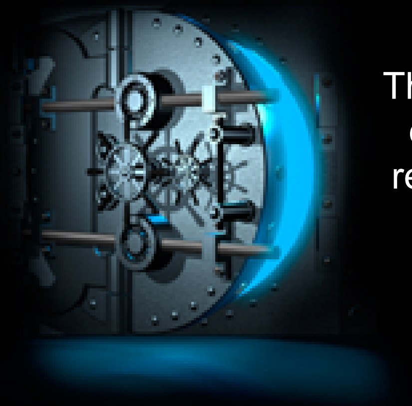

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DEC 7 2016

Ref: 16-F-1537

John Greenewald
The Black Vault
[redacted]

Dear Mr. Greenewald:

This is in response to your Freedom of Information Act (FOIA) request, attached. We received your request on October 18, 2016, and assigned it case number 16-F-1537.

Mr. Brian Eshenbrenner, Director, Mission Services Office, for Defense Advanced Research Projects Agency (DARPA), in his capacity as Initial Denial Authority, determined that some information in the enclosed document should be withheld pursuant Exemption 6 of the FOIA, 5 U.S.C. § 552 (b)(6), which applies to information that if released, would constitute a clearly unwarranted invasion of the personal privacy.

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You have the right to appeal to the appellate authority, Ms. Joo Chung, Director of Oversight and Compliance, Office of the Secretary of Defense, by writing directly to ODCMO Directorate for Oversight and Compliance, 4800 Mark Center Drive, ATTN: DPCLTD, FOIA Appeals, Mailbox# 24, Alexandria, VA 22350-1700. Your appeal must be postmarked within 90 calendar days of the date of this response. Alternatively, you may use the OSD FOIA request portal at http://pal.whs.mil/palMain.aspx or email your appeal: OSD.FOIA-APPEAL@mail.mil If you use email, please include the words "FOIA Appeal" in the subject of the email. Please also reference case number 16-F-1537 in any appeal correspondence.

There are no assessable fees associated with this response. If you have any questions regarding this matter, please contact Ms. Nusheen Sikandar at (571)372-0437 or email at nusheen.sikandar.civ@mail.mil.

Sincerely,

for Stephanie L. Carr
Chief

16-F-1537

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PDF URL: (pdf) - 2 MB -
Accession Number: ADB297443
Personal Author(s): Grasso, Robert J
Corporate Author: BAE ADVANCED SYSTEMS AND TECHNOLOGY NASHUA NH
Report Date: 24 Mar 2004
Descriptive Note: Final rept. 10 Sep 2003-24 Mar 2004
Pages:59 Page(s)

Thank you so much for your time, and I am very much looking forward to your response.

Sincerely,

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Counter UAV Optical Detection, Location, and Negation Feasibility Study

Contract Final Report

For the period covering 10 September 2003 to 24 March 2004

CDRL 0002
Doc. No. A001

24 March 2004

Prepared for:

Contract: MDA972-03-C-0071
Advanced Technology Office
(b)(6)

Prepared by:
Advanced Systems and Technology
Information and Electronic Warfare Systems
P.O. Box 868
Nashua, New Hampshire 03061-0868

Sponsored by
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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The BAE Systems approach identifies the key DARPA hard technology development required in order to realize the Counter UAV mission vision. This Concept Development study developed several CONOPS and engagement scenarios that serve to define the preliminary systems requirements analysis. From this analysis, we developed several simulations to help analyze system concept approaches and performance issues. We then performed technology trades to determine the applicability and maturity of current sensor technologies to the problem. A field test was performed where actual data was collected and analyzed. Finally, directed energy countermeasures were investigated as a means to defeat these threats at standoff ranges.

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 Summary

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The Counter UAV system is envisioned to provide support to forward batteries, observers, or emplacements. The system would be mounted on a tracked or wheeled vehicle and would consist of a laser radar (LADAR) that would provide both the search, detection, and identification capability. With this information, range, range bearing, angle track, and time to arrival will be determined. A directed energy weapon (DEW) would then provide the countermeasure capability. Here, high energy lasers (HEL), high power microwaves (HPM), or optical jamming, optical scattering and reflection (OSAR) would be used to defeat the threats. Additionally, the LADAR would provide kill assessment.

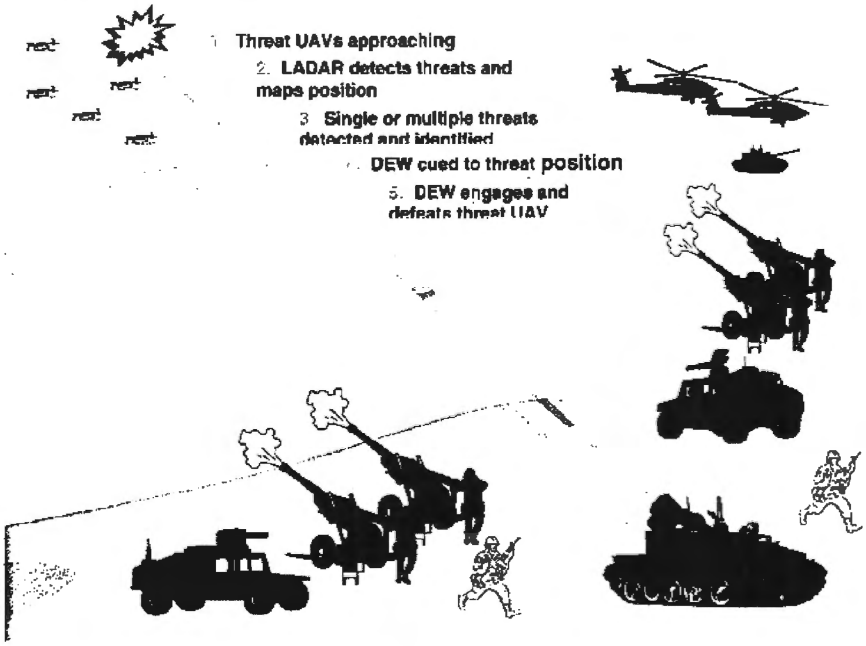


Figure 1: Counter UAV envisioned operation

The steps in a typical engagement include: 1) scanning the horizon for threats; 2) threat detection and spatial positioning with target-object map formation; 3) identification of threats to the extent they can be discriminated from other objects in the vicinity (here, LADAR has a distinct advantage as the anticipated angle-angle-range imagery would provide visual threat verification);

4) positioning of the DEW to the region of interest (while the depiction above shows a ground based countermeasure, proximity countermeasures may be employed that engage the threat at the threat location), and; threat engagement and defeat (the LADAR will view and verify threat defeat).

This study effort included the completion of the Concept of Operations (CONOPS), mission capabilities, requirements definition, technical trades, sensor concepts and evaluation, and sensor concepts as a function key mission needs. The Final DARPA briefing is scheduled for 17 March 2004 at DARPA. The program completion is scheduled for 10 March 2004.

Deliverables for the study includes the final briefing/report documenting the concept development work, trade studies and analysis that form the basis for a strong technical rationale and framework for a follow-on multiple phase DARPA program. As part of the objective for this effort and a result of this study was identifying the best solution and recommendations for DARPA and compelling mission need that can then use to provide the foundation for a new DARPA program start.

2 Introduction

2.1 Scope

This document and its Appendices provide a summary of the work accomplished on contract MDA972-03-C-0071. Section 2 provides an overview of the system and a summary of the development chronology. Section 3 describes the work accomplished along with a discussion of the studies, experiments, demonstrations and tests carried out during the contract life. Section 4 lists the conclusions. Section 5 puts forth the recommendations based on the work accomplished. The prime contractor was BAE Systems Information and Electronic Warfare Systems.

2.2 Motivation

The proliferation of small and very small Unmanned Aerial Vehicles (UAVs) that can be outfitted with inexpensive intelligence sensors (e.g. cameras and Infrared (IR) imagers) and potentially be used to deliver payloads (e.g. N/B/C or Explosive) is an immediate threat to homeland security and forces and installations abroad. Inexpensive means must be developed to detect these small autonomous aircraft and disable or destroy both the sensors and/or the aircraft with no collateral damage and in open field and dense urban environments.

Several challenges must be overcome to develop a robust detection and negation capability. The 1st challenge is detection. Small and very small (e.g. Micro Air Vehicles) UAVs are difficult to detect due to size which results in a extremely small cross-section, non-ferrous materials used in their construction, and low altitude flight. The detection method must include persistent volumetric search and the ability to cue a narrow field of view sensor or negation device to the aircraft. Multiple means of detection (e.g. optical, RF, acoustic) must be employed that exploit the unique characteristics of small UAVs and their sensors. This must be done without affecting other aircraft in flight or personnel on the ground.

