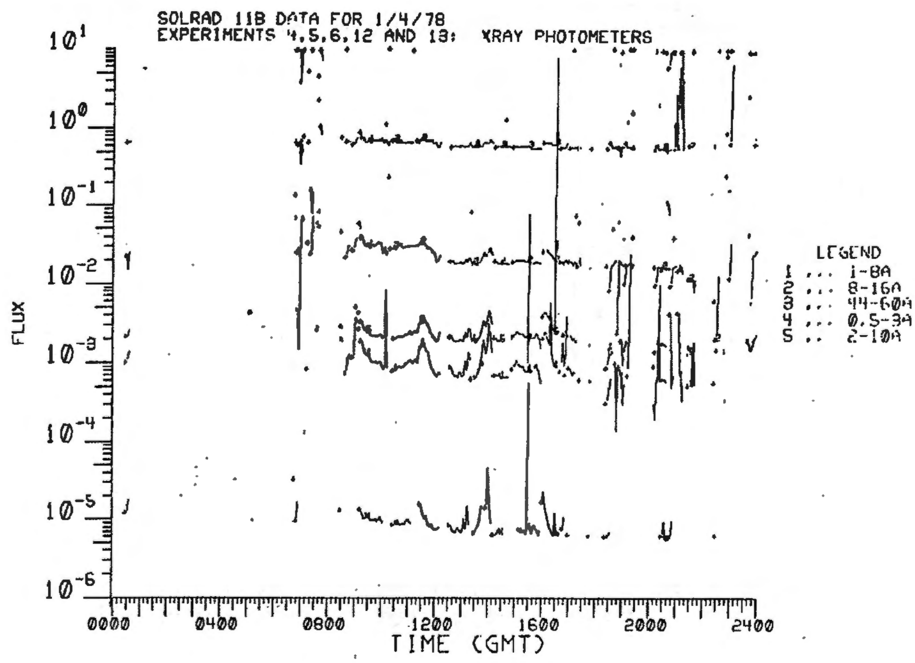


Figure 46

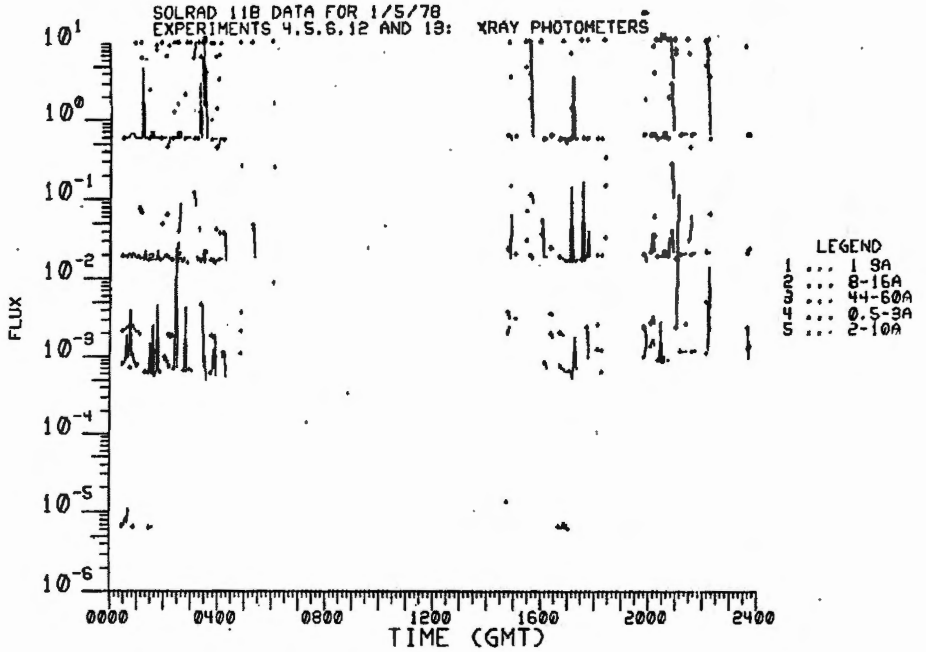


Figure 47

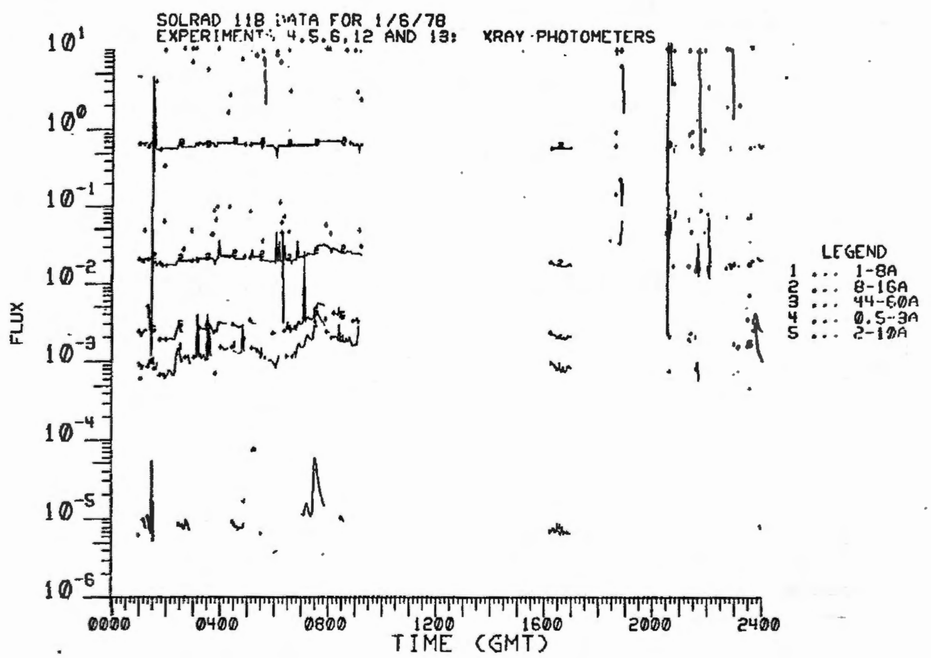


Figure 48

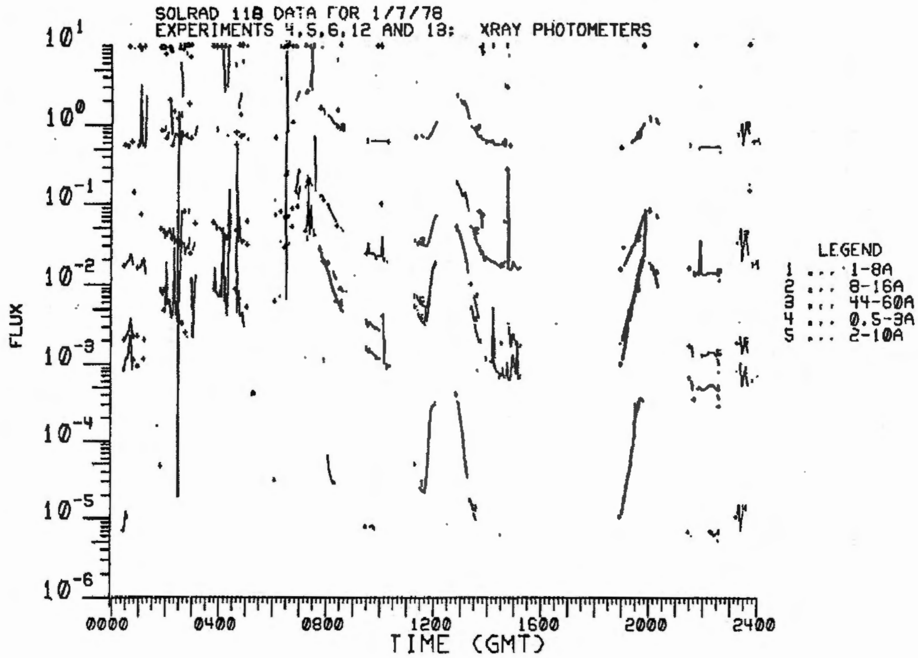


Figure 49

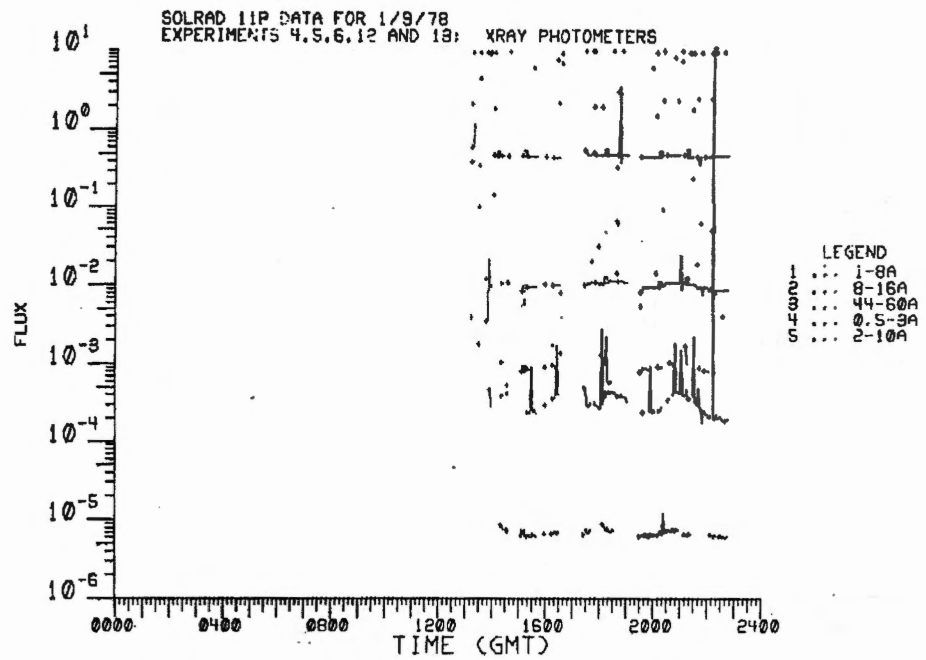
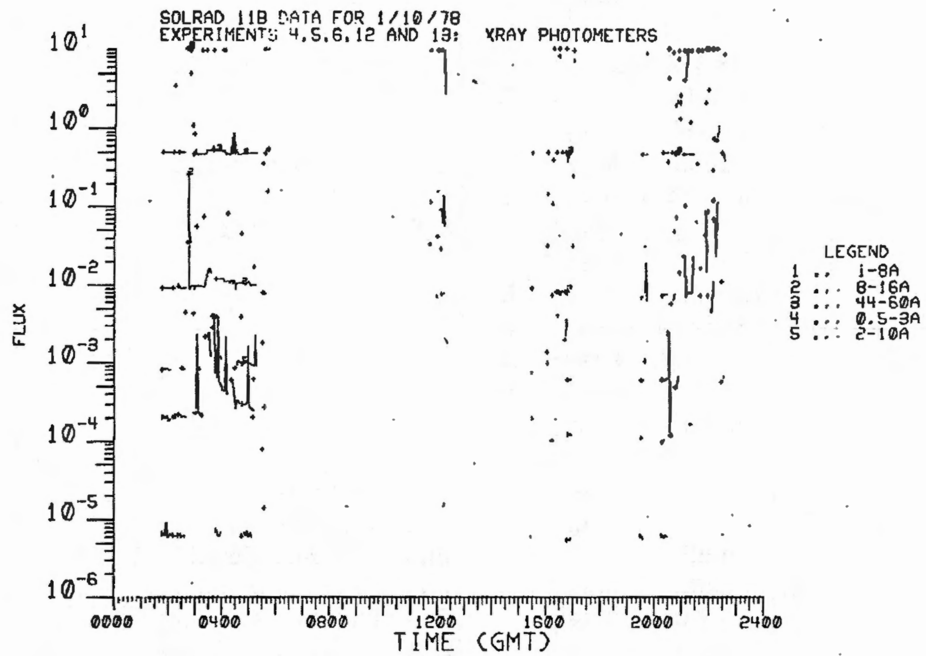


Figure 50



SOLRAD 11B DATA FOR 1/10/78
EXPERIMENTS 4,5,6,12 AND 13: XRAY PHOTOMETERS
FLUX
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0000
0400
0800
1200
1600
2000
2400
TIME (GMT)
LEGEND
1 .. 1-8A
2 ... 8-16A
3 ... 44-60A
4 ... 0.5-3A
5 ... 2-10A

Figure 51

UNCLASSIFIED

Table 14 – December Event Data

Date	Time Span	Type	Import	Comments
1 DEC	200	Mag		End of event. Murmansk, USSR
	224-232	x-ray	B	
	419-428	x-ray	B	
	622-630	x-ray	C	
	958-1006	x-ray	C	
	1551-1556	x-ray	B	
	1612-1628	x-ray	B	
	2000	Mag		GSC. Fredericksburg, Va.
	2012-2024	x-ray	C	
	2028	Mag		SSC. Wingst, W.G.
	2103-2112	x-ray	C	
	2306-2315	x-ray	B	
2 DEC	549-556	x-ray	B	
	557-604	x-ray	B	
	935-940	x-ray	B	
	1054-1104	x-ray	B	
	1410-1421	x-ray	B	
	2000	Mag		GSC. Boulder, Colo.
3 DEC	0100	Mag		SSC. Kakioka, Ja.
	1600	Mag		End of event. Magadan, USSR
4 DEC	0100	Mag		End of event. Murmansk, USSR
	0300	Mag		End of event. Kakioka, Ja.
	1400	Mag		GSC. Murmansk, USSR
5 DEC	043-102	x-ray	B	
	0300	Mag		Bay. Murmansk, USSR
	913-935	x-ray	B	
	1353-1406	x-ray	B	
	1452-1511	x-ray	C	
	1632-1640	x-ray	C	
	1808-1823	x-ray	B	
	1900	Mag		End of event. Fredericksburg, Va.
	1957-2022	x-ray	B	
	2210-2230	x-ray	C	
	2307-2323	x-ray	C	
	2357	Mag		Bay. Wingst, W.G.

Table 14 (Continued) – December Event Data

Date	Time Span	Type	Import	Comments
6 DEC	0037-0051	x-ray	C	
	0142-0148	x-ray	B	
	0201-0220	x-ray	C	Event log incomplete for remainder of 6 DEC.
7 DEC	0239-305	x-ray	C	
	0334-341	x-ray	C	
	0452-502	x-ray	C	
	0522-533	x-ray	C	
	607-643	x-ray	C	
	706-716	x-ray	C	
	734-741	x-ray	C	
	825-839	x-ray	C	
	948-1013	x-ray	C	
	1032-1107	x-ray	C	
	1135-1204	x-ray	C	
	1207-1217	x-ray	C	
	1350-1356	x-ray	C	
	1359-1413	x-ray	C	
	1531-1603	x-ray	M	
	1535-1609	SID	2	SWF. Sagamore Hill, Mass.
	1637-1726	x-ray	C	
	1733-1805	x-ray	M	
	1858-1911	x-ray	C	
	1935-1949	x-ray	C	
	1920-2010	x-ray	C	
	2147-2155	x-ray	C	
	2250-2309	x-ray	C	
	2317-2334	x-ray	C	
8 DEC	0127-134	x-ray	C	
	0152-157	x-ray	C	
	0309-315	x-ray	C	
	0344-355	x-ray	C	
	0501-523	x-ray	B	
	0536-543	x-ray	C	
	0709-719	x-ray	B	
	0940-0945	x-ray	B	
	1328-1336	x-ray	C	
	1357-1422	SID	2	SWF. Ramey AFB, P.R.
	1550-1602	x-ray	C	

UNCLASSIFIED

Table 14 (Continued) – December Event Data

Date	Time Span	Type	Import	Comments
8 DEC	2039-2044	x-ray	C	
	2133-2140	x-ray	B	
	2317-2322	x-ray	B	
9 DEC				No data from Seldads
10 DEC	0256-322	x-ray	M	
	0308-337	SID	2+	SWF. Hiraiso, Ja.
	0659-728	x-ray	C	
	0753-811	x-ray	M	
	0953-1008	x-ray	C	
	1028-1041	x-ray	C	
	1108-1115	x-ray	C	
	1353-1358	x-ray	C	
	1452-1458	x-ray	C	
	1525-1530	x-ray	C	
	1705-1718	SID	1	SFD. Sagamore Hill, Mass.
	1707-1712	x-ray	C	
	1708-1724	SID	1	SWF.
	2000	Mag		GSC. Kakroka, Ja.
	2015-2026	x-ray	B	
	2100	Mag		GSC. Fredericksburg, Va.
11 DEC	015-058	x-ray	C	
	306-504	Mag		CRO. Kakroka, Ja.
	454-504	x-ray	B	
	600	Mag		GSC. Churchhill, Can.
	0943-0952	x-ray	C	
	948-1002	Sid	2	Tehran, Iran
	1717-1729	x-ray	C	
	1900	Mag		GSC. Boulder, Colo.
	1906-1931	x-ray	C	
	2013-2034	x-ray	C	
	2100	Mag		Bay. Wingst, W.G.
	2144-2219	x-ray	M	
12 DEC	2220-514	Sid	2+	SWF. Hiraiso, Ja.
	502-514	x-ray	B	
	0737-808	x-ray	C	
	1007-1016	x-ray	B	
	1056-1105	x-ray	C	
	1121-1148	x-ray	C	
	1126-1150	Sid	1-	SEA, SPA, SWF
	1151-1215	x-ray	C	

Table 14 (Continued) – December Event Data

Date	Time Span	Type	Import	Comments
12 DEC	1420-1437	x-ray	C	
	1425-1436	Sid	1	SFD, SWF. Sagamore Hill, Mass.
	1542-1556	x-ray	C	
	1842-1853	x-ray	C	
	2251-2302	x-ray	B	
	2341-0005	x-ray	B	
13 DEC	0031-0043	x-ray	C	
	0134-0143	x-ray	C	
	0636-0645	x-ray	B	
	654-738	x-ray	B	
	0700	Mag		End of event. Moscow, USSR
	1500	Mag		End of event. Fredericksburg, Va.
	1519-1537	x-ray	B	
	1739-1800	x-ray	B	
	1912-1927	x-ray	B	
14 DEC	1443-1509	x-ray	B	
15 DEC	2233-2255	x-ray	B	
16 DEC				No events of interest
17 DEC	1239-1254	x-ray	B	
	1437-1452		B	

Table 15 — January Event Data

Date	Time Span	Type	Import	Comments
1 JAN	0510-0518	x-Ray	C	
	0551-0610	x-Ray	C	
	0722-740	x-Ray	C	
	0916-0933	x-Ray	C	
	1245-1309	x-Ray	B	
	1403-1411	x-Ray	C	
	1630-1642	x-Ray	C	
	1723-1733	x-Ray	C	
	2141-2251	x-Ray	M	
2 JAN	0111-0116	x-Ray	C	
	0342-0357	x-Ray	C	
	1729-1742	x-Ray	B	
	1912-1929	x-Ray	C	
	2048-2053	x-Ray	C	
	2103-2108	x-Ray	C	
	2231-2305	x-Ray	C	
3 JAN	0200-0214	x-Ray	C	
	0220-0248	x-Ray	C	
	0222-0257	Sid	1-	SWF. Hiraiso, Ja.
	0352-0407	x-Ray	C	
	0645-0654	x-Ray	C	
	0727-0753	x-Ray	C	
	0928-0939	x-Ray	C	
	1013-1033	x-Ray	C	
	1058-1112	x-Ray	C	
	1140-1153	x-Ray	B	
	1524-1531	x-Ray	C	
	1852-1904	x-Ray	B	
	2042	Mag		GSC. Kakioka, Ja.
	2141-2147	x-Ray	C	
	2228-2252	x-Ray	C	
4 JAN	0217-0305	x-Ray	C	
	0408-0415	x-Ray	B	
	0622-0630	x-Ray	B	
	0716-0725	x-Ray	C	
	0803-0808	x-Ray	B	
	0827-0840	x-Ray	C	
	1052-1108	x-Ray	B	
	1525-1538	x-Ray	B	
	2000	Mag		GSC. Boulder, Colo.
	2047-2110	x-Ray	C	

Table 15 (Continued) – January Event Data

Date	Timespan	Type	Import	Comments
5 JAN	0735-0745	x-Ray	C	
	1351-1420	x-Ray	C	
	1628	Mag		SSC. Kakioka, Ja.
6 JAN	0656-0731	x-Ray	C	
	0959-1021	x-Ray	C	
	1425-1448	x-Ray	C	
	2230-2237	x-Ray	B	
	2307-2317	x-Ray	C	
	2313	Mag		Bay. Wingst, W.G.
8 JAN	0156-0257	x-Ray	C	
	02110-0300	Sid	2	SWF. Sydney, Australia
	0705-0725	x-Ray	B	
	0709	Sid	2	SWF. Tehran, Iran
	1700	Mag		END. Tehran, Iran
	1856-1950	x-Ray	C	
	2041	Mag		GSC. Irkutsk, USSR
9 JAN	0801-0844	x-Ray	C	
	1212-1245	x-Ray	C	
	2250-2302	x-Ray	B	
10 JAN	0655-0729	x-Ray	B	
11 JAN	2238-2257	x-Ray	B	
12 JAN	1057-1104	x-Ray	B	
	2347-0000	x-Ray	B	
14 JAN	1100-1127	x-Ray	B	
17 JAN	1029-1052	x-Ray	C	
	1351-1417	x-Ray	C	
18 JAN	0429-0444	x-Ray	B	
19 JAN	0400	Mag		End of event. Murmansk, USSR
	1741-1746	x-Ray	B	
20 JAN	1315-1344	x-Ray	B	
	2205-2216	x-Ray	C	
21 JAN	0835-0855	x-Ray	B	
22 JAN	0546-0551	x-Ray	B	
	0635-702	x-ray	C	
	0655-0700	x-Ray	C	

Table 15 (Continued) – January Event Data

Date	Time Span	Type	Import	Comments
23 JAN	0002-0009	x-Ray	B	
	0250-0300	x-Ray	B	
	0414-0420	x-Ray	B	
	2016-2024	x-Ray	B	
	2202-2212	x-Ray	B	
24 JAN	0619-0628	x-Ray	B	
	1200-1211	x-Ray	C	
	1300-1307	x-Ray	C	
	1429-1525	x-Ray	B	
	1714-1728	x-Ray	C	
25 JAN	0144-0152	x-Ray	C	
	0222-0231	x-Ray	C	
	0430-0439	x-Ray	C	
	0626-0640	x-Ray	C	
	1200	Mag		GSC. Murmansk, USSR
	1300	Mag		GSC. Moscow, USSR
	1430-1438	x-Ray	C	
	1535	Mag		SSC. Wingst, W.G.
	1637-1657	x-Ray	C	
	1943-1953	x-Ray	B	
	2106-2114	x-Ray	B	
	2214-2234	x-Ray	C	
26 JAN	0201-0350	x-Ray	C	
	1009-1020	x-Ray	C	
	1127-1139	x-Ray	C	
	1234-1239	x-Ray	C	
	1338-1353	x-Ray	C	
	1850-1859	x-Ray	C	
	2042-2056	x-Ray	C	
	2248-0016	x-Ray	C	
27 JAN	0155-0200	x-Ray	C	
	0211	Mag		END. Murmansk, USSR
	0327-0345	x-Ray	C	
	0331	Sid	1	SWF. Hiraiso, Ja.
	0737-0751	x-Ray	C	
	0832-0905	x-Ray	C	
	1023-1040	x-Ray	C	
	1322-1340	x-Ray	C	
	1352-1403	x-Ray	C	
	1414-1428	x-Ray	C	
	1546-1609	x-Ray	C	
	1855-1901	x-Ray	C	
	2043-2057	x-Ray	C	

Table 15 (Continued) – January Event Data

Date	Timespan	Type	Import	Comments
28 JAN	0013-0016	x-Ray	C	
	0423-0428	x-Ray	C	
	0540-0551	x-Ray	C	
	0808-0821	x-Ray	C	
	1148-1154	x-Ray	B	
	1957-2006	x-Ray	C	
29 JAN	0938-1001	x-Ray	C	
	1628-1643	x-Ray	C	
	1855	Mag		GSC. Boulder, Colo.
	2103-2111	x-Ray	C	
	2334-0002	x-Ray	C	
30 JAN	0056-0102	x-Ray	C	
	0133-0206	x-Ray	C	
	0945-1043	x-Ray	C	
	1648-1653	x-Ray	C	
	1937-1942	x-Ray	C	
	2205-2210	x-Ray	C	
	2323-2332	x-Ray	C	
	2340-2353	x-Ray	C	
31 JAN	0658-0719	x-Ray	C	
	1116-1127	x-Ray	C	
	1229-1244	x-Ray	C	
	1315-1335	x-Ray	C	
	1333	Sid	1	SFD. Sagamore Hill, Mass.
	1357-1417	x-Ray	C	
	1405-1410	x-Ray	C	
	1442-1447	x-Ray	C	
	1512-1519	x-Ray	C	
	1941-1946	x-Ray	C	
	2012-2017	x-Ray	C	
	2301-2313	x-Ray	C	