The 2nd challenge is pointing accuracy. These small aircraft exhibit significant wobble in flight and are highly maneuverable requiring high precision tracking in order to accurately cue negation methods. High precision mechanical pointers may not provide sufficient accuracy electronic methods of steering beams and controlling optics may be required. The 3rd challenge is negation. Methods to dazzle or disable UAV-borne optical sensors with very small optical apertures in multiple bands (visual and IR) must be developed. This may require one to several optical sources and receivers to cover the range of sensors that may be employed. The nature of the sensors themselves must be understood to determine how to effectively deceive or destroy the electronics elements within the sensor. A unique aspect of these aircraft is their construction materials. Foam, carbon fiber coverings, light wood, plastic propellers, are most often used in the construction making destruction of the aircraft itself a promising possibility with affordable solid state laser technology.

2.3 Document Classification

This document is unclassified in its entirety.

3 Concept Development Study Overview

3.1 Introduction

This Concept Development study developed several Concept of Operations (CONOPS) and engagement scenarios that serve to define the preliminary systems requirements analysis. From this analysis, we developed several simulations to help analyze system concept approaches and performance issues. We then performed technology trades to determine the applicability and maturity of current sensor technologies to the problem. A field test was performed where actual data was collected and analyzed. Finally, directed energy countermeasures were investigated as a means to defeat these threats at standoff ranges.

- **DARPA ATO conducting feasibility studies to countering hostile UAVs**
  - Detect, engage, and defeat small hostile force UAVs that can present a threat to friendly forces in forward operating areas.

3.1.1 Operational Overview

Operation envisioned may include detection, identification, and suppression of individual threats as well as detection, identification, and suppression of threats in groups. Threats may include purpose built UAVs and UAVs constructed from model airplane components. These threats may carry payloads that can include visible or infrared optics to gather intelligence data, or disrupting electronics or jammers to interfere with friendly forces operations. CONPOS may include a single hostile UAV with optics to locate forward emplacements, a single hostile UAV with electronic jammers to disrupt forward radar, or multiple hostile UAVs with optics and electronics to observe and disrupt forward operations.

The Counter UAV system is envisioned to provide support to forward batteries, observers, or emplacements. The system would be mounted on a tracked or wheeled vehicle and would consist of a laser radar (LADAR) that would provide both the search, detection, and identification capability. With this information, range, range bearing, angle track, and time to arrival will be determined. A directed energy weapon (DEW) would then provide the countermeasure capability. Here, high energy lasers (HEL), high power microwaves (HPM), or optical jamming, optical scattering and reflection (OSAR) would be used to defeat the threats. Additionally, the LADAR would provide kill assessment.

Typical operation is shown in Figure 2 and the steps in a typical engagement include: 1) scanning the horizon for threats; 2) threat detection and spatial positioning with target-object map formation; 3) identification of threats to the extent they can be discriminated from other objects in the vicinity (here, LADAR has a distinct advantage as the anticipated angle-angle-range imagery would provide visual threat verification); 4) positioning of the DEW to the region of interest (while the depiction above shows a ground based countermeasure, proximity countermeasures may be employed that engage the threat at the threat location), and; threat engagement and defeat (the LADAR will view and verify threat defeat).

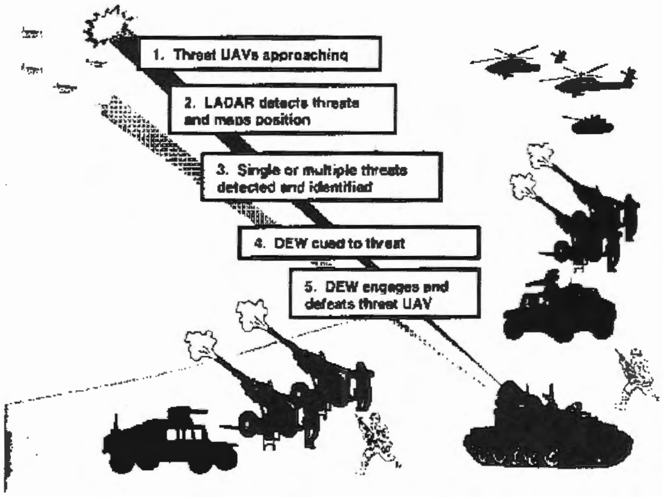


Figure 2: Counter UAV system operation

A key element to this concept study phase is to identify: "What are the high value military payoffs that the Counter UAV system provides that is not available to the warfighter today," and will not be enabled by other DARPA programs. It is envisioned that a Counter UAV system will possess the following attributes:

1. ***Detector--<u>Suppressor</u>* for *the threat UAV Combat Mission***
    - Search, detect, engage, and suppress threat UAVs
2. ***<u>High Resolution</u> of multiple small signature fast moving targets***
    - Angle-angle-range LADAR imagery
3. ***<u>Advanced LADAR</u> imagery enabling***
    - Search, detection, identification and engagement of multiple targets
    - Active object discrimination at stand-off ranges
4. ***<u>Directed Energy Weapon</u>***
    - Aberration compensation for turbulence correction and fine aimpoint control

Based upon the studies conducted here, the proposed solution would consist of an Angle-angle-range Flash LADAR encompassing wide-area scan with high resolution imagery providing detection and ID. This approach enables rapid man-in-the-loop threat confirmation for immediate target engagement and suppression.

The recommendations presented in this report are the result of methodical systems analysis and performance trades to permit the identification and definition of specific enabling technologies to perform the Counter UAV mission. The discrete steps performed in this analysis leading to the recommendations and conclusions presented here include:

- **Mission capabilities and requirements definition**
- **Operational concept**
- **Identification of candidate technologies**
- **Trade space definition**
- **Trade analysis and technology feasibility assessment**
- **System architecture development and technology suite refinement**
- **Preliminary concept**
- **Performance projections, modeling and simulations**
- **Final technical presentation/report**

The Counter UAV study included an initial program kickoff meeting held at BAE Systems AS&T facility in Merrimack, New Hampshire. An interim program review was conducted 21 January 2004 at BAE Systems AS&T facility in Merrimack, New Hampshire. The intent of this meeting was to brief results of the program to date and receive any guidance from the DARPA PM as to program direction. At this review, the DARPA Program Manager instructed us to participate in a live-fire exercise scheduled for 9 through 12 February at Ft. Bliss. A final program briefing is scheduled for 20 March 2004 at DARPA.

3.2 Threats and CONOPS

3.2.1 Threats

Threat UAV information was obtained from a number of open and classified sources; although no classified information is presented here. There are many UAV programs underway in many foreign countries that are both friendly and hostile to the US. There are currently 161 operational UAV programs in 50 countries. Also, the UAVs range in size from very small, the principal threat here, to very large (the large threats have been excluded here). The threats researched here include those that have a spatial extent of about 2 meters at their largest point. Hence, they are very small; and, from this perspective, very difficult to detect.

The open literature was extensively researched to provide information about threats and threat characteristics. In this capacity, the literature search included only those threats that had an extent of 2 meters, could carry optical or electronic payloads, and are purpose built or built from simple, and readily available, model airplane components. Also, National Air and Space Intelligence Center (NASIC) and National Ground Intelligence Center (NGIC) were queried as to any information that had concerning this class of UAV. NASIC provided BAE Systems with a classified CD containing threat and signature information for a variety of UAVs.

A live-fire exercise was scheduled at Ft. Bliss where UAVs were flown and missiles fired to defeat these threats. BAE Systems instrumented a data collect to obtain both absolute and relative measurements of these live fire exercises. Here, BAE Systems collected data of the threat, threat-missile engagement, and threat radiometric data over the test series.

Sources of threat information used in this study include:

- **Open literature threat information**

    - FAS/Worldwide UAV Systems
    - Jane's, PeriscopeOne
    - Internet Sites
- **Classified literature threat information**
    - NASIC and NGIC
        - Modeled and measured RCS data
        - Limited IR signature data
- **BAE Systems Ft. Bliss field measurements**
    - Absolute threat radiance measurements
        - Calibrated 3-band radiometer
    - Relative threat radiance
        - Visible camera
        - MWIR (3 to 5 µm) camera
        - LWIR (8 to 12 µm) camera

Classes of threats include conventional fixed wing types as well as rotary wing and vertical take-off and landing (VTOL). Intended missions include:

- Intelligence/Surveillance/Recon
- Target attack (Land and sea)
- Electronic warfare
- Suppression of air defense (SEAD)
- Unmanned fighter aircraft
- Communications
- Propaganda

Photographs of two typical purpose built UAVs are shown in Figure 3. UAV threats may consist of fixed and rotary wing variety. Their missions may include intelligence gathering, surveillance of forward emplacements, and recce missions. They may be used for target attack with conventional, or unconventional, weapons, perform electronic warfare missions, SEAD, or, in more sophisticated incarnations, be used as unmanned fighter aircraft.