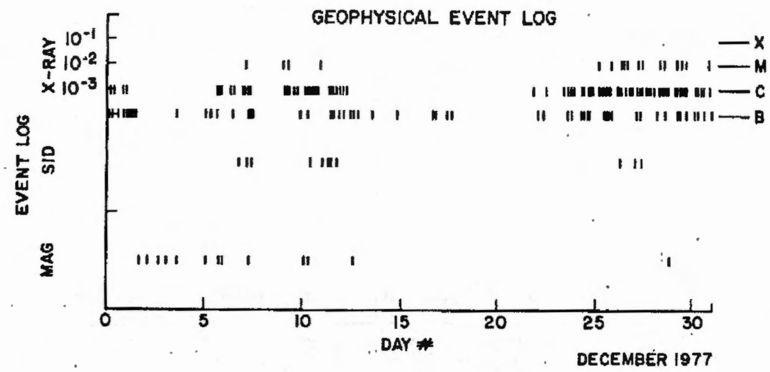


Figure 52

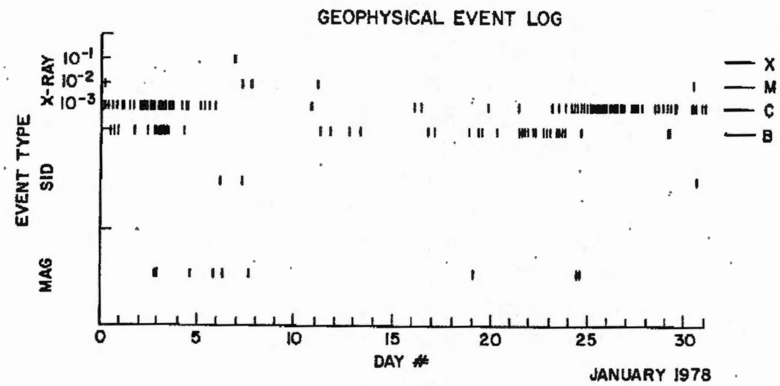


Figure 53

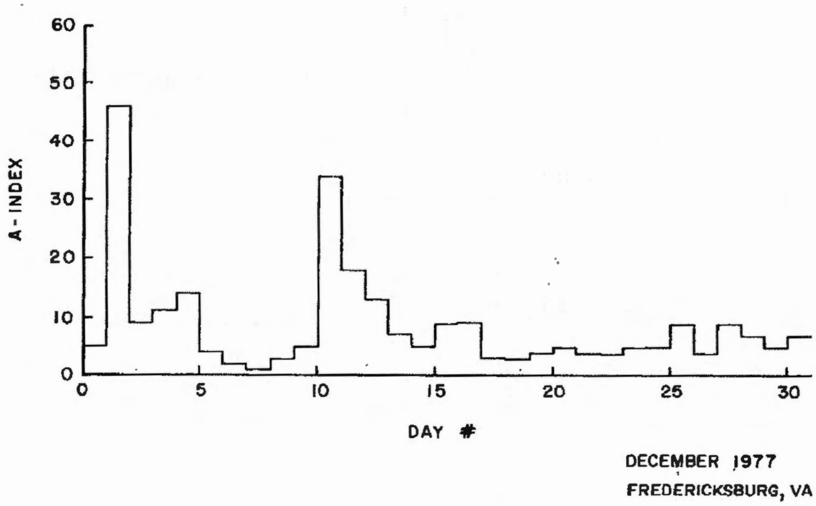


Figure 54

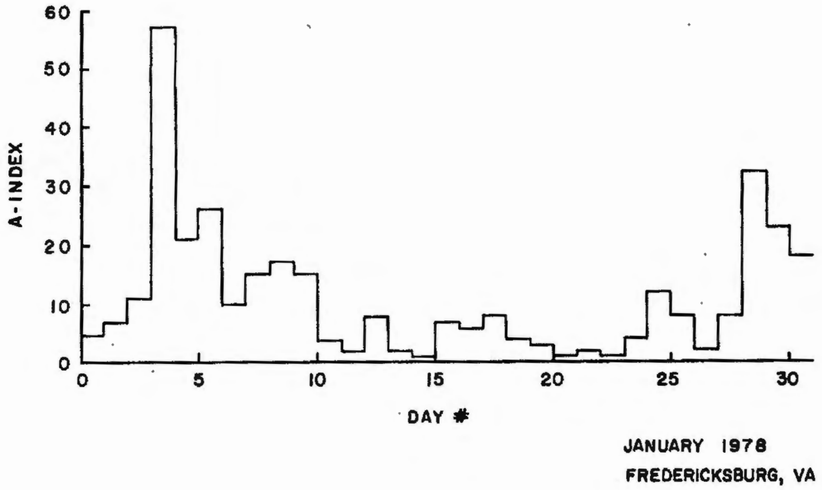


Figure 55

Total Electron Content (TEC) data for December and January are also given in graphical form specifically, in a percentage deviation format where each hourly relative deviation is referenced to its monthly average. Goose Bay Labrador (Figures 56-57), Sagamore Hill Mass. (Figures 58-59), Cape Kennedy-Fla. (Figures 60-61), and Ramey AFB, (Figures 62-63) were selected from a number of TEC stations which the Air Force maintains worldwide, since these are adjacent to the area where the sonic events occurred. Deviation of TEC gives an indication of the amount the F-region of the ionsphere is disturbed.

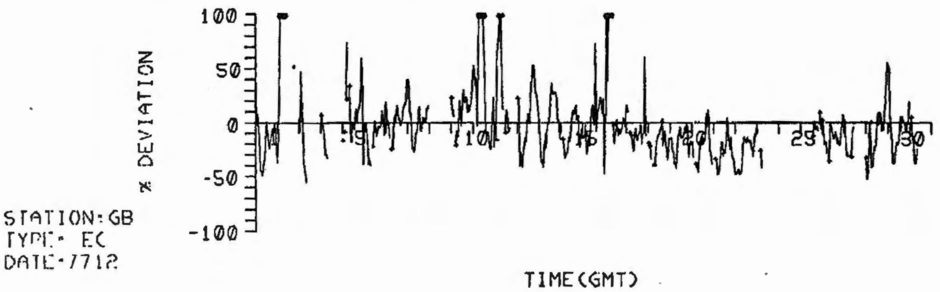


Figure 56

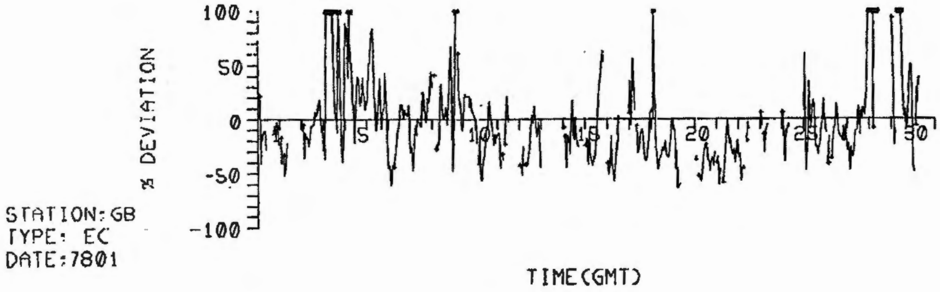


Figure 57

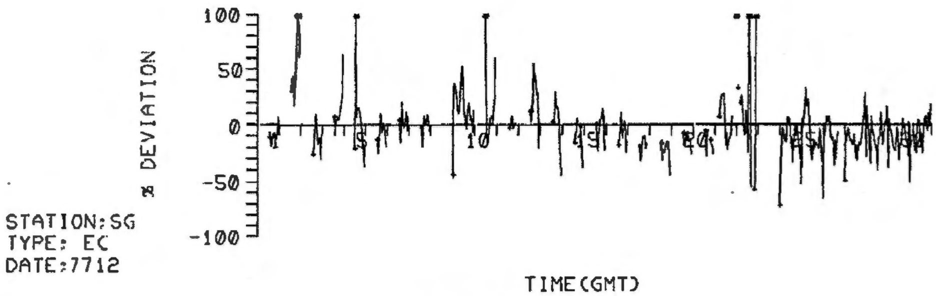


Figure 58

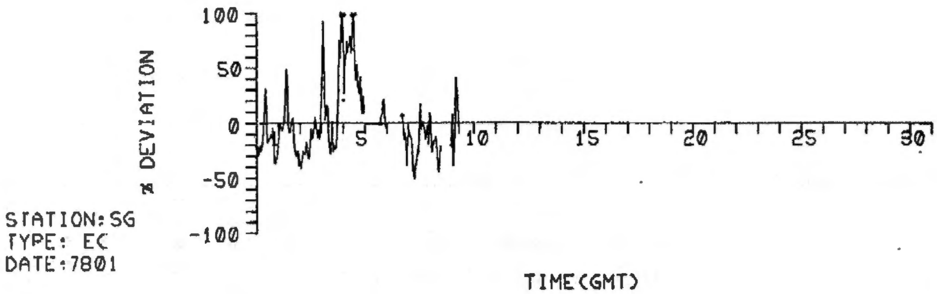


Figure 59

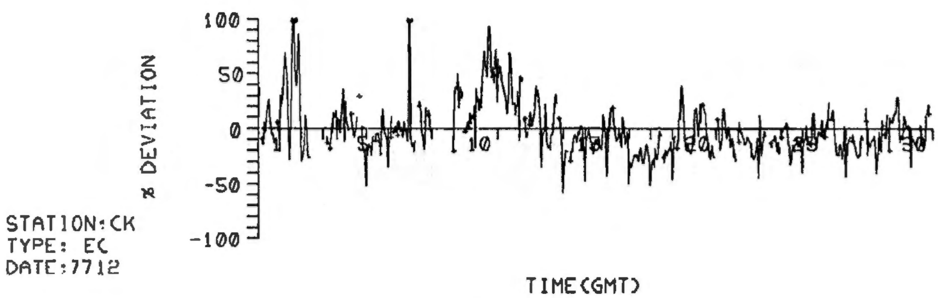


Figure 60

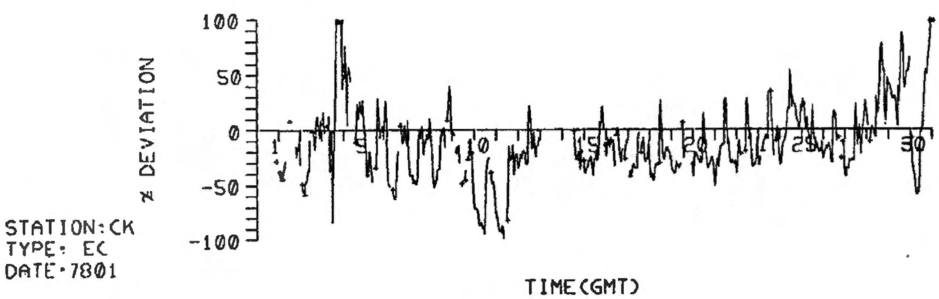


Figure 61

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Figure 62

Figure 63

The peak F2 layer electron density is called NF2 and may be extracted from the vertical incidence ionosonde parameter f_0F2. Percentage deviations in NF2 are given for Goose Bay (Figures 64-65), Wallops Island. (Figures 66-67), and Cape Kennedy (Figures 68-69).

The percentage deviations in the height of the F2 maximum are obtained from the M3000 parameter and are available only for Goose Bay (Figures 70-71) and Cape Kennedy (Figures 72-73).

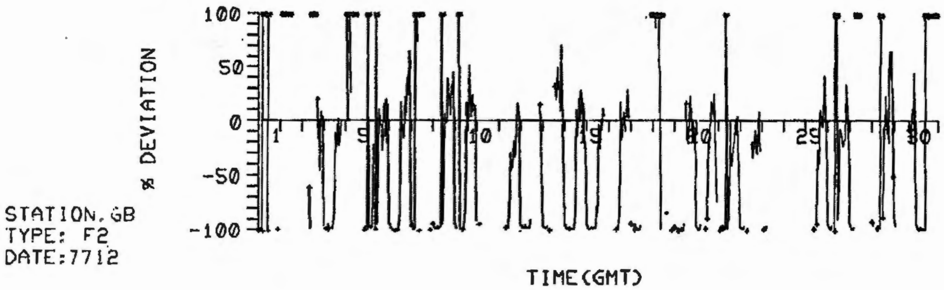

Figure 64

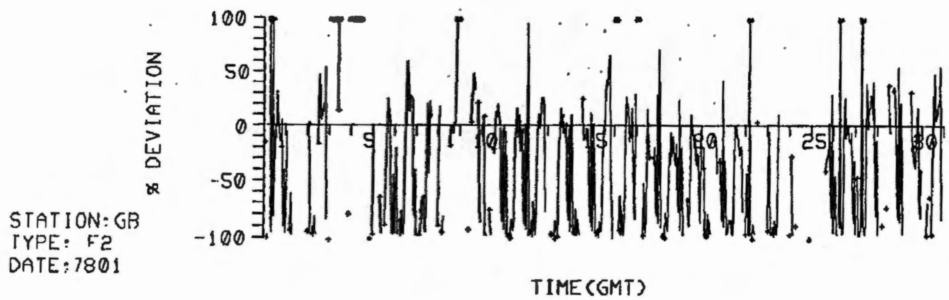

Figure 65

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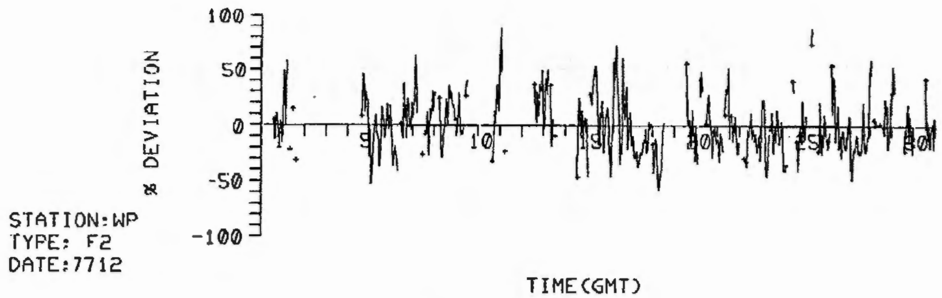