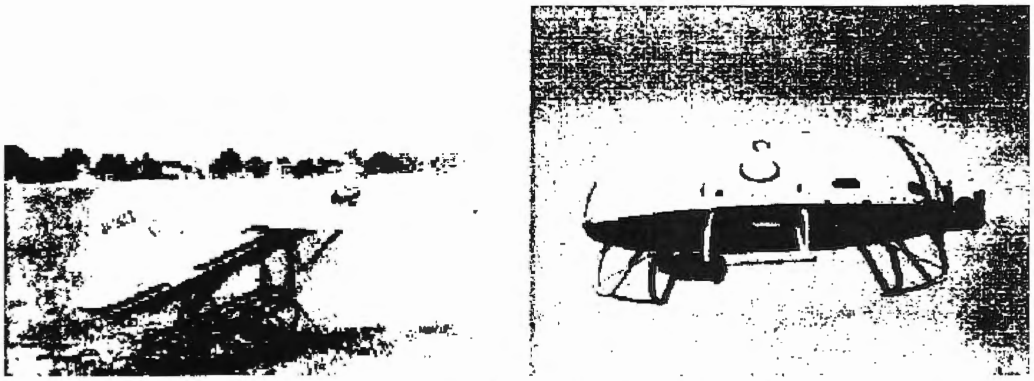


Figure 3: Typical Fixed wing UAV and VTOL UAV

Threats and their physical and operational characteristics are shown in Table 1 for UAVs from several countries. All threats here address the spatial extent limits of 2 meters.

Table 1: Threat characteristics

Name	Country	Weight	Wingspan	Length	Ceiling	Range	Speed
		Kg	M	M	Ft	Km	KPH
SLURS	USA	4.54	1.52	1.22	500	9.3	100
Backpack	USA	11.34	0.91	0.98	5000	9.3	N/A
Sea Ferret	USA	68	1.83	1.83	20000	296	464
Sender	USA	4.54	1.22	1.22	5000	93	166
Delilah	Israel	185	1.75	2.68	25000	250	797
Harpy	Israel	120	2.03	2.29	9800	574	249
Lark	S. Africa	120	2.07	2.41	15000	115	209

While the threats here represent a typical cross section of foreign military developed and deployed threats. In reality, however, threats may be as unsophisticated as simple model aircraft. The two UAVs shown in Figure 4 are purpose built to be used for various military applications. They are Aerosonde, Australia origin, and Pointer, US origin. Figure 5 shows two model aircraft that can be used for UAV purposes. They have a wingspan of 2 meters.

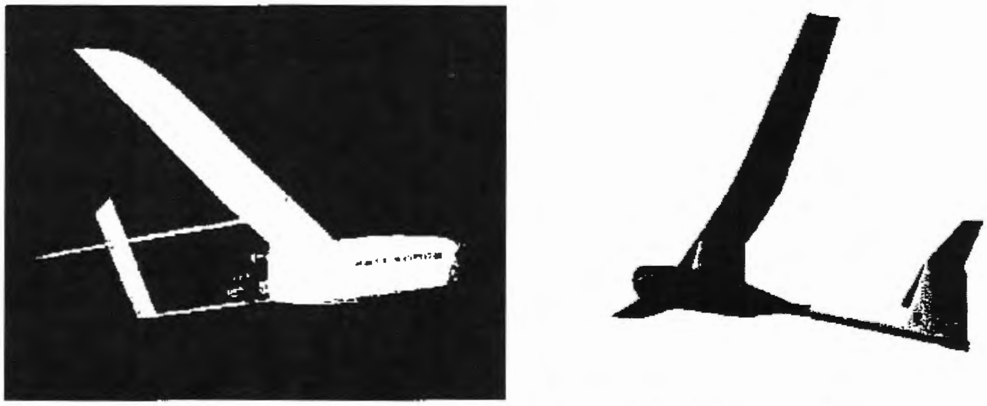


Figure 4: Aerosonde and Pointer purpose built military UAVs

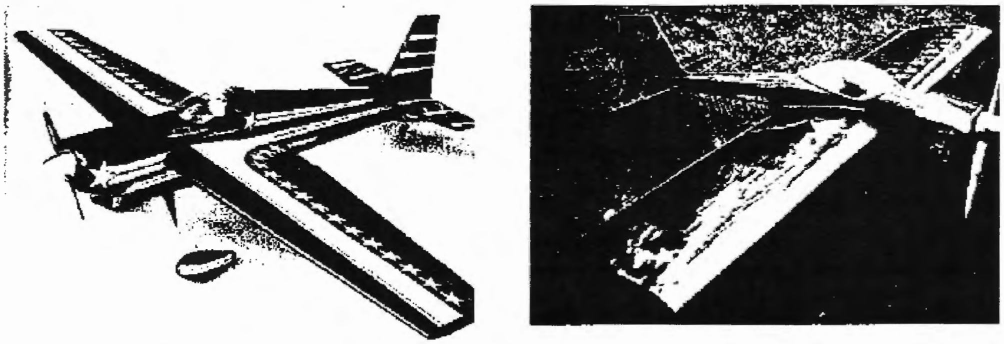


Figure 5: Two examples of model airplanes that may be used as UAVs

Data was collected on birds as well as their size and signatures can be representative of UAVs. Also, birds can present false alarm issues relative to sensors. While it is not given here, IR data was collected by BAE Systems at the Ft. Bliss trials of a large hawk that has a signature very similar to the UAV being tested. Birds can represent threat UAVs at detection ranges classification or identification required to discriminate. Do not want to harm birds and, also, must be certain of threat to ensure false alarm reduction. Birds do have quantitative radar cross section as shown in Table 2. While there is little quantitative data in IR and at optical frequencies BAE Systems collected qualitative IR data at the Ft. Bliss trials.

Table 2: Quantitative radar cross section data for selected species of birds

Bird species	Radar band	Cross section (dBsm)
Grackle	X	-28
	S	- 26
	UHF	- 42
Sparrow	X	- 38
	S	- 29
	UHF	- 57
Pigeon	X	- 28
	S	- 21
	UHF	- 30

3.2.2 Concept of Operations (CONOPS)

Military Commanders have a need to provide protection for their forces in any operational area of the world. Based on the complexity of the battlespace environment, this means having a responsive capability to conduct area defense forward areas over extended periods of time. Current attack assets available include short range air defense missiles, artillery, and small arms fire employed as defense against high value targets. But some of these defenses have a relatively high cost per target, are very inaccurate, or rely upon close proximity encounters.

In contrast, a sensor that can detect threats before they become a problem, provide an identification and discrimination capability, have an effective, low cost, countermeasure, and provide kill assessment can provide protection at relatively long standoff distances.

Therefore, the need exists for a cost-effective, responsive, precision attack capability against single and multiple UAVs.

Counter UAV fills the operational need by being a fully autonomous, long range acquisition, and effective countermeasure. It provides a high endurance search capability for distributed small targets, and can detect, identify, and assess multiple target sets thorough on-board high resolution sensors with a man-in-the-loop but, have an upgrade to automatic target identification algorithms when they become available.

To address widely dispersed targets or target sets, Counter UAV has a requirement to carry a search and identification sensor and a DEW countermeasure, to engage and suppress multiple threats at standoff distances. Multiple threats can be attacked in real-time with precision and post-attack imaging can provide immediate battle damage assessment and re-attack if necessary. Low altitude operation of any platform places it in a high threat environment, but Counter UAV is projected to have a high discrimination feature built in as well as a man-in-the-loop operation.

DEW coupled with multiple kills against moving targets provides effective low cost per target. High resolution LADAR imagery and geographic location of targets provides key information in areas where enemy defenses may not have been adequately suppressed. This CONOPS is shown in Figure 6.

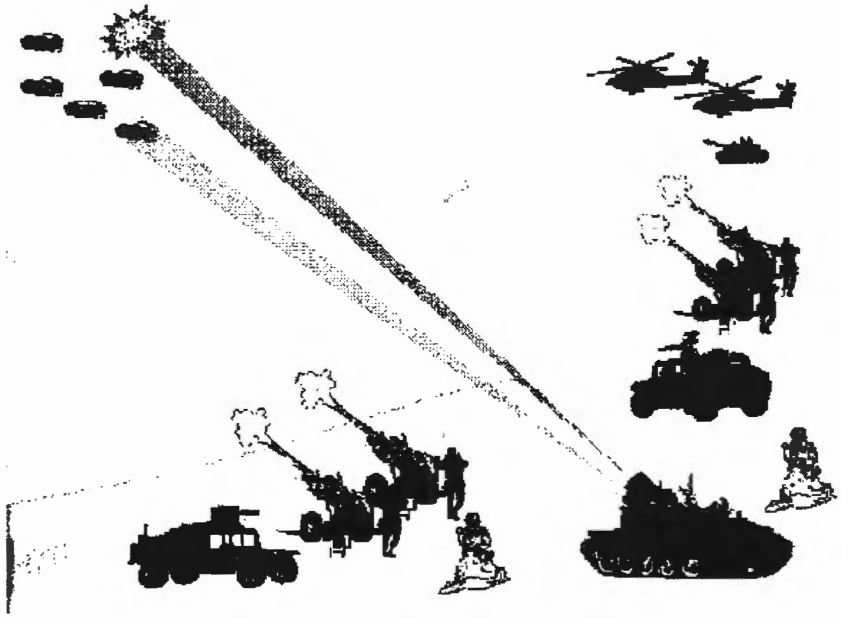


Figure 6: Counter UAV CONOPS

The CONOPS for Counter UAV is support to forward observers, radar sites, artillery emplacements, Patriot and MLRS batteries. In operation, the system will search large areas for threat UAVS, detect and identify threats using angle-angle-range flash LADAR, construct target object map of all objects present within the scan region, and revisit specific areas of interest and identify threats. In this capacity, the sensor will provide the ability to discriminate objects, thus, ensuring they are, indeed, threats. A directed energy weapon is envisioned for threat engagement and suppression with the LADAR providing kill confirmation. To provide protection at standoff distances, a 20 km detection range is envisioned with a 10 km suppression range. A typical Counter UAV operational scenario is shown in Figure 7.

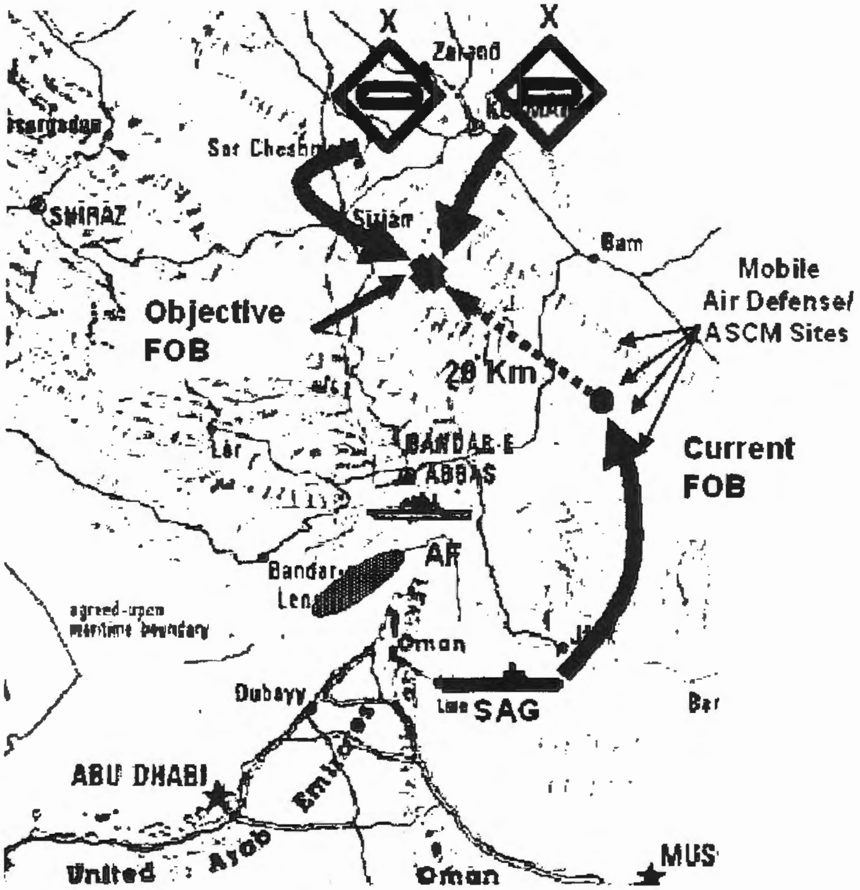


Figure 7: Counter UAV operational scenario

To perform it's mission, Counter UAV needs to autonomously perform a number of mission functions typically performed by multiple different platforms. The engagement sequence proceeds from search and detection, to identification and confirmation. Next tracking and targeting are performed, leading to engagement and suppression. During suppression, the sensor can assess target damage and re-engage if required. During the search and detection process, Counter UAV must search a large volume near and above the horizon while providing a high probability of detection. Once threats are detected, Counter UAV also provides geolocation coordinates of the threat. Counter UAV has the capability to detect and track multiple targets. After detection, Counter UAV enters the target identification and confirmation stage. Here, LADAR images are provided to onboard personnel for target identification and threat confirmation. Identification must be performed at sufficient range against small targets so that the engagement can proceed at the determined engagement point. Man-in-the-loop operation is provided with growth to ATR algorithms when sufficiently developed. Datalink images and fast target identification should allow the man-in-the-loop authorization to proceed with minimal delay.

Once confirmation has been achieved, Counter UAV will track the target and collect targeting data for the engagement. An appropriate vulnerable aimpoint will be selected and sent to the onboard targeting designator or to the DEW itself. If multiple targets are present, Counter UAV will prioritize to ensure that the closest threat is engaged and suppressed first.

During the engagement, Counter UAV can assess the target damage using LADAR imagery and assess, in real-time, whether a follow-on engagement is required. Counter UAV must perform the following actions to fulfill mission requirements:

- **Search and Detection**
    - Large volume high-speed search
    - Target object map formation
- **Identify and Confirm Threats**
    - At sufficient range so they do not present a problem
    - Small to very small cross sections
    - Man-in-the-Loop capability
- **Track and Target**
    - Moving and targets
    - Minimize divergence and boresight errors
    - Multiple threat engagement prioritization
- **Engage**
    - DEW for suppression
    - Prioritization based upon LADAR data
- **Assessment**
    - Assess target defeat
    - Re-attack if necessary

3.2.3 Requirements

A set of notional requirement were constructed based upon discussions with DARPA and based upon typical missions. This was performed to have a metric to which to measure systems performance in the modeling, analysis, and simulation phase of the program. Table 3 provides an initial set of operational requirements for the Counter UAV system. The platform is envisioned to be either a tracked or wheeled vehicle that can operate in all environments. Deployment is to forward observation, air defense, or artillery emplacements. The system should be self contained and able to remain on station for days. Operation can be on internal or external power. Targets are small UAVs no larger than 2 meters at their largest extent. Detection range is 20 km while engagement range is 10 km. A flash LADAR system providing angle-angle-range operation will provide detection and identification. This architecture is superior to scanning or imaging-only (angle-angle) functions.

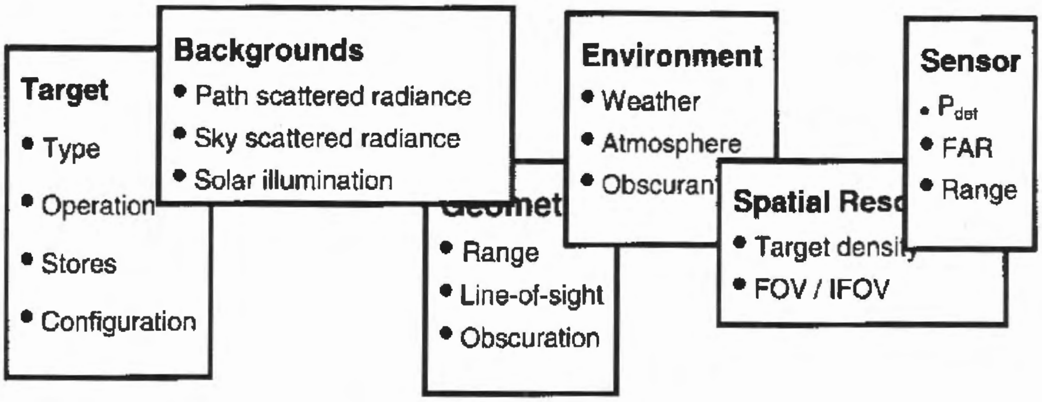
Table 3: Counter UAV performance requirements

PARAMETER	PERFORMANCE	RQMT(D/R)
Operations worldwide	Self-transportable, tracked vehicle, all environment operation	D
Deployment	Forward observation, air defense battery, artillery battery	R
Endurance	Multiple days on station, internal or external power	R
Targets	Small hostile UAVs	R
Target size	2 meters at largest extent	R
Target detection range	20 km	D
Target engagement range	10 km	D
System payload	Flash LADAR – detect Flash LADAR – identify HEL for suppression	D
Minimum search area	10 km^2	D
Minimum search rate	1.25 km^2/min	D
Probability of detection	> 0.9	D
Probability of classification	> 0.9	D
False alarm rate	< 1 per 2 – 5 km^2	D
Spatial resolution	1 to 3 cm	D

3.3 "DARPA Hard" Problem Summary

Many factors affect detection of threats in real-world environments. These include attributes of the target, background, and environment, which, for the most part, remain fixed with respect to sensor operation. Attributes pertaining to the system include sensor performance, physical search geometry, and spatial resolution. Of these, backgrounds and environment will have the greatest direct impact upon sensor system performance. While background and the environment have a direct impact upon sensor performance, and can degrade performance severely, techniques such as range-gated-imaging can improve performance to permit feature extraction from highly cluttered scenes.

Sensor performance will be manifested as a detection probability, false alarm rate, and maximum range where the SNR is above threshold conditions. Geometry depends upon the platform aspect in relation to look-ahead angle and altitude, if the area below is desert, urban, or forested, and the types of obscurations present. Spatial resolution is dependent upon target characteristics, density of threats, and the size of the threat.



Counter UAV must detect and identify small airborne targets in a forward battlespace environment. Targets of opportunity include small threat UAVs with a 2 meter spatial extent at their longest dimension. Hence, system performance was driven by the detection of 2 meter threats.