Figure 66

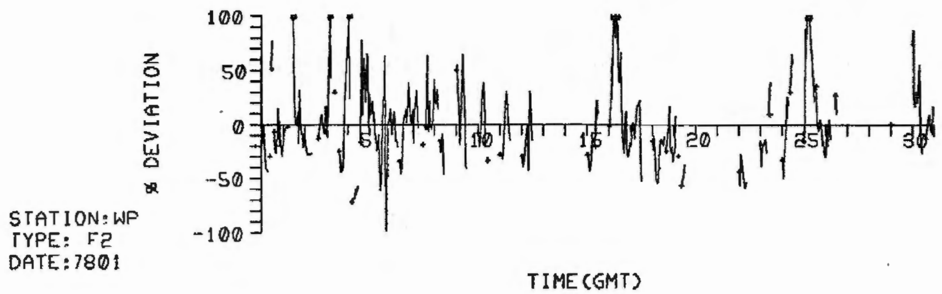

Figure 67

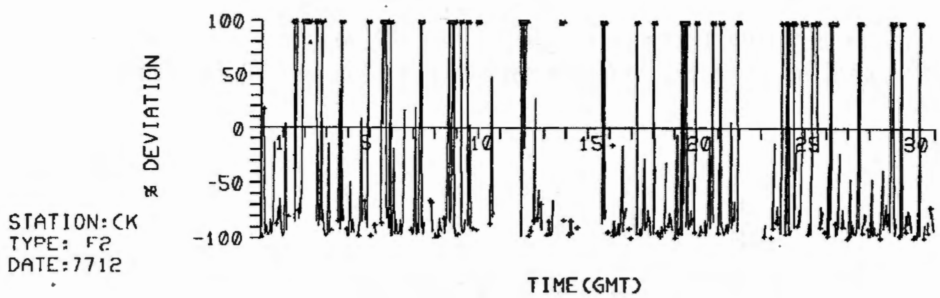

Figure 68

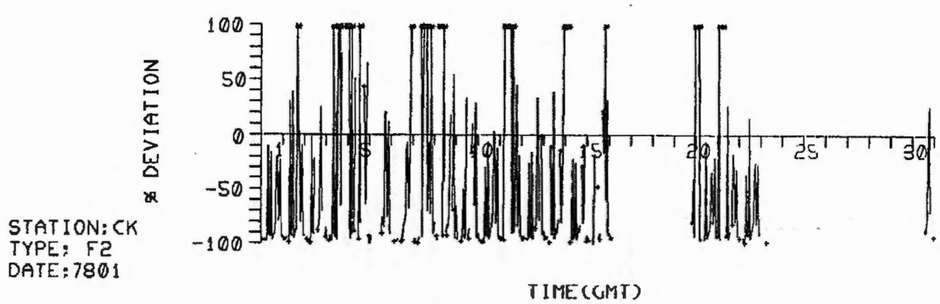

Figure 69

Figure 70

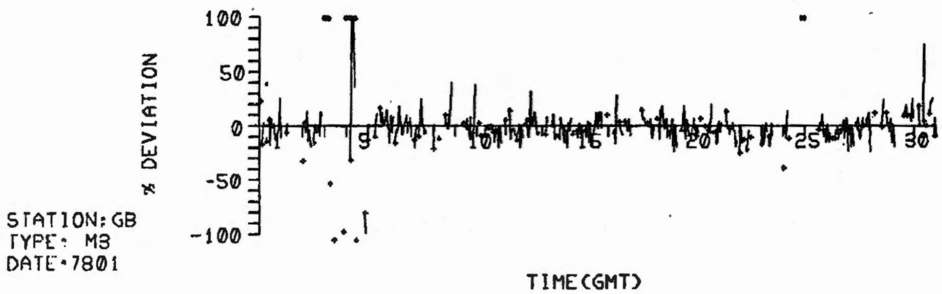

Figure 71

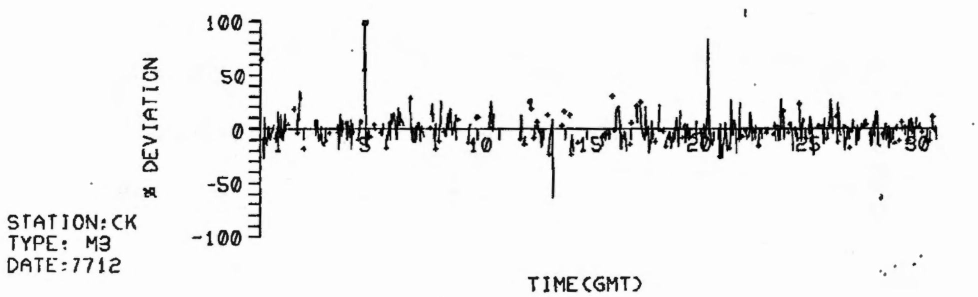

Figure 72

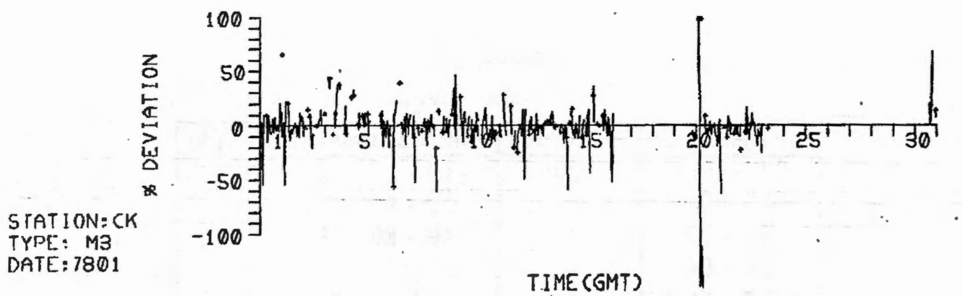

Figure 73

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Propagation disturbances at VLF as obtained from the Naval Observatory are depicted in Figures 74 and 75. The importance index ranges from 1 to 9 and corresponds to phase changes at VLF translated to time delay in microseconds as in Table 16.

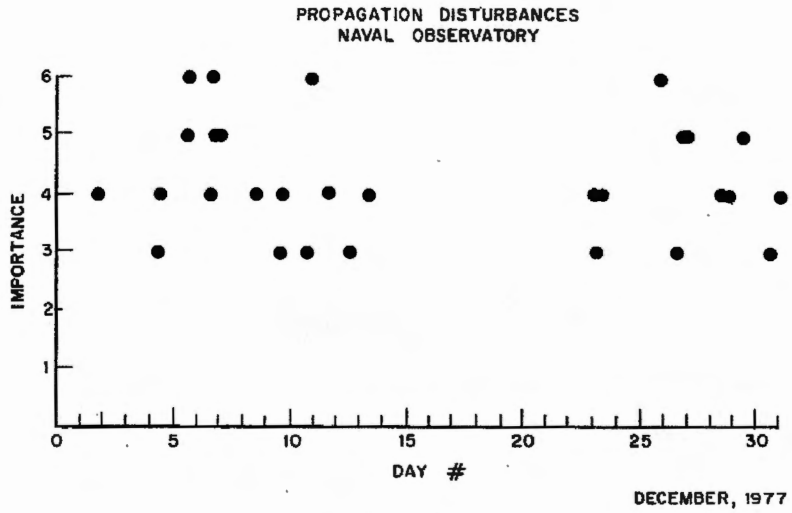

Figure 74

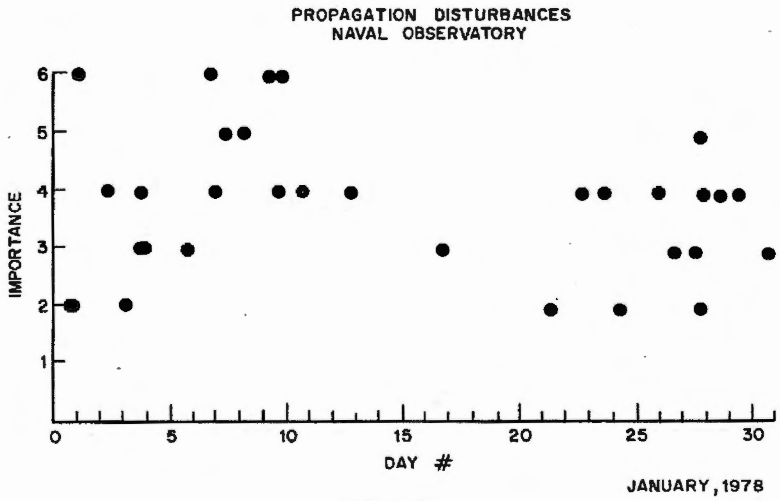

Figure 75

Table 16
VLF Phase Changes

Microseconds	Magnitude	Microseconds	Magnitude
0.0 - 00.5	1	10 - 20	6
0.5 - 01	2	20 - 40	7
1.0 - 02	3	40 - 80	8
2.0 - 04	4	over 80	9
5.0 - 10	5		

Unfortunately, these propagation effects are only for the global region which is sunlit during daytime hours for Washington, D. C. Therefore flares which produce global effects when the U.S. is in darkness are not recorded.

In searching for associations between sonic events and various solar-geophysical phenomena, we try not to prejudice the case by selecting data in a particular way. We would be remiss, however, if no attempt were made to discuss the data presented with a view toward discrediting or reducing the "weight" of certain chance coincidences of events.

With respect to solar x-ray activity, we note that electromagnetic radiation reaches the earth in $\sim$ 7 minutes. Therefore, for all intents and purposes, the photoionization produced at the affected ionospheric layers is immediate, and the subsequent behaviour of the layer is governed by the chemistry of recombination (lower ionosphere) or attachment (upper ionosphere). Since recombination is very rapid in the lower ionosphere where most of the flare energy is deposited (as evidenced by SID phenomena) there will be no delayed effects attributed to electromagnetic flare energy deposition. Also, high energy solar flare protons arrive approximately an hour after an optical or x-ray flare but are deflected toward the poles and produce polar cap absorption events (PCA) with little or no effect at low and middle latitudes. Thus, even if there were some logical hypothesis to suggest that solar effects yield mechanisms responsible for the sonic events observed, this would not be expected to be related to solar flare protons. Furthermore, these sonic events would tend to "track" the x-ray, EUV, radio, or optical flare data rather closely.

Magnetic storms (always characterized by substantial magnetic activity) may occur 20 to 40 hours following a solar flare and are related to the response of the magnetosphere to the perturbation of the solar wind plasma.

Unusually intense-amplitude scintillation of UHF radiowaves is observed as the scintillation boundary is driven southward by the expanding auroral oval. The high magnetic activity indicates that electric currents are active during the storm time especially in the ionospheric E-region and below. Magnetic storms also produce gross changes in the middle latitude F-region electron population, F-layer height, and TEC. For example, during the initial positive phase of a magnetic storm, the TEC increased markedly perhaps by as much as 100% or more for a few hours. Subsequently during the recovery or main phase of the storm, the TEC is depressed below the average for 1 or 2 days. The initial phase of the storm is responsible for the most dramatic events in the F region of the ionosphere, at least at middle latitudes. Thus we would effect sonic events to be conducted with sudden storm commencements (SSC). This implies sudden layer height changes, electron density fluctuations, and TEC excursions. If there is no storm, per se, we look for an association with simply an enhancement in magnetic activity reflected in either the K or A indices. Fredericksburg is a convenient midlatitude observatory. It is noteworthy that TEC tracks fairly well with the magnetic activity indices, but with a lag proportional to the distance between the oval region and the midlatitude observatory involved.

We conclude this section by reiterating a few salient points.

- X-ray flares and SID phenomena must track the sonic events very closely to be even circumstantial agents for the production of the events. The data indicate that this is not the case.

- Solar flare protons are an unlikely source since they are deflected toward the poles. The sonic events were midlatitude.

• Magnetic storm phenomena, TEC, layer height, and F2 maximum electron density fluctuations have longer time constants than SID phenomena, and it is possible that these time windows may include some of the sonic events by chance. Caution is urged. Besides, the data indicate a generally poor correlation between these phenomena and the sonic events.

Character of Noise from Aurora

Auroral sounds are discussed at length in a review by S.M. Silverman and T.F. Tuan [1] The first point of difference between these and the reported sounds is in the nature of the sounds themselves. Auroral sounds are reported as like the rustling of silk, hissing, perhaps whizzing sounds, never as booms. This in itself would be sufficient to rule out an auroral origin.

In addition, there is only a vanishingly small probability of auroral occurrence at the latitude in question on all but one day of the reports. The accompanying table (Table 17) gives the date, the A-value (a measure of magnetic activity for the day as a whole) and the maximum K-index during the day at Fredericksburg, Va. There is one near major storm ($A = 46$, $K = 6$) on 2 December, and active days ($15 \leqslant A \leqslant 30$) on 3 and 5 January. Whether these produce aurora, however, is latitude dependent. For a geomagnetic latitude of the order of 50° (of the order of the New Jersey coast) the K_p for which an aurora may be expected is 6, or 5 if the latitude is about 52° [2]. This aurora can be ruled out for all the cited days except December 2 and possibly January 5.

Table 17
Magnetic Acitivity on Days of Reported Atmospheric Sounds

	A	Max. K at Fredericksburg
1977 Dec 2	46	6
15	5	2
20	4	2
21	5	3
22	4	2
23	4	2
1978 Jan 3	11	4
5	21	5
12	2	2
16	7	3

A final argument against an auroral origin is that auroral sounds occur only when an intense, very active aurora is directly overhead. The citizens' reports state that the sounds are heard from some distance away, so that this too does not fit an auroral origin.

Atmosphere as Source

Winter Lightning (Super bolts)

Acoustic impulses with peak energy in the infrasonic region might be produced by lightning discharges of extraordinary magnitude. The viability of such a process depends on the existence of appropriately energetic strokes, production of acoustic energy at the proper peak frequency with adequate efficiencies, and the presence of appropriate propagation conditions. Theoretical models of the thunder process are presently quite primitive and are less than universally accepted; so the discussion will be largely confined to observations.

Numerous parameters related to the lightning discharge have been measured with varied degrees of success. Among these are optical and acoustic power and integrated energy, current flow and integrated charge transfer, optical and acoustic output spectra, discharge channel temperature and overpressure, and radio frequency radiation. From these, estimates of total energy input, conversion efficiencies for optical and acoustic production, and relationships between input energy and spectral composition have been derived. Typical lightning strokes dissipate electrical energies of the order of 10^8 to 10^9 Joules and produce an optical energy of about 10^6 Joules with the acoustical output less well known, ranging upward from this value. Estimates of the efficiency of conversion of electrical energy into acoustic vary from nearly 100% to 0.2%, with a value near 0.33% being most probable in our judgement. Optical production efficiencies vary between 0.2% and 1% with 0.33% again a probable value.

A relationship has been derived relating the acoustic frequency of peak energy production to the inverse square root of the total energy input per unit length of stroke. Total energy values are derived from observed optical outputs using the semiexperimentally derived efficiency factors cited above. A typical discharge thus yields a peak acoustic output at 150 Hz by this relationship, in agreement with observation. Production of a 7-Hz peak would require a total energy input 100 to 1000 times greater than typical.

In a recently published study [2], lightning "superbolts" with optical outputs three orders of magnitude greater than the typical values given above are detected from the Vela satellite system. The optical energies of these discharges range from 1.0 to 2.7×10^9 Joules. The author lists 17 occurrences in a period of 3-1/3 years and estimate a net detection probability of 2×10^{-3} and an incidence rate for superbolts of 5 in 10^7 flashes. Estimates of global occurrence of discharges of this magnitude, whether based on the Vela observations and detection probability or based on global flash rates and the 5 in 10^7 value, yield about 7.5 superbolts per day. This estimate is probably somewhat high because these events were seen only in local winter when lightning activity is low, but the rate is certainly great enough to deserve consideration.