The threats must be detected and identified from an ground based platform. Here, a LADAR approach is identified as the best solution to providing sufficient resolution at standoff ranges to detect the most difficult threats. Man-in-the-loop operation is envisioned with ATR when it becomes available. An operator will always make the final decision and will augment any ATR function.

Threats must be acquired at sufficient range to not impact forward base operations. To this end, detection and identification must be to the limits of detection performance driven by sensor range performance. Counter UAV will prioritize threats so as to engage the most threatening first, then engage and defeat all threats.

The challenge for the Counter UAV program is the following:

- **The autonomous detection and identification of small threat UAVs in varied environments**
  - Purpose built UAVs and modified RC aircraft
  - Small cross sections
- **Detect and identify from ground platform**
  - Use active systems (LADAR) approach
  - Sufficient resolution at standoff ranges
  - Man-in-the-loop with ATR as available
- **Acquire at ranges sufficiently long to impact target**
  - Prioritize threats
  - Engage and defeat

There are several challenges for Counter UAV that fall with the realm of “DARPA Hard.” These include the sensor search volume where a large area has to be searched with such fidelity to locate 2 m targets. To this end, threats must be located and identified BEFORE they become a problem. Also, the sensor system must be able to identify threats to determine exactly what they are. Threat cross sections will be very small; hence, sensor spatial resolution is driven by the 2 m requirement. Ambient environment will impact sensor performance, and, hence, drives performance. To this end, atmospheric effects such as transmission, particulate scattering, and upwelling and downwelling radiance must be considered. Also, the environment must be considered in terms of viewing geometry, and natural and manmade obscurants.

Beam divergence and boresight errors can affect sensor performance by compromising pointing of both the LADAR and the DEW beam. While this is a minor issue with detection it becomes a great issue with HEL. The handoff between target angle sensors is dependent upon update rates and track stability. In both the case of beam divergence and handoff, compensation can be employed, if necessary, to provide the degree of pointing and handoff accuracy desired. The system must operate at eyesafe wavelengths so as to not present a hazard to friendly troops, personnel on the ground, or friendly aircraft operating in the vicinity. The spatial and range resolution required dictates laser pulsewidths on the order of 3 nsec or less.

3.4 Key Technology Issues

3.4.1 Introduction

Baseline system performance is predicated upon the area coverage which is specified by target location error, the speed of the platform, operating altitude, and look angle. Here, altitude and look angle will have minimal impact as the range to target is defined as 1/cos * altitude. The angular resolution is specified by the number of pixels that fall on the target. Hence, for reliable detection, classification, and identification a certain number of pixels must be on the target; these are derived from the Johnson criteria. With the approach described here, however, we are using single pixel detection due to the long detection ranges anticipated. The pixel rate is the number of pixels that can be covered in a given time and is simply the field-of-regard FOR/scan time. Range to target becomes a function of sensor look angle that will vary with altitude and detect and ID functions; for small angles the range only may be considered. Since, according to the Johnson criteria, detection requires less pixels than identification, it can be performed at greater ranges. Hence, the detect range will always be greater than the identification range. Range resolution determines the range to which the target can be measured and is dictated by the laser pulsewidth. Hence, shorter pulsewidths have smaller range resolutions. In the Counter UAV case, range resolution on the order of 1 m is sufficient which dictates a 3 nsec pulsewidth.

- **Area coverage**
  - Specified by target location error (TLE), platform speed, altitude, and sensor look angle
- **Angular resolution**
  - Specified by number of pixels on target
    - Possibly only one pixel on target at 20 Km detection range
  - Required for reliable acquisition
- **Pixel rate**
  - FOR (in pixels)
- **Range to target**
  - Function of threat altitude and look angle

    - Negligible at small angles
  - Varies with detect and ID functions
- **Range resolution**
  - Precision to which range-to-target can be measured
  - Desire ≤ 1 m range resolution
    - Use digitized multi-pulse approach

3.4.1.1 Search, Detection, and Identification

Counter UAV will search for threats using a wide area search. Threats are detected, is there an object present, is a closer look required, classified, to what class does the object belong and does it present a potential threat, and identified, what specifically is the object, is the object a threat or an asset, and, if a threat, what is the threat potential. Threats are then tracked and evaluated to prioritize those which represent the most imminent threat and to prioritize for engagement. A decision is then made to either ignore the threat and move on, perhaps it was not a threat, auto-engage, where the platform and ATR functions provide the engage decision, or, most likely, handoff to an operator. The operator will make to decision to engage by evaluation the imagery and the ATR data. Finally, the threat will be engaged and suppressed and suppression confirmed. An operational block diagram of the Counter UAV system operation is shown in Figure 8.

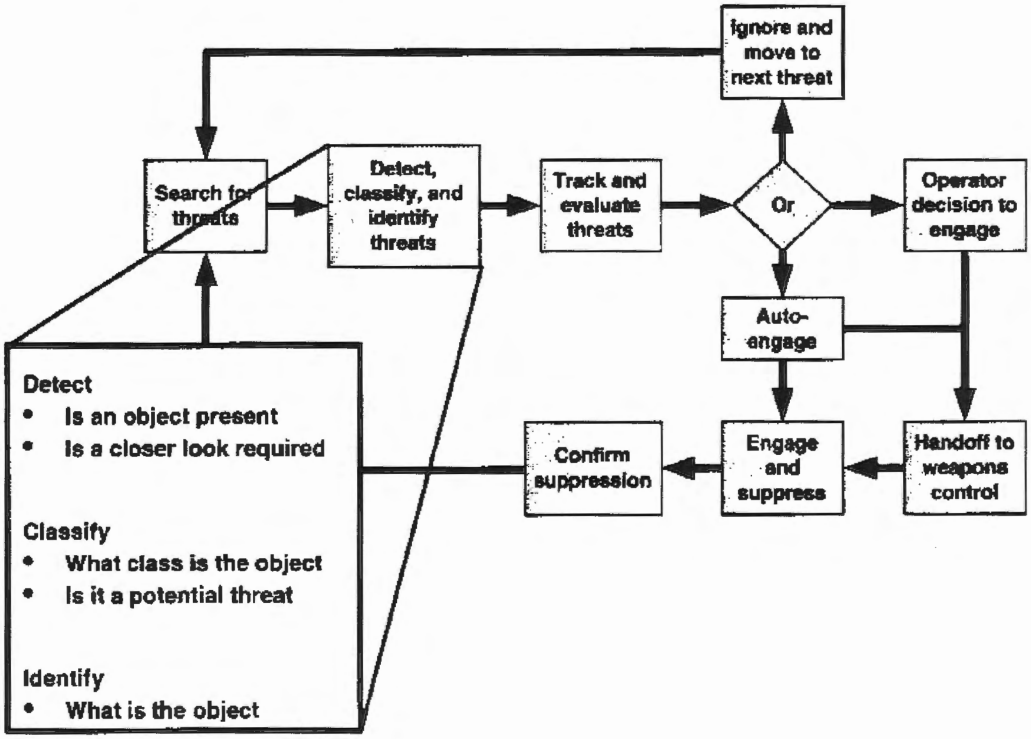


Figure 8: Counter UAV system operation block diagram

Detection consists of a wide area search with an active imaging sensor providing angle-angle-range data of targets. Identification may be from multiple aspects and will coordinate with an operator-in-the-loop. Here, a short pulse laser is required for range resolution. Engagement is for threat UAVs. Here, the LADAR will observe the engagement. Typical Counter UAV mission and technology enablers are shown in Figure 9.