Since conversion efficiencies for acoustic and optical energy are roughly the same, we estimate that the acoustic energy of a superbolt such as observed by Vela is of the order of 1000 times greater than the typical value cited. Even in the worst case of an inverse R^3 attenuation, the typical limit of thunder audibility of 20-30 km will be increased to over 180 km. Since winter lightning discharges are likely to be 1-2 times the length of a typical stroke, the peak acoustic frequency for a superbolt is calculated to lie in the 5-10 Hz range.

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There is some evidence that winter thunderstorms can produce particularly severe though infrequent lightning discharges. Such thunderstorms would be expected to occur primarily over the oceans to the east of large continental land masses when cold fronts move out over warm water. To the west of these cold fronts there is likely to be an unstable layer capped by a strong inversion which could act as a sound duct carrying the thunder landward. Therefore it appears that the requisite conditions can be satisfied to produce the observed phenomena via the superbolt mechanism.

The Vela satellite system reported detection of 5 events of optical output > 10^{13}W during the winter of 1976-1977 in the area of northeast United States and the north Altantic. A summary of the detection is shown below.

Date	Time (z)	Coordinates	
		Lat.	Long.
10 Nov 76	1647:53	37N	73W
27 Dec 76	1143:56	36N	60W
26 Jan 77	1328:19	43N	74W
2 Feb 77	1003:04	35N	65W
5 Feb 77	1412:37	40N	69W

The records of the Lamont-Doherty and Weston observations were searched to see if these events had generated acoustic signals recorded by these systems. No detections were found. In view of this and the invariant location of the December 1977-February 1978 events over a three-month period, winter lightning was not considered a likely source of the events under investigation.

References

1. Silverman, S. M. and Tuan, T. F., 1973, Adv. Geophys. 16:155-266.
2. Silverman, S. M., 1970, Space Sci. Rev. 11, 341-379; see Figure 5, p. 356.
3. Golde 3, R. H., *Lightning*, Vol. 1, Academic Press, London.
4. Turman, B. N., 1977, "Detection of Lightning Superbolts," J. Geophys. Res., 82, 2566-2568.
5. Uman, M. A., *Lightning*, 1969, McGraw-Hill Book Co., New York.
6. Wagner, L. S.and Uffelman, D. R., "Solrad-11 On-Line Systems (SOCOLS) Applications Software, Interim System," NRL Memorandum Report 3466.

Aerosal Release of Energy

This section discusses the explosive freezing of water vapor molecules. It assesses the energy release from these effects to determine their feasibility as candidates for the atmospheric even of 15 December 1977, on the coast of New Jersey.

Freezing of Water Vapor

The freezing of the water vapor molecules is the inverse process of the sublimation of ice. When the molecules freeze the latent heat of sublimation is released. The energy release per gram is 623 Cal. This corresponds to 2.9×10^{23} eV per mole and is equivalent to 0.48 eV per molecule. Thus the condensation and the freezing of each H_2O molecule results in the release of 0.48 eV. At the right altitude a sudden change in temperature due to vertical motion, seeding of clean air, or passage of a shock wave can in theory cause the change to ice to proceed with explosion-like velocites.

To obtain an energy release equivalent to 1 ton (4.2×10^{16} erg $= 2.62 \times 10^{28}$ eV) one must have the freezing of 5.45×10^{28} molecules. This raises the following question. How large an air volume is required to accomodate these molecules? This can be obtained using the data in Figure 76, where the H_2O molecules' density distribution is given as a function of altitude. This density distribution corresponds to the average of the air temperature profiles given in Figure 77. Using the above information, we calculate the air volume, as a function of altitude, required for the energy release of 1 and 10 tons, respectively.

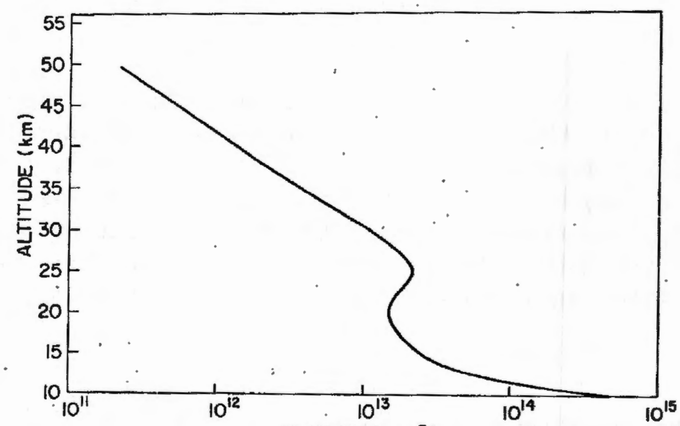

Figure 76

Altitude (km)	Volume (km^3) For	
	1 Ton	10 Ton
45	78.0	780
40	38.0	380
35	14.0	140
30	4.5	45

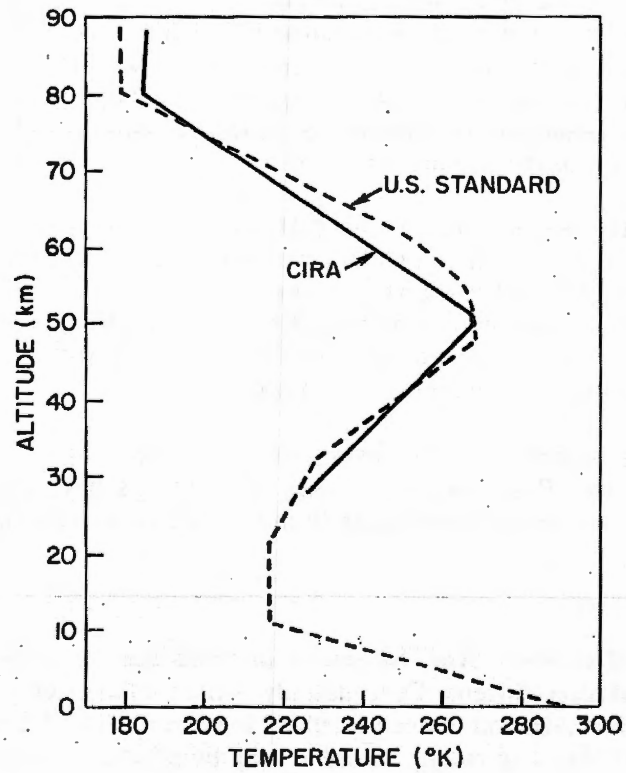

Figure 77

It is apparent that the air volumes required for an energy release of ~ 10 tons are quite large in the 30-45 km range but reasonable for 1 ton at lower altitudes. The distribution of supercooled water at these lower altitudes will be in a thin horizontal sheet. The radiated acoustic energy from such a geometry will be in a small angle aimed nearly vertically and therefore would not disseminate a signal over the wide areas where events were observed and measured.

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References

1. Blattner, W.G.M. and Wells, M.B., Radiation Research Associates Report, AFCRL-TR-75-0317 (31 May 1975)

Atmosphere as Background

Ionospheric Perturbation

It is well known that acoustic-gravity waves propagating through the ionosphere cause plasma density and temperature perturbations. Although there are a variety of natural sources for these waves, it is exceedingly difficult to determine the nature and location of the source from an examination of ionospheric data. Only in usual circumstances (e.g. nuclear explosion, volcanic eruption) is it possible to clearly and uniquely identify the source. At ionospheric heights molecular viscosity and thermal conduction provide important dissipative mechanisms and limit the distance that smaller-scale waves can propagate without prohibitive attenuation.

Atmospheric Conditions

On the days during this winter that acoustical phenomena were recorded and/or heard, some general statements can be made about meteorological conditions. Usually the passage of a cold front over the U.S. east coast preceded these events. The vertical temperature profiles over the New York and Charleston areas exhibited small lapse rates below 3 km and in many instances small temperature inversions were present. In the upper troposphere on most days strong horizontal winds were blowing in a generally eastward (westerly) direction. Even stronger winds were present in the 50-60 km region. The large shear associated with these winds provided strong refraction and ducting of acoustical energy in the downwind direction but inhibited propagation in the upwind direction.

Particular attention was devoted to the 2 December 1977 events. At the time of these occurrences in the New York area the cloud cover was almost complete, with scattered clouds at low and medium heights and overcast at higher altitudes. The vertical temperature profile exhibited a temperature inversion in the 1.4- 1.9-km region. Strong vertical shear was present in the horizontal winds which reached peak velocities of ~ 75 m/s at about 8 km. Near the stratopause wind velocities of ~ 100 ms^{-1} were observed.

Similarly on 2 December 77 Charleston had complete cloud cover and a temperature inversion at 1.6 to 3.5 km. Peak horizontal winds of ~ 70 m/s at 12.5 km and ~ 90 m/s at 55 km were reported. No reports of lightning or thunder were recorded at either location.

Summary

The original concern over the source of these sounds arose from the response of New Jersey and Charleston citizens. Consequently, where citizen reports correlated with good scientific records the investigation concentrated on the events (i.e., 2 December 1977, 12 January, and 16 January 1978). The events recorded only by scientific instruments but which were not strong enough to cause widespread citizen concern were studied as sources of additional data in an attempt to understand the 2 December event. No attempt was made to study phenomena not associated with acoustic signals or to study isolated reports of acoustic signals in other parts of the U.S.

Although the time constraints of the study did not permit deployment of additional sensors, the data assembled from equipment in operation and citizens' reports allowed us to determine many important things about the signals. Unfortunately, the Lamont-Doherty Observatory was not able to record the 2 December events on tape. However, tape recordings were available for most of the significant events of January. Dr. Donn of Lamont reported that the events of 16 January, which were similar in amplitude to the 2 December events, showed energy peaks ranging from 1 to 3.5 Hz. Weston Observatory reported that the 16 January events had the same frequency appearance as the 2 December events and that all 180 events recorded in December, January and February showed a peak frequency between 1 and 7 Hz. Dr. Donn pointed out that for strong signals his equipment responds to incoming frequencies up to 20 Hz. No significant energy was detected by the Lamont-Doherty microbarograph at frequencies above 10 Hz from any of the events in question. The Lamont Observatory also operates a small array of seismometers near their microbarograph stations. These seismic stations did not detect any of the acoustic signals detected by the nearby microbarographs. Since the Lamont seismic equipment is similar to and of the same sensitivity as the Weston equipment, the failure to detect is attributed to the fact that the Lamont seismic stations are most sensitive at higher frequencies (around 20 Hz) and have essentially no response at frequencies below 7 Hz. The U.S. Geological Survey seismic equipment operated by Baptist College staff is sensitive to signals from 1 to 35 Hz. Unfortunately, the quality of the records did not permit spectral analysis.

Citizens' reports made a major contribution to the characterization of the frequency content of the events. An analysis of citizens' reports, especially those which described the events in convincing detail, shows that the events were heard only indoors, and usually in a frame house with storm windows (Appendix 2). A number of cases have been found where people who were outdoors and isolated from built-up areas did not hear the noise, wheras people in the same vicinity who were indoors sensed a strong signal. Examples included reports from workmen at a housing development. Those workmen who were in buildings or within arms' reach of the building heard the noise, but workmen who were some distance from the buildings did not. Other examples show that police dispatchers inside a headquarters building heard the event, but officers on patrol did not. An electronics technician from Monmouth, N.J., reported sensing the event of 2 December from within his residence. His next-door neighbor was hanging clothes out of doors at the time and did not notice the noise. The neighbor was, however, startled by seeing the garage doors of her home (closed at the time) shake and vibrate so violently that she though it would go to pieces. A similar pattern was generated from Charleston area citizens' reports. The typical reporter in the Charleston area was in a fairly large, frame house often built twenty or more years ago. Outside observers were not disturbed, at least to the point of complaining or reporting in writing. What residents heard did not come directly from a remote source to their ears. Typically, they reported the rattling of windows, doors, or crockery on shelves. Apparently what they sensed and heard was the response of their house to a low-frequency oscillating air shock with a wavelength of the order of the dimensions of a typical dwelling.

In sum; the preponderance of evidence is that the events which startled residents over wide areas of New Jersey and the Charleston area are the same or similar to the acoustic events recorded by Lamont, Weston, and Baptist College. These events, when observed, were infrasound (below audible frequencies) between 1 and 7 Hz. For the purposes of other calculations made during this study it has been assumed that 3 Hz is the most likely dominant frequency.

Citizens' reports of the duration of the events vary widely, as might be expected considering the performance of unaided observers in estimating the duration of short unexpected events. The duration of signals measured by Lamont and Weston observations also vary. Trained seismologists who reviewed the evidence were in substantial agreement that the 2 December events lasted for 30 to 40 seconds. The duration of a large number of events has been measured from records at Weston Observatory, and a pattern of pulse duration for particular days is observed. This variability has been taken as evidence that the pulse duration is largely a function of multipath propagation conditions, and source height as was found to be predicted on theoretical grounds.

The amplitude or apparent loudness of the events is not well documented, but it appears that the 2 December events were among the largest detected between December and February. The afternoon event of 2 December was the loudest of all of the events considered. Only the 16 January 78 event near New Jersey was reported as being of near equal amplitude to the 2 December event. In South Carolina the events of 12 January and 21 February were reported as being as disturbing as the 2 December morning event. Lamont acoustic equipment saturated during the 2 December events (equivalent to 50 μbars peak to peak), and Dr. Donn estimates (by comparison to citizens' responses to measured sonic booms) that the signal at Lamont could have been as much as 200 μbar.

The seismic detectors actually responded only to vertical displacements. It would be misleading to try to convert these measurements into an equivalent source strength without considerable calibration effort. Nevertheless, it can be said that the acoustic signals as recorded by seismic stations vary by a significant factor. The largest event of 2 December produced a vertical ground displacement of 50 nm. This displacement was equivalent to the signal which would have been generated by an earthquake of 2.5 to 3 on the Richter scale, assuming that the epicenter of the event was located at a point just off the coast of New Jersey. This estimate of Richter magnitude uses the Richter formula developed for the west coast of the U.S., modified for east-coast propagation conditions. The formula is

$$R_{magnitude} = \log \left(\frac{\text{amplitude in millicron}}{\text{period in sec}} \right)$$

$$+\log \text{ (of distance (km))} - 1.39,$$

and of course is valid only for true tectonic events. It is not a valid measure of the energy of an airborne event. Parenthetically, it should be noted that seismologists conservatively estimate that there are 150,000 to 200,000 tectonic events of Richter magnitude 2 or better per year worldwide.

In all cases observed, signals had velocities across the microbarograph array and between seismic stations which were near to the speed of sound in air at sea level. No seismic signals were transmitted through the ground between stations. No horizontal responses were observed on seismometers which correlated with the arrival of the acoustic signal arrival at any station. Thus, the study concluded that none of the observed signals has a direct seismic origin. Furthermore, there were no combined acoustic and seismic signals which would have been generated by a large underwater explosion or sea bottom seismic activity that coupled with the atmosphere to produce an acoustic signal.

Based on the observed acoustic velocity of the signals, it was possible to calculate lines of equal time difference, assuming constant acoustic velocity between all stations in the Weston network. Although a localization obtained in this manner was inherently inaccurate, it served to provide a useful first approximation to the actual location of the events. Even without prescreening the data for particularly small or doubtful events, out of 183 events recorded by Weston Observatory between 28 November and19 January, over 85% gave solutions at the vicinity of 39°N 74°W or 40°N 73.5 W. The microbarograph observations at Lamont consistently give directions of arrival between bearings 175° and 190° from Lamont. The 2 December events giving 182°, the one event on 11 January coming from 186°, and the three events of 12 January 187°, 180°, and 184°. The six events measured between 1705 and 2026 Z (1205 and 1526 EST) on 16 January gave arrival directions from Lamont of 189°, 188°, 188°, 180°, 177°. These azimuths are consistent with the source locations suggested by the Weston data.

Profiles of the speed of sound as a function of altitude were developed for 2 December. Winds aloft were a significant perturbation to the acoustic velocity profile. In fact, it was necessary to generate a separate velocity profile from each postulated source location along the bearing to each of the five receiving stations (Fig. 78). These profiles were used as a basis for ray tracing calculations between postulated event locations and receiving locations. Several hundred ray tracing calculations were performed and matched to the observed data. The need to find good propagation paths between the many locations that received the signal, the need to account for the failure to sense the signal in many areas of New York and New Jersey, and the need to account for the 30- to 40-second signal duration observed at Lamont and at the Weston array, limited the possible source altitudes to 2500 meters or less. The strong west winds on 2 December required the possible source locations to be west of a north-south line through the Lamont station. The most likely location for the 2 December events was determined to be at 39°30'N, 74°10'W. This location is at a range of 170 km and bearing of 186° from Lamont and is about 10 km southeast of Beach Haven, New Jersey. This determination of source location is probably accurate to within ± 10 km in range and ± 4° in bearing.

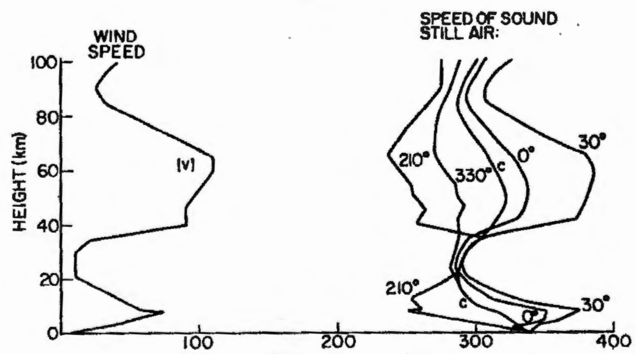
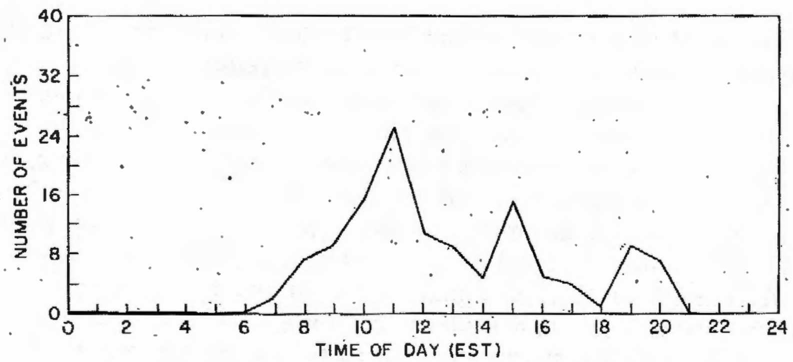


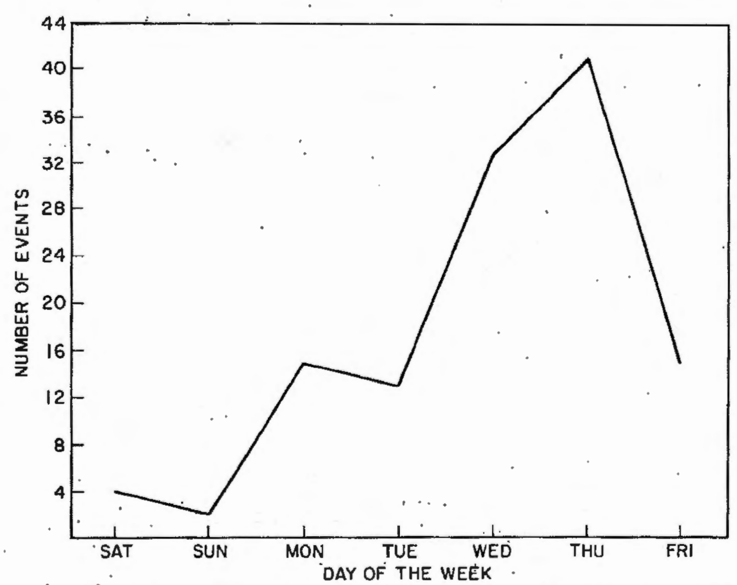
Figure 78

The days and times of the events suggest a cultural rather than a natural cause. Citizens' reports displayed a pattern, indicating that the events occurred primarily during work days and daytime hours. The same pattern was observed on inspection of the measurements made at Lamont and Baptist College. The statistics become even more impressive when the large number of events measured by the Weston network is considered. The Weston records were reviewed for the period from 1 November 1977 to 19 January 1978. The records were analyzed by experienced seismologists who could identify and reject the usual cultural signals (quarry blasts, etc.) but who were given no information on when to expect the acoustic signals of unknown origin. No acoustic signals were detected in November until the morning of Monday, 28 November, when five events appeared as though a switch had been thrown. Between that date and 19 January, 183 signals were detected. Nearly all of these signals occurred on work days between 0700 and 2100 EST (Fig. 79). During this entire period, few signals were detected on Saturdays, Sundays, or national holidays (Figs. 80-81). Signals were rarely detected between 1200 and 1330 EST. The diurnal pattern shows three peaks. One peak occurred between 1000 and 1100 EST, a second at 1500 EST, and a third around 1900 EST.



ACOUSTIC EVENTS WESTON OBSERVATORY I NOV 77 – IO JAN 78

Figure 79



ACOUSTIC EVENTS WESTON OBSERVATORY I NOV 77 – IO JAN 78

Figure 80

ACOUSTIC EVENTS WESTON OBSERVATORY

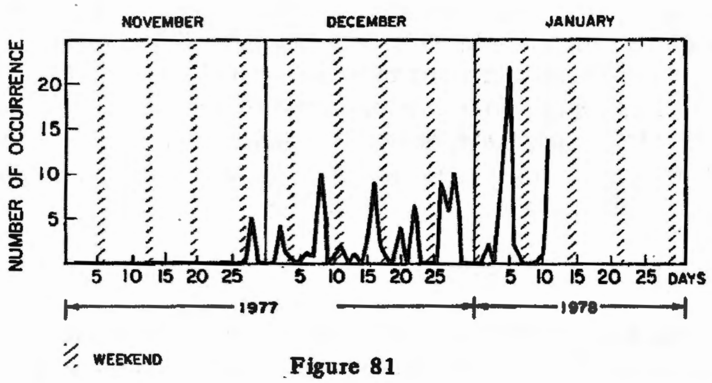


Figure 81

Although the events have a manmade pattern, characterizations of the events in frequency and duration and NRL investigations of possible causes lead us to say that the series of acoustic events which startled so many residents in New Jersey and in the Charleston area were not the result of the following manmade causes:

- Nuclear explosions
- Military research and development activities
- Military ordnance
- Civilian use of high explosives
- Ship disasters
- USSR ship operations
- Geophysical exploration
- Antipodal events
- Missile launches
- Missile reentry
- Low-altitude satellites
- *Concorde* (except Nova Scotia).

The following natural phenomena were reviewed and classified as unlikely causes of the events under investigation

- High altitude aerosols
- Meterorites
- Winter lightning
- Direct seismic generation
- Biogenic methane
- Tectonic methane.

Isolated causes

A small number of reports from residents do not fit the general pattern. They are isolated from the majority in location of observers, times of events, or both. The events are described in different terms, and visual displays are often associated with these events. They do not correlate with instrumented measurements. The most likely explanation is that they are of normal occurrence but are noticed and reported because of heightened awareness of citizens due to excellent communications through the various news media. An example is a series of reports of an event in New Jersey at about 02:00 EST in the morning of 21-22 December. The report associated a flash of light closely in time with a loud noise. It was found that a protective transformer fuse had functioned explosively at 01:58 EST on a transformer in the area. The flash and sound as well as the electrical transient associated with this event apparently stimulated a number of citizens' reports from the local area. Had there been need, most of the other anomalous reports probably could have been explained by painstaking investigation. In some cases the anomalies apparently result from errors in recalling times and dates of events when reports were submitted weeks later.

CONCLUSIONS

The acoustic events of 2 December 1977 and following dates which startled residents of New Jersey and the Charleston area are part of a series of events recorded by acoustic and seismic stations in the vicinity. The source of these events is cultural and the degree of disturbance of east-coast residents was influenced by propagation conditions. The most likely sources of these events appears to be high-performance military aircraft operating supersonically. On every occasion when significant reports were made by residents and confirmed by scientific measurements, supersonic-capability aircraft were found to be operating in nearby warning areas (Table 18). In many cases, interviews with pilots confirmed that supersonic flight with maneuvers took place. Based on calculations undertaken during the course of this study, it appears that the disturbance of citizens can be reduced substantially by changing flight patterns to reduce supersonic incoming courses radial to populated areas, by avoiding sharp climbs; descents or turns in supersonic flight near the western borders of the training areas, and by developing simple acoustic ray tracing procedures suitable for use by base meteorologists to determine the existence of meteorological conditions which would exacerbate the effects of aircraft operations on residents near training areas.

Table 18
Event Correlation with Military Aircraft

Significant Events			X = Supersonic Capable Aircraft in Warning Area							
			NY	NJ	NJ/DE	VA	SC	SC	SC	GA
Date	Time	Area	W-105/106	W-107	W-108	W-386	W-177	W-133/134	W-132	W-157
2 Dec	0930	SC						X	X	X
	0945	SC						X	X	X
	1007	NJ	X	X	X	X				
	1053	NJ	X	X	X	X				
	1548	NJ	X	X	X					
15 Dec	0837	SC	X			X	X	X	X	X
	0847	SC	X			X	X	X	X	X
	0958	SC	X			X	X	X	X	X
	1013	SC	X	X	X		X	X	X	X
	1024	SC	X	X	X		X	X	X	X
20 Dec	0856	SC	X				X			
	1333	SC	X		X		X	X	X	X
22 Dec	0848	SC	X				X	X	X	X
	0935	SC	X	X	X		X	X	X	X
	1015	SC	X	X	X		X	X	X	X
	1550	NJ		X	X	X				
3 Jan	1453	SC	X				X			
4 Jan	0900	SC	X					X	X	X
	1047	SC	X	X			X	X	X	X
	1054	NJ	X	X			X	X	X	X
5 Jan	0745	SC	X				X	X	X	X
	0810	SC	X				X	X	X	X
6 Jan	0930	SC	X				X	X	X	X
11 Jan	1050-1110	NJ		X	X					
12 Jan	1411	SC	X				X	X	X	X

Acknowledgments

The Naval Research Laboratory gratefully acknowledges the responsive and vital assistance provided by citizens, local officials, the press, and representatives of other federal agencies. In particular, major contributions of data were made by

Dr. W. Donn, Lamont-Doherty Observatory, Palisades, NY
Dr. E. Chiburis, Weston Observatory, Weston, Mass.
Mr. William Wagner, Vestigia Inc., Dover, NJ
Mrs. Joyce Bogwell, Baptist College, Charleston, SC
Mr. Drayton Cooper, TV Channel 2, Charleston, SC
Mr. Garry Forrest, Carolina Power and Light Co., Raleigh, NC
Dr. F. H. Reder, Ft. Monmouth, NJ
Dr. George Kashak, Ft. Monmouth, NJ
Mrs. James Winchester, Spring Lake, NJ
Mr. George McCarthy, Asbury Park Press, Asbury Park, NJ
Mr. Edward Sheratt, Jersey Central Power and Light Co., Toms River, NJ
Mr. Thomas Shea, Dept. of Labor and Industries, Trenton, NJ
Police Dispatcher Christine Parker, Long Beach, NJ
Patrolman Robert Engle, Ships Bottom, NJ
State Police Sgt. First Class Edward Blackburn, Tuckerton State Police, NJ
Police Sgt. McNeil, Forked River, NJ
Mr. Anthony Broderick Federal Aviation Administration, Washington, D.C.
Mr. Richard A. Wood, U.S. Weather Service, Tucson, AZ
Mr. Peter Anderson, Environmental Protection Agency, New York, NY
LTJG Richard Rearden, U.S. Coast Guard, New York, NY
Maj. James Craig, USAF, Patrick AFB, Fla
Mrs. Joyce Milliner, NASA, Wallops Island, VA
Maj. Peter Bernstein, MacDill AFB, FLA
Mr. Nicholas L. Rosner, Evapograph, New York, NY.