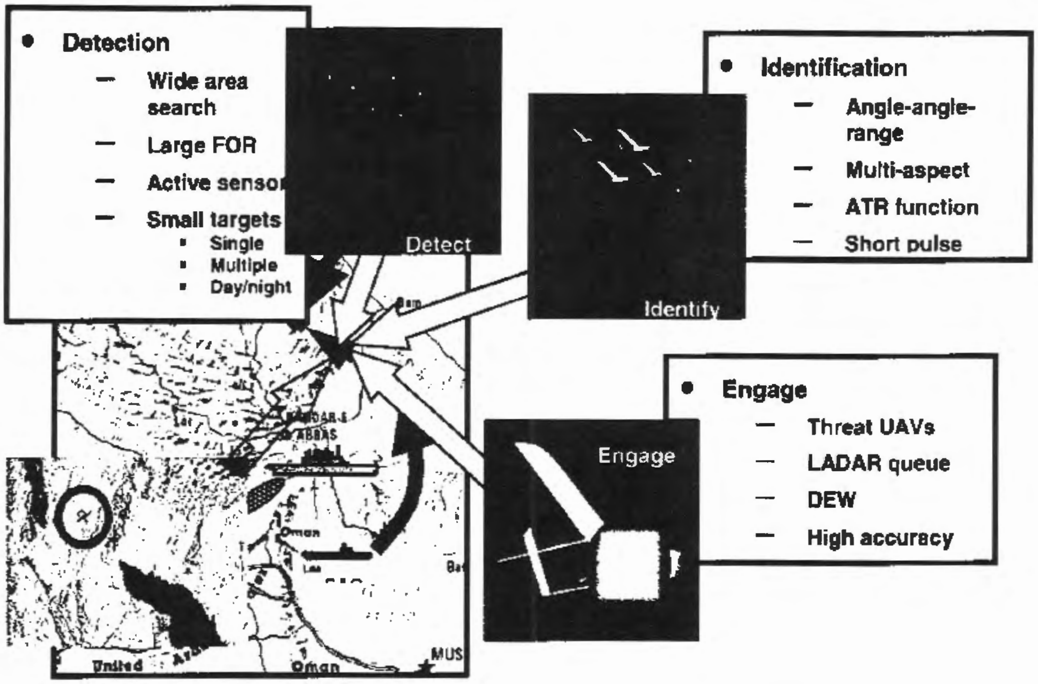


Figure 9: Counter UAV mission and technology enablers

Counter UAV requires confident threat detection and confirmation. Hence, an active sensor approach is recommended as this will provide multi-perspective information relative to targets position in space and provide positive identification. The Counter UAV sensor will be operator-in-the-loop, but can be upgraded to ATR capable as target recognition is based upon spatial feature recognition. Detection will be at the one pixel level while classification and identification will be at the Johnson limit. Targeting will be performed for precision engagement. The LADAR sensor will also provide kill assessment.

A LADAR is the best sensor, after evaluating many candidate concepts, for the Counter UAV mission. In this capacity, Flash LADAR, which is a single shot evolution of classic scanning LADAR, is the superior choice. This sensor will provide target ID in stressing environments. This sensor will provide angle-angle-range information, thus providing information about the target on a pixel-by-pixel level. Hence, range will be to each pixel. This architecture can provide multi-perspective viewing. The LADAR will also provide range, range bearing, and angle track information for the DEW used in engagement. Here, the LADAR can be used with the engagement laser to monitor the event in real time. Hence, providing kill assessment. A man-in-the-loop will be required for the en game as people will make the final engagement decision. Figure 10 depicts the BAE Systems solution for achieving Counter UAV system performance against the notional program requirements.

Requirements

- **Perform confident threat detection and suppression**
  - 20 km detection
  - 10 km suppression
- **Resolve threats at range**
  - Small cross section
  - Positive identification
- **DEW Suppression**
  - Low cost per shot
  - Deep magazine

Solution

- **LADAR is best candidate sensor**
  - Angle-angle-range flash LADAR
  - Provides both range and intensity
- **Angle-angle-range information**
  - Detect and ID capability
  - High spatial and range resolution
- **LADAR provides DEW pointing**
  - Angle and range
  - Use LADAR to view engagement
- **Man-in-the-loop for end game**
  - People make final engagement decision

Figure 10: Counter UAV mission and technology enablers

3.5 Evaluation Methodology

Counter UAV requires a large volume, high speed, search that is eye safe. Threats must be identified and confirmed at standoff ranges before they become a problem. Very large to very small cross section threats represent those likely encountered. Precision pointing and tracking are required both for detect and identify functions, and for precision munitions delivery.

In this capacity, the laser average power must be reasonable; 20 W was assumed as it represents that required to perform the intended functions at the ranges encountered. A detection threshold of 1 pixel is driven by probability of detection for 2 m targets. The FOR, detection range, and frame rate must be consistent with the threat size and revisit time. Threat size drives the number of pixels for a given IFOV. Short pulses are required for meeting range resolution.

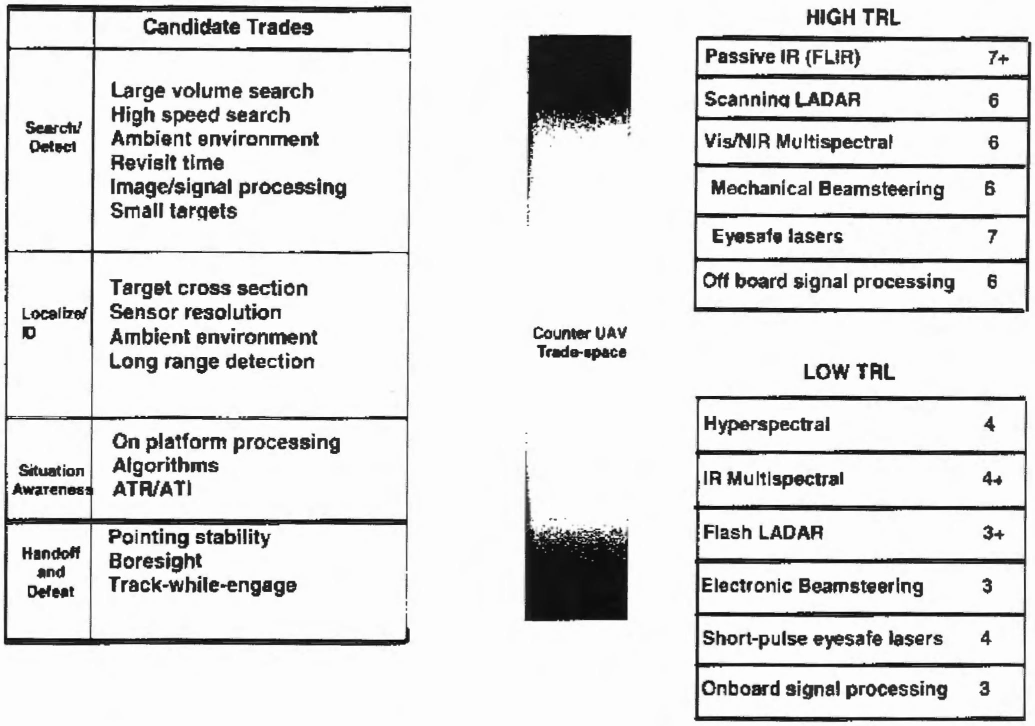
Required is a large volume, high-speed, eye safe search capability. Next, threats have to be detected, identified, and confirmed to ensure the correct targets are being engaged. This must also be performed at sufficient range so that threats do not become a problem. Precise pointing and tracking of the directed energy weapon is required with respect to the threats so as to minimize beam divergence and boresight errors and to correct for the effect of turbulence which can seriously degrade the amount of energy delivered to the target. System design drivers are:

- **20 km detection range**
  - Small target cross section
  - Laser power drives detection range

  - Detection threshold of 1 pixel
- **ID drives pixels-on-target**
  - Require 144 pixels for ID
  - Consider 64 pixels for classification
- **Angle-angle-range flash architecture**
  - Provides single pixel detection of multiple objects in FOR
  - Re-visit objects of interest
  - Close-look via ransom access pointing to object of interest

3.5.1 Counter UAV Trade Space

The Counter UAV trade space encompassed both passive and active sensors of both simple and complex architectures. Paramount is addressing the 2 m target size at typical operational altitudes. Here, various concepts were assessed with respect to meeting sensor system performance in the battlespace environments likely encountered. Concepts and performance were traded against target cross sections and operational environments to determine the best candidate sensors. Here, scanning LADAR and flash LADAR represented the best candidates based upon objectives. Thus, LADAR was the method of choice. To this end, an analysis was performed to determine the performance of scanning vs. flash LADAR for an airborne platform role. It was found the flash have several distinct performance advantages over a scanning architecture, and, was thus selected. The technology trade space, relevant technologies examined, and technology readiness levels (TRL) for the respective technology is shown in Figure 11.



	Candidate Trades
Search/ Detect	Large volume search High speed search Ambient environment Revisit time Image/signal processing Small targets
Localize/ ID	Target cross section Sensor resolution Ambient environment Long range detection
Situation Awareness	On platform processing Algorithms ATR/ATI
Handoff and Defeat	Pointing stability Boresight Track-while-engage

HIGH TRL

Passive IR (FLIR)	7+
Scanning LADAR	6
Vis/NIR Multispectral	6
Mechanical Beamsteering	6
Eyesafe lasers	7
Off board signal processing	6

LOW TRL

Hyperspectral	4
IR Multispectral	4+
Flash LADAR	3+
Electronic Beamsteering	3
Short-pulse eyesafe lasers	4
Onboard signal processing	3

Figure 11: Counter UAV technology trade space

3.5.2 Sensor Architecture

The LADAR sensors considered include: 1) 1D range profile. Here the information is range only with no visual information. It is comprised of a single pixel detector. It is very mature and presents little risk; 2) 2D angle-angle. This sensor provides image type pictures of objects within the range gate of the sensor. While it does provide significant information relative to a "snapshot" like image, it is intensity only with no range information. One pulse provides one return image; 3) 3D angle-angle-range where intensity plus range information is available. This is the most immature detection architecture and, hence, requires further development. Both linear avalanche mode and Geiger mode detectors may be considered.

The first system architecture evaluated, shown in Figure 12, is 1D range profile. Here, range only is available. It is the most mature technology having its foundation in most laser rangefinders and essentially gives many returns from one pulse. Typically, the detector captures information from the first pulse, last pulse, or some number of pulses in-between. Little information about the target is available from this technique.

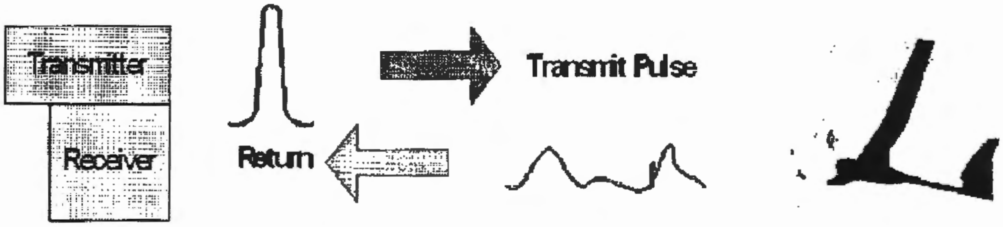


Figure 12: 1D range profile sensor

The second system architecture evaluated, shown in Figure 13, is 2D angle-angle. Here, intensity only is available; there is no associated range component. It is the most mature imaging LADAR technology having its foundation in laser range gated imaging systems and yields target intensity data from one laser pulse. However, the laser power must be increased to accommodate all pixels in the array, hence, the amount of laser power required is the amount needed to produce the desired SNR for a single pixel times the total number of pixels in the array. Since this technique is capable of producing images, much target information is available. One significant drawback is the fact that the range of the target must be known so as to set the gates to capture the object of interest within the desired gate width. Therefore, necessitating some sort of first pulse range.

Figure 13: 2D angle-angle sensor

The third system architecture evaluated, shown in Figure 14, is 3D angle-angle-range. Here, both intensity and range are available, thus providing range-per-pixel. It is the most immature imaging LADAR technology, but, has the greatest payoff in the sense that all target information is available on a single laser pulse. As with the 2D angle-angle approach, the laser power must be increased to accommodate all pixels in the array, hence, the amount of laser power required is the amount needed to produce the desired SNR for a single pixel times the total number of pixels in the array. Since this technique is capable of producing images, much target information is available. As this technique produces range-per-pixel, pixels may be rotated in space to gain different perspective views of the object.

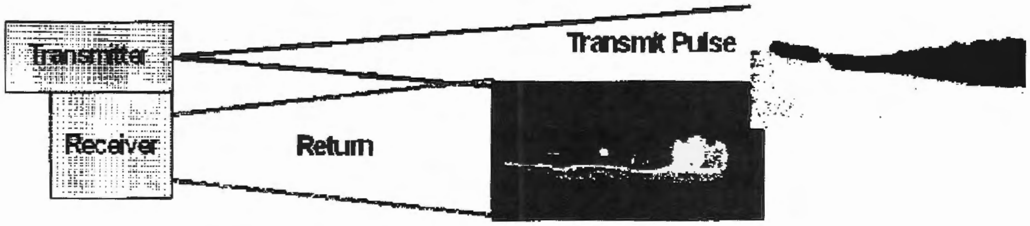


Figure 14: 3D angle-angle-range sensor

3.5.3 Detection Architecture

Three detection architectures were examined. The first is a classic scanning approach using a single element detector and scanning over this element. Here, one dimension is scanned using a HOE scanner and the system is scanned azimuthally to construct an image. While this approach has been used with great success, it does take significant time to build an image and typically requires a very high PRF to build an image quickly. Hence, range ambiguity becomes an issue. Resolution is determined by the beam size.

The second approach is a linear detector array of 1 x N where an elevation scan provides the image in one dimension and an azimuthal scan provides the other. Here, a higher pixel rate is achieved than with a raster scan and the resolution is determined by the detector size. Although superior to the raster scan, it does take time to build an image.

The last approach is a flash architecture where images are constructed on a single laser pulse. Resolution is determined by the detector (pixel) size and image formation is near instantaneous. Due to the one-flash, one-image advantage, large areas can be scanned very quickly.

Our selection for a baseline Counter UAV LADAR architecture consists of flash providing angle-angle-range imagery.

The first detection architecture, a raster scan approach, is shown in Figure 15. Here, resolution is determined by the beam size. This approach has a moderate search rate where the ultimate rate is determined by the rate of the scanner and the pulse repetition frequency (PRF) of the laser. While laser power is modest, issues are image build time, where some time interval, seconds or minutes depending upon the instantaneous field-of-view (IFOV) of the sensor, the scan rate, and the laser PRF, and range ambiguity for a very high PRF.

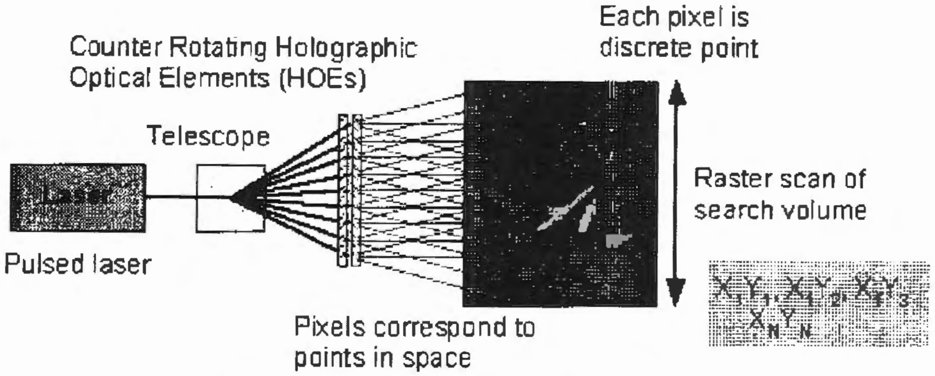


Figure 15: Raster scan LADAR architecture

The second detection architecture, a line scan approach, is shown in Figure 16. Here, resolution is determined by the detector size. This approach has a moderate search rate where the ultimate rate is determined by the rate of the scanner and the pulse repetition frequency (PRF) of the laser. While laser power may range from modest to high, issues are image build time, scan rate, laser PRF, and range ambiguity for a very high PRF.

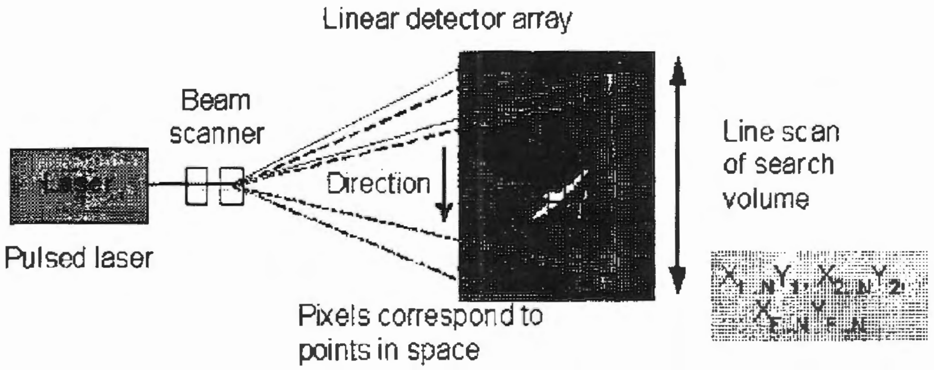


Figure 16: Line scan LADAR architecture

The third detection architecture, the flash approach, is shown in Figure 17. Here, as with the line scan approach, resolution is determined by the detector size. This approach has a fast search rate where the ultimate rate is determined by the laser PRF, and the focal plane array read-out time. While laser power can be high, image formation is near instantaneous. Also, range per pixel is given with an image consisting of both range and intensity information. Due to the relatively low PRF, range ambiguity is not an issue with this approach.

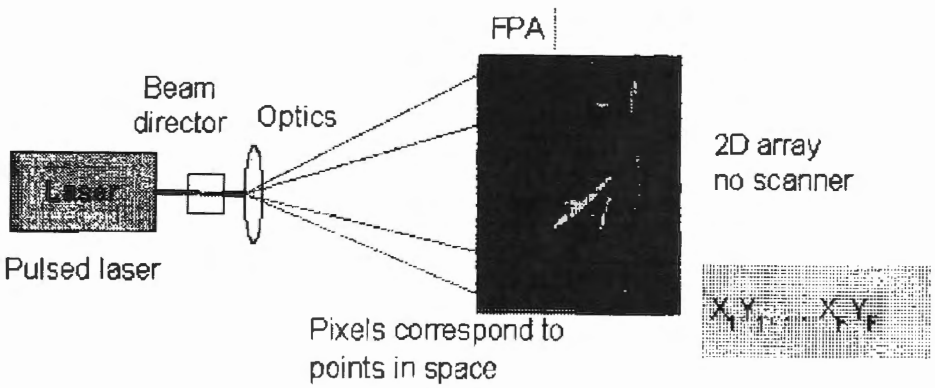


Figure 17: Flash LADAR architecture

3.6 System Architecture

3.6.1 Introduction

An angle-angle-range flash LADAR is selected based upon superior performance for the Counter UAV mission. Here, the sensor would provide range-per-pixel on a single laser pulse with a single illuminated pixel providing detection. Using this approach, the far field can be scanned by tiling, thus covering more area on a single laser pulse. As an example, a single 64 x 64 array would be able to address 4,096 pixels on a single laser pulse while a scanning system would have to scan individually over this area. By tiling, a larger field-of-regard can be covered in a shorter time than with a corresponding scanning system where each pixel must be scanned. This recommended architecture is based upon the following criteria:

- **Range per pixel**
  - Angle-angle (intensity) with range images
  - Modest laser power
- **Area scan for long range detection**
  - Tile scan area
  - Single hit detection
- **FLASH for identification**
  - Angle-angle-range image
  - Provide positive ID before engage
- **System simplification**
  - Two functions in one architecture
- **Increased area coverage**
  - High frame rates

  - Fast acquisition time
- **Simplified pointing**
  - One pulse gives the information
- **High accuracy**
  - Angular resolution of array

The angle-angle-range flash LADAR represents the next generation LADAR. A system concept for the angle-angle-range flash LADAR is shown in Figure 18.