The following persons actively participated in discussions with members of the study group while the work was in progress. They have not reviewed this report before publication and are not responsible for either the conclusions or any errors contained in the report. Their informed and stimulating comments and advice are gratefully acknowledged:

Dr. Yash Aggarval, Lamont-Doherty Observatory
Dr. Arthur Few, Rice University
Dr. Thomas Gold, Cornell University
Dr. Leslie Hale, Pennsylvania State University
Dr. Gerald Leies, U.S. Air Force
Dr. Gorden MacDonald, Mitre Corp.
Dr. Dominic Magliere, NASA-Langley
Dr. Jack Reed, Sandia Corp.
Dr. Douglas Revelle, Carnegie Institution
Dr. Samuel Silverman, U.S. Air Force
Capt. B. N. Turman, U.S. Air Force

Appendix 1

THE UNDER SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301

RESEARCH AND ENGINEERING

UNCLASSIFIED

28 DEC 1977

MEMORANDUM FOR ASSISTANT SECRETARY OF THE NAVY (RESEARCH, ENGINEERING AND SYSTEMS)

SUBJECT: Investigation of Acoustic Phenomena

Over the past few weeks, considerable interest has evolved regarding the unexplained acoustic phenomena which have occurred off the east coast of the U.S. The Department of Defense has been asked to investigate these incidents to try and explain their cause and, if appropriate, their effects.

Accordingly, it is requested that the Navy perform a short, intensive investigation of these incidents in an attempt to discover their cause. It is suggested that the Naval Research Laboratory, due to its multi-disciplined technical capability, could perform this function. Close coordination should be maintained with the Central Intelligence Agency, as they have been tasked to investigate these incidents also.

I would appreciate receiving interim reports at appropriate intervals, plus a final report within approximately 60 days.

Gerald P. Dinneen

Gerald P. Dinneen
Principal Deputy

282831

 Encl (1) to NRL ltr 1405-2:REP:bd

Appendix 2

Date	Place	Time(EST)	Location	Character of Sound	Accompanied by
Sept/Oct/Nov 77	White Lake, NY		Inside	Large blast.	
Week of 14 Nov 77	St. Simons Is., GA	Afternoon	Inside	Blast...seemed to have more power than sonic boom.	
26 Nov 77	Hardwick, VT	1:14 or 2:14 p.m.	Inside	Boom...like roof blown off house...much like sonic boom....no planes heard in area; like cannon fire.	
early Dec 77	Toms River, NJ	Between 8:00 & 10:00 a.m.	Outdoors	"like a plane breaking sound; continued and became increasingly loud"; "appeared to be from deep in the earth"; lasted approximately 4-5 minutes.	
2 Dec 77	Bradford Cty, PA	3:40 p.m.	"area 6 miles west of Rt. 6 or 6 miles west of Wyalusing, PA"	"That sure wasn't any little rumble". Came in sort of waves.	
2 Dec 77	Long Branch, NJ	1520/1600 approx.	Indoors; all windows closed	"A very loud, frightful rattling noise".	
2 Dec 77	Asbury Park, NJ	1500/1600 approx.	Inside	"Very loud rattling, noise". "Duration approximately 8-9 seconds". "Followed after approximately 5 seconds by another noise lasting approximately 3 seconds."	
2 Dec 77	Pt. Pleasant, NJ	11:00 a.m.		Sound like a truck.	House shook.
2 Dec 77	Bricktown, NJ	3:30 p.m.	Indoors	Sound like explosion in basement.	House shook; dog upset.
2 Dec 77	Bricktown, NJ	3:00 p.m.		Rumbles, lasted 2 or 3 seconds.	Clear weather.

Date	Place	Time(EST)	Location	Character of Sound	Accompanied by
2 Dec 77(?)	Old Bridge	4:00 p.m.		Sonic boom(?); echoed; low; 5-7 seconds	
2 Dec 77	Monroe Twps., NJ	4:00 p.m.		Rumble; lasted few seconds.	Cold and clear.
2 Dec 77	Wall Twsp., NJ	≈2:00 p.m.		Bang and rumbling for several seconds; faded away fast.	Dog nervous.
2 Dec 77	Egg Harbor City, NJ	3:40 p.m.	Outdoors-stepped out of car 6-10′ from house. 3 people in garage, wife in house heard louder than he	"4 distinct sonic booms from 3 aircraft"	
2 Dec 77	Freehold, NJ	4:00 p.m.			"Bldg. started to shake, or tremble, for at least 10 sec."
2 Dec 77	Mt. Holly, NJ			"Loud rumble". "Lasted several seconds".	Cracked archway in house.
2 Dec 77	Belmar, NJ	3:00 p.m.			House shook; windows rattled.
2 Dec 77	Haledon, NJ	10:10 a.m.			Windows vibrating.
2 Dec 77	Cliffside Park, NJ	11:00–12:00 a.m.			House shook for few seconds.
2 Dec 77	North Beach, NJ	10:00 a.m.			Storm door shook violently for several minutes.
2 Dec 77	Tuckerton, NJ	2:00 p.m.	Indoors	"Sounded like a truck hit the back of my house".	
2 Dec 77	East Brunswick, NJ		Indoors	"A rumble and the house shook"; "It was very quiet-we heard what sounded like an underground explosion and rumble".	"The house shook"; neighbor also felt it.

Date	Place	Time	Location	Character of Sound	Accompanied by
2 Dec 77		≈9:00 a.m. afternoon	Indoors	"Heard and felt too the "tremendous boom"; "Seemed...like in a tunnel." "Similar type blast... soundedpowerful". "Also heard a tremendous blast since, coming from the atmosphere".	Shook house – the earth trembled.
2 Dec 77	Whiting, NJ	3:00–4:00 p.m.	Indoors	"A distinct snap!snap! before the (2) blasts". "Two so close together or it seemed like one"; "second greater of the two".	No transients across TV screen.
2 Dec 77	Cliffwood Beach NJ		Inside	"Thought propane gas tank outside–house had exploded"; "neighbor across street–heard a gush of wind and then the – side of her house shook". "Friend in Marlboro said he experienced same thing".	"House began to tremble"; "Floor vibrated". "Daughter was outside and felt nor heard anything".
2 Dec 77	Hazlet, NJ	4:00 p.m.	Inside	"Heard this 'bang' right over our house–first impression–something very heavy fell on roof". "Sounded like thump rather than an explosion".	
2 Dec 77	Red Bank, NJ	3:45 p.m.	Inside		"Everything shook... window...big chair in which I was sitting".
2 Dec 77	Belmar, NJ	≈1:00–2:00 p.m.	Inside	"Heard and felt "Blast" subsequent booms..." type heard when blasting is going on a few miles away".	"House shook, windows rattled...for 5 seconds".

Date	Place	Time (EST)	Location	Character of Sound	Accompanied by
2 Dec 77	Toms River, NJ	3:40 p.m.	Inside		House shook as if in earthquake; vibrations <u>not</u> accompanied by booming noise. None of neighbors heard any noise.
2 Dec 77	Paterson, NJ	Early evening	Inside	"Similar...to an explosion.. a few blocks away,...only stronger".	No light flashes.
2 Dec 77	Jackson, NJ	≈3:00 p.m.	Inside	"12' x 65' mobile home shook; loud rumble".	
2 Dec 77	Howell Tnsp., NJ	3:45 p.m.			2 shocks ≈ 1 sec. apart about same intensity; plants fell fell from window sill.
2 Dec 77	Farmingdale, NJ	11:00 a.m.		Like truck	Fireplace shook – 1½-2 minutes.
2 Dec 77	Paterson, NJ	before 2:00 p.m.			Saw TV effect momentarily.
2 Dec 77	Brielle, NJ	3:41 p.m.			Felt concussion; lost TV; shook house; cracked window. No light.
2 Dec 77	Bricktown, NJ	3:45 p.m.		Noise lasted for several seconds.	House shook like earthquake; dog frightened.
2 Dec 77	Brigantine, NJ	≈9:15 a.m. 9:35 a.m.	radio tower–35 ft. high, in house	"Very strong blast occurred, shaking house violently for approximately 3 or 4 seconds". "Wife did not hear blast outside".	2 flashes bluish light 10-15 sec. apart.
2 Dec 77	Hammonton, NJ	3:30-4:00 p.m.	Indoors	"Blasts. . . felt like an explosion next door".	Heard planes when went outside.
2 Dec 77	Ridgefield, NJ	≈4:00 p.m.	Indoors	"Sounded like two thumps on . . . door". "Swishing noise".	Heard planes when went outside.

Date	Place	Time (EST)	Location	Character of Sound	Accompanied by
2 Dec 77	Aberdeen, NJ	3:30-3:45 p.m.	Indoors		House shook for several seconds; felt like rocket taking off, but of shorter duration. No noise
2 Dec 77	North Wildwood, NJ	after 9:30 a.m.	Inside	"Rumble just rattled windows".	
2 Dec 77	Highstown, NJ		Inside	"Feel more than hear".	Shaking resembles something heavy being dropped upstairs.
2 Dec 77	Toms River, NJ	afternoon	Inside	Loud blast "more powerful than 18 Jan 78" not heard 6-8 blocks away.	House shook; pictures rattled.
2 Dec 77	Spring Lake, NJ	10:00 a.m. 3:30-3:45 p.m.	Inside	Heavy knocking on door. Workmen next day said had heard terrific explosion, like rumbling. Workmen away from building did not hear it.	House shuddered, ending with jolt.
3 Dec 77	Princeton, KS	10:30 p.m. central time	Inside	Terrific explosion; also heard 2 miles away.	Shook house badly.
3 Dec 77	Elizabeth, NJ	1:00 a.m.	Indoors	"Series of nine explosions; lasted about 20 minutes".	
7 Dec 77	Randolph, NJ	7:00 p.m.		"Sounded like crash of thunder with no rumbling".	
7 Dec 77	South Amboy, NJ	3:30 (p.m.?) 4:00 (p.m.?)		Rumble.	Shook house.
7 Dec 77	Tuckerton, NJ	7:00 p.m.	Indoors	"The same thing occurred".-"Sounded like a truck hit the back of my house".	
17 Dec 77	Panama, NY	between 2:30 & 3:30 p.m.	Inside	Felt 5 tremors or blasts-15-20 minutes apart; thought it was sonic boom, but louder and stronger.	Window rattled; cat frightened
20 Dec 77	Farmingdale, NJ	11:00 a.m. 6:45 p.m.		Like truck.	

Date	Place	Time (EST)	Location	Character of Sound	Accompanied by
20 Dec 77	Highlands, NJ	9:00-10:00 a.m.	Inside	Popping sound.	Light in sky; bright white w/fuzzy edges; ≈ size of tennis ball; dog nervous.
21 Dec 77	Villas, NJ	1:00-1:30 a.m.	Indoors	Rumbling and bang.	Vibrated house; flash in sky.
21 Dec 77	Hillsdale, NJ	9:00-10:00 a.m.	Indoors	Explosion; rumble (woke up).	Maybe flash.
21 Dec 77	Mays Landing, NJ	P.M.	Inside	"Rumble;–Similar to 1973 Delaware.	Vibration.
21 Dec 77	Tuckerton, NJ	6:30-7:00 p.m.			Shocks and tremors.
21&22 Dec 77	Elizabeth, NJ	7:00 p.m.	Indoors	"Series of nine explosions; lasted about 20 minutes". "Same sounds, same duration". (as 3 Dec 77).	
22 Dec 77	S. Asbury Pk.	8:30 a.m. & 4:00 p.m.	Indoors		No lights; chandelier sway
24 Dec 77	Sloatsburg, NY	3:45 a.m.	Inside	Three blasts "Sounding like tire blowouts". Daughter also awakened. Wife & son did not hear.	
27 Dec 77	Paterson, NJ	9:15 a.m.	Ground sound		
30 Dec 77	Stone Harbor, NJ	5:30 a.m.	Indoors	"Rumble".	
3 Jan 78	Villas, NJ	12:15 p.m.		Heard tremors under patio.	Toolshed (attached) moved away from house.
3 Jan 78	Neptune, NJ	10:25 p.m.		"A blunt sound like a blast in a distant".	2 flashes of light
4 Jan 78	Cape May, NJ	Morning hours		4 explosions	
4 Jan 78	Villas, NJ	12:45 p.m.	Outdoors (on front porch)	"An explosion in the middle of the road". "Awful loud rumble".	
5 Jan 78	S. Asbury Pk	4:00 p.m.	Indoors		No lights; chandelier sway.
O/A 5 Jan 78	Villas, NJ			Rumblings and explosions.	

Date	Place	Time (EST)	Location	Character of Sound	Accompanied by
6 Jan 78	Wayne, NJ	1:30 p.m			
6 Jan 78	Wayne, NJ	2:00 p.m.		Explosive sound and rumble.	
6 Jan 78	Paterson, NJ			Ground sound.	
6 Jan 78	Wykoff, NJ	9:00 a.m. & 9:20 a.m.		Felt blasts.	Bird nervous before.
6 Jan 78	Wykoff, NJ	9:00 a.m. & 9:20 a.m.		Heard blasts.	
6 Jan 78	Pompton Plains, NJ	≈1:30 p.m. & 4:00 p.m.		Blast. Blast.	
12 Jan 78	Rockaway, NJ	1404 and 1407	Indoors		3-second vibrations on home windows; "Did not hear or see any other pertinent scientific facts".
2 Jan 78	Livingston, NJ	≈10:30-11:30 a.m.		Loud explosion	Shook house.
18 Jan 78	Toms River, NJ	11:20 a.m.	Inside	"Loud blast".	House shook; pictures rattled.
19 Jan 78	Long Branch, NJ	2200-2400 approx	Indoors	"A short and not very loud boom".	Light flash preceding boom.

UNCLASSIFIED

Appendix 3

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Branch of Earthquake Hazards
3060 South Highland Drive
Las Vegas, Nevada 89109

January 17, 1978

Mr. Robert Proodian
Naval Research Laboratories
Code 1405
Washington, D. C. 20375

Dear Mr. Proodian:

A preliminary inspection of the South Carolina Seismic Network grams from December 2 indicate an acoustical type signal. The energy is coming from the air and from the general easterly direction and is not an earthquake or blast type of signature.

I suggest this data be supplemented with VPI's data and further analyzed by Gil Bollinger.

Sincerely,

Kenneth W. King
Chief, Field Operations

Appendix 4

STATE OF NEW JERSEY
DEPARTMENT OF LABOR AND INDUSTRY
LABOR RELATIONS AND WORKPLACE STANDARDS
LABOR AND INDUSTRY BUILDING
TRENTON, NEW JERSEY 08625

JOHN J. HORN
Acting Commissioner

WILLIAM J. CLARK
Assistant Commissioner

February 15, 1978

Jack Brown
6701 Office Code
Naval Research Laboratory
Washington DC 20375

Dear Mr. Brown:

Enclosed are the summary sheets of the quarry blasts of over 20,000 pounds for the months of November and December 1977. With the exception of Mt. Hope Materials, the quarry records are from quarries in mid-New Jersey.

We do not have any knowledge on Fort Dix or Fort Monmouth. In the past, Picatinny Arsenal near Dover, New Jersey, has conducted open explosive testing. These blasts would be heard 20 miles away, but not close. We haven't had any complaints for several years and do not know if testing is being done here. Hercules Powder Company, in Roxbury also near Dover, periodically disposes of small amounts of explosives by detonation. These can be heard for several miles.

On December 12, 1977, a woman living over 10 miles from the Trap Rock Quarry in Kingston, New Jersey, complained of a blast at the quarry. Her time did not quite match the blast time. We have been at a loss to explain this, but it does raise our interest in your project. If possible we would appreciate any information you might uncover which could help us in regards to quarry blasting.

Very truly yours,

Thomas K. Shea

Thomas K. Shea, PE
Chief Mine Safety Engineer

AD-18.4 (12-76)

New Jersey Department of Labor & Industry
Division of Workplace Standards
Bureau of Engineering & Safety
Box 709, Labor & Industry Building
Trenton, N. J. 08625

MONTHLY EXPLOSIVES USE REPORT

TE: Complete all applicable entries on the front and reverse sides and submit to the Bureau of the Engineering and Safety at the above address within ten (10) days after the end of each month.

HOLDER			
NAME: Trap Rock Industries, Inc.	STREET ADDRESS: Laurel Avenue		
CITY, STATE, and ZIP CODE: Kingston, New Jersey 08528	COUNTY: Somerset	TELEPHONE NO.: 609-924-0300	

Inventory Report for Month of November, 19 77	High Explosives Pounds	Detonators (Caps) Number	Gunpowder Pounds	Prima Cord Other In Feet
Beginning Actual Count Inventory — First of Month	3,574.66	1,468	--	25,700
Purchases during the Month	102,910.00	1,337	--	--
Total (Item 1 Plus Item 2)	106,484.66	2,805	--	25,700
Amount Used (Fill in on back) Blasting Summary	101,888.00	778	--	8,800
Miscellaneous Adjustments (Explain Reason below)	--	--	--	--
Month Ending Inventory on Hand by Actual Count	4,596.66	2,027	--	16,900

Describe reason for adjustments above. Manufacturing and other non-blasting uses reported here.

C. Name of Supplier	High Explosives Pounds	Detonator (Caps) Number	Gunpowder Pounds	Other
Explo-Tech, Inc.	102,910.00	1,337	--	--

Trap Rock Industries, Inc.
(Licensee)

-400 (R-10-75)

EXPLOSIVES USED IN BLASTING

List all blasts containing over 500 pounds of explosives separately. Otherwise list daily totals for each blasting site.

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
11/2/77 12:30 pm	KE-26	R. Renfer #0394	45,790	34	3,103			1	Bank	
11/9/77 1:05 pm	KW-4	R. Renfer #0394	11,512	22	1,248			1	Bank	
11/15/77 1:45 pm	KE-27	R. Renfer #0394	26,707	26	2,658			1	Bank	
11/22/77 1:00 pm	KE-28	R. Renfer #0394	27,676	22	2,778			1	Bank	
11/1/77 10:00 am	East Quarry	E. Leonardi #0333	8	50	8			1	Secondary	
11/2/77 9:30 am	East Quarry	E. Leonardi #0333	7	48	7			1	Secondary	
11/4/77 11:00 am	East Quarry	E. Leonardi #0333	15	97	15			1	Secondary	
11/7/77 10:00 am	East Quarry	E. Leonardi #0333	10	50	10			1	Secondary	
11/8/77 11:30 am	East Quarry	E. Leonardi #0333	15	72	15			1	Secondary	
11/9/77 9:00 am	East Quarry	E. Leonardi #0333	8	48	8			1	Secondary	
11/10/77 12 noon	East Quarry	E. Leonardi #0333	12	47	12			1	Secondary	
11/11/77 11:00 am	East Quarry	E. Leonardi #0333	14	53	14			1	Secondary	
11/14/77 11:45 am	East Quarry	E. Leonardi #0333	10	42	10			1	Secondary	
11/15/77 10:00 am	East Quarry	E. Leonardi #0333	8	38	8			1	Secondary	
11/16/77 11:00 am	East Quarry	E. Leonardi #0333	11	49	11			1	Secondary	
11/17/77 10:15 am	East Quarry	E. Leonardi #0333	12	45	12			1	Secondary	
11/18/77 9:30 am	East Quarry	E. Leonardi #0333	10	33	10			1	Secondary	
11/21/77 2:00 pm	East Quarry	E. Leonardi #0333	63	2	63			1	Secondary	
	TRI - Kingston Quarry									

EXPLOSIVES USED IN BLASTING

List all blasts containing over 500 pounds of explosives separately. Otherwise list daily totals for each blasting site.

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P.V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
12/5/77 1:00pm	KE - 29	R. Renfer #0394	28,458	23	3,071			1	Bank	
12/12/77 2:00pm	KE - 30	R. Renfer #0394	26,120	23	2,995			1	Bank	
12/20/77 1:00pm	KSW - 4	R. Renfer #0394	14,775	30	1,016			1	Bank	
12/21/77 11:30am	KW - 5	R. Renfer #0394	12;046	24	1,092			1	Bank	
12/5/77 11:00am	East Quarry	E. Leonardi #0333	10	70	10			1	Secondary	
12/7/77 10:30am	East Quarry	E. Leonardi #0333	8	65	8			1	Secondary	
12/9/77 12 noon	East Quarry	E. Leonardi #0333	12	95	12			1	Secondary	
12/13/77 10:00am	East Quarry	E. Leonardi #0333	17	68	17			1	Secondary	

Report for Dec 1977
Trap Rock Industry - Kingston Quarry
Southern Somerset Co near Rock Hill
N.J

EXPLOSIVES USED IN BLASTING

List all blasts containing over 500 pounds of explosives separately. Otherwise list daily totals for each biasting site.

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
1/16/77 1:45p.m	P-10	Ralph Renfer #0394	42,538	32	2,958				Bank	

Report for Nov. 1977

Trap Rock Industry

Pennington - off Rt 31 in Hopewell Township

Mercer County, N.J

Report for Dec 1977 shows one - 5,721 blast on 12/22/77 at 1:00PM

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List all blasts containing over 500 pounds of explosives separately. Otherwise list daily totals for each blasting site.

[illegible] 1987 Sheet 1 of 2

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
11/1	Primary Crusher	J. McAndrew #0419	1/8 stick	1	0.05#	2500' SE	—	1	Block Hole	
11/1	Mine		—	225	—	—	—	—	—	
11/2	Quarry-3rd Bench	J. McAndrew #0419	82 sticks	97	15#	2150' NW	—	1	Block Holes	
11/2	Primary Crusher	" "	3/8 stick	2	0.10#	2500' SE	—	2	" "	
11/3	Quarry-4th Bench	D. Harrison #0442	29,700	194	2025#	2100' NW	—	1	Bank	
11/3	Mine	R. Lutz #0302	450	—	—	—	—	2	Ring shots	
11/4	Mine	R. Lutz #0302	800	230	—	—	—	2	1 - Ring 1 - Sublevel	
11/7	Mine	R. Lutz #0302	—	100	—	—	—	100	Block Holes	
11/8	Mine	R. Lutz #0302	250	—	—	—	—	1	undercut	
11/9	Mine	R. Lutz #0302	500	75	—	—	—	2	Ring	
11/10	Mine	R. Lutz #0302	150	36	—	—	—	1	Ring	
11/11	Primary Crusher	J. McAndrew #0419	1/4 stick	1	0.10#	2500' SE	—	1	Block Hole	
11/14	Primary Crusher	" "	1/2 stick	2	0.10#	2500' SE	—	2	" "	
11/14	Mine	R. Lutz #0302	800	54	—	—	—	4	3 Ring 1 Undercut	
11/15	Mine	R. Lutz #0302	900	55	—	—	—	1	Ring	
11/16	Mine	R. Lutz #0302	550	98	—	—	—	2	Ring	
11/16	Primary Crusher	J. McAndrew #0419	1/4 stick	1	0.10#	—	—	1	Block Hole	
11/17	Mine	R. Lutz #0302	500	73	—	—	—	2	1 Ring 1 Sublevel	
11/18	Mine	R. Lutz #0302	600	58	—	—	—	1	Ring	
11/18	Quarry-4th Bench	D. Harrison #0442	21,200	174	2916#	2300' NW	—	1	Bank	

Rockaway Twp. Morris Co. N.J.
Near Dover, N.J.

EXPLOSIVES USED IN BLASTING

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Dec 1977

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
12/1/77	MINE (21-13 STOPE)	J. WOMER 0533	220	10	30 ~~22~~	–	–	1	RING	
12/2/77	MINE (21-13 STOPE)	C. ROSS 0529	275	16	30 ~~[illegible]~~	–	–	1	RING	
12/3/77	MINE (21-23S SUBLEVEL)	C. ROSS 0529	100	26	7.1 ~~[illegible]~~	–	–	1	SUBLEVEL DRIFT	
12/5/77	QUARRY	HARRISON EXPLOSIVES #77-31	22,000	212 ~~[illegible]~~	2025	2500 NW	–	1	BANK	
12/6/77	PRIMARY	J. McANDREW #0419	¼ stick	1	.01	2500 SE			BLOCKHOLE	
	MINE (21-11 STOPE)	C. ROSS 0529	305	25	30	–	–	1	RING	
12/6/77	MINE (21-13 STOPE)	J. WOMER 0533	313	30	30	–	–	1	RING	
12/7/77	QUARRY	HARRISON EXPLOSIVES #77-32	14,400	116 ~~[illegible]~~	2025	2500 SE	–	1	BANK	
[illegible]	MINE (21-11 STOPE)	C. ROSS 0529	300	16	30	–	–	1	RING	
[illegible]	MINE (21-13 STOPE)	C. ROSS 0529	440	29	30	–	–	1	RING	
12/9/77	MINE (21-11 STOPE)	C. ROSS 0529	400	32	30	–	–	2	RING	
12/10/77	MINE (21-23S STOPE)	C. ROSS 0529	125	30	7.1	–	–	1	SUBLEVEL DRIFT	
12/12/77	MINE (21-25 STOPE)	W. RIDNER 0530	350	62	18.2	–	–	1	UNDERCUT	
12/13/77	PRIMARY	J McANDREW #0419	¼ stick	1	0.1				BLOCKHOLE	
	MINE (21-25 STOPE)	W. RIDNER 0530	200	28	18.2	–	–	1	UNDERCUT	
12/13/77	MINE (21-11 STOPE)	W. RIDNER 0530	213	7	30	–	–	1	RING	
12/13/77	MINE (21-11 STOPE)	C. ROSS 0529	263	8	30	–	–	1	RING	
12/14/77	MINE (21-13 STOPE)	J. WOMER 0533	400	9	30	–	–	1	RING	
12/14/77	MINE (21-13 STOPE)	C. ROSS 0529	481	13	38	–	–	1	RING	
[illegible]	MINE (21-23N STOPE)	C. ROSS 0529	850	42	29	–	–	1	3 RINGS	
[illegible]	MINE (21-23N STOPE)	W. RIDNER 0530	50	8	10	–	–	1	BLOCKHOLE	
[illegible]	MINE 21-23N STOPE	W. RIDNER 0530 C. ROSS 0529	700	35	29			2	RING	

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for each blasting site.

Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
12-2-77 [illegible]:00 P.M.	Quarry U-20	N. Prumatico #0050	2970	8	742	2200		1	Wall	
12-8-77 [illegible]:05 P.M.	Quarry T-19	N. Prumatico #0050	12610	30	1606	2300		1	Wall	
12-29-77 [illegible]:55 P.M.	Quarry T-19	R. Tallini #0405	7775	10	745	2200		1	Wall	
12-1-77	Quarry	D. Teyhen #4839	2	2	1	2000		1	Boulders	

Report for Nov 1977

3M Company

County Rt 13

Belle Meade

Somerset County

N. J.

~~[illegible]~~

EXPLOSIVES USED IN BLASTING

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Date & Time	Site Location	Person in Charge & Permit Number	Pounds Explosives	Number of Caps	Max. Lbs. Per Delay	Nearest Structure (Feet)	Seismic Reading (P. V.)	No. of Blasts	Type of Shot (Bank, trench, etc.)	Remarks
1/4/77 :55 P.M.	Quarry U-20	R. Talliwi #0405	13975	17	2457	2200		1	Wall	
1-18/77 :13 P.M.	Quarry TU-19	R. Talliwi #0405	16500	20	2559	2200		1	Wall	
	Report for Dec 1977									
	3M Company									
	Belle Mead County 12+13									
	Somerset County									
	N.J.									

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