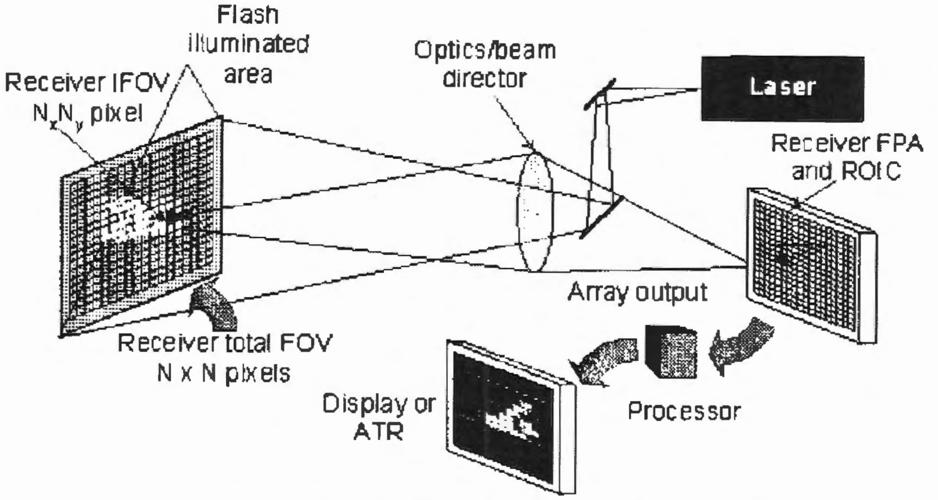


Figure 18: Angle-Angle-Range Flash LADAR architecture

3.6.1.1 Approach

A target search must be employed to detect and identify threats. Tiling the area provides the ability to search large areas within a short time, therefore, increasing situational awareness. Once a detection is made, objects are cataloged and revisited for identification. The angle-angle-range sensor produces high-resolution images of the objects, thus, facilitating discrimination. Target search required to detect AND identify threats. This requires a large volume search to detect objects at the desired 20 km range. Once objects are detected, a target-object map is constructed to facilitate tacking of objects. The preferred scan approach is step-FLASH which is, essentially, stare with tile. While this approach requires some pointing, tile overlap ensures object detection within the total search volume. The approach will be a long range, WFOV search with flash LADAR coupled with a medium range, positive ID function, again, with flash LADAR. Here, a specific area will be able to be investigated, thus ensuring positive threat ID. In this capacity, random access pointing will permit examination of a specific object corresponding to its location on the target object map. With this approach, positive ID with angle-angle-range is achieved.

The detector is the key to a flash LADAR system. Detectors are currently available for angle-angle information, providing only intensity information. Geiger mode detectors area also available, but operate at non-eyesafe wavelengths. To be successful, detectors must evolve to angle-angle-range with greater sensitivity. Since prime laser power scales as the power received per pixel times the number of pixels in the array, laser power can grow to unmanageable proportions. Hence, more sensitive detectors with superior noise characteristics are required. APD's are the most sensitive detectors and can operate in linear or Geiger mode. Geiger mode is attractive because of its photon counting ability, but, with small fill factors, can provide only limited angle-angle information. However, with a sufficiently short pulse laser these images can be rotated in space to reveal depth to the object. Room temperature InGaAs shows much promise as a Geiger mode detector array material.

Also, sub-arrays should be considered as alternatives to full size arrays. So as sufficient pixels are available to perform the detection and identification functions, arrays can be as small as 64x64. In this capacity, laser power is able to be reduced, and with a modest PRF, and area can be scanned in sufficient time to perform the target detection and identification tasks. A photograph and SEM photograph of BAE Systems SWISS detector is shown in Figure 19.

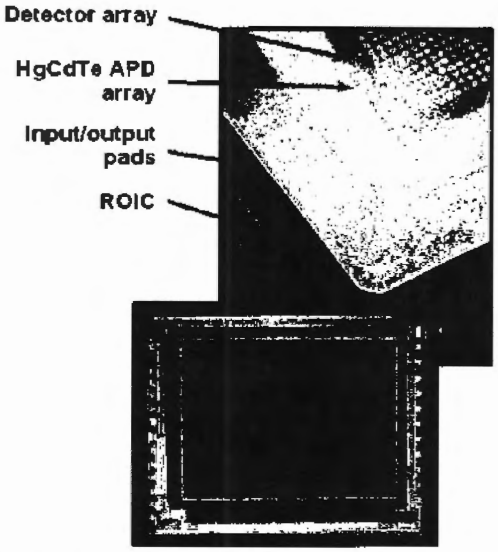


Figure 19: BAE Systems SWISS detector for flash LADAR

3.7 Evaluation of Technologies and Concepts

3.7.1 Sensor System Performance

Probability of Target ID for 3D Images does not have the traditional, mathematical models or accepted standards that probability of target ID for 2D intensity images do. Hence, the 2D probability-of-detection models were used here. The following data is taken from Rozel, 1969. A 2D intensity image will ultimately be used by the operator to determine the target ID of an observed object. 3D information will be important to remove clutter and assemble an image from multiple looks. It will also allow the viewed image to be rotated and viewed from the unique perspectives. The 3D image will also allow proper shading to be applied to a captured image.

As shown in Figure 20, and from Rozel, target detection can occur with very few pixels on target. Target detection with probability of 95% will occur with about 4 pixels on the target. Target classification will occur with 8 or more pixels on target. Target identification will be performed with 12 pixels, to the first level, 18 pixels, to the second level, and 32 pixels to the third level. Given a 1 meter cross section target, the spatial resolution required will be 4 cm or less; the 2 meter cross section target resolution will be 8 cm. At lower signal to noise ratio the required number of pixels on target may be more leading to finer spatial resolution requirements.

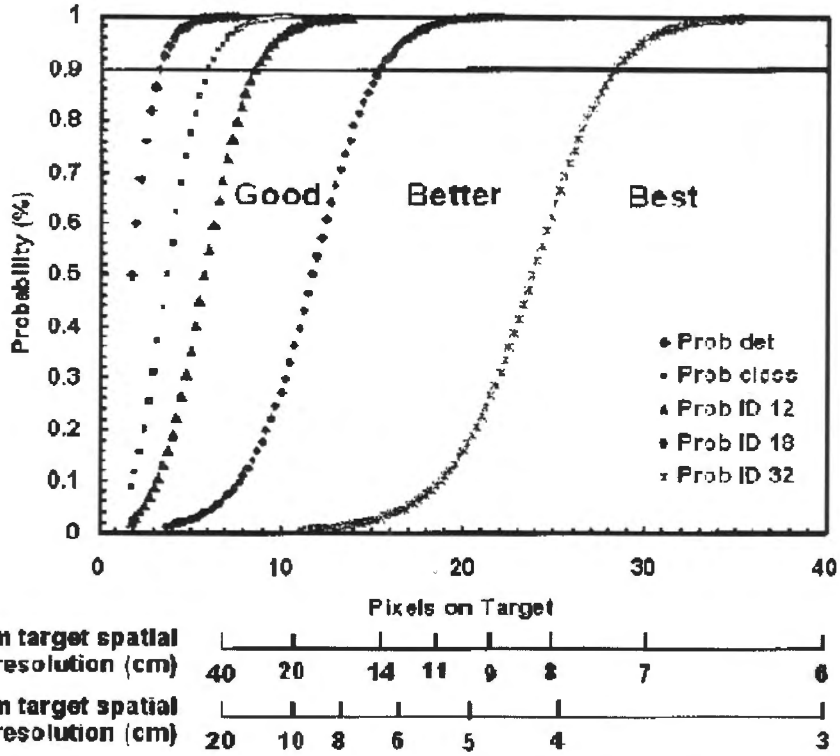


Figure 20: Probability of detection, classification, and identification

Figure 21 shows a family of IFOV curves. The ordinate on the graph is the number of pixels that fall on the target. If the focal plane has only 64 pixels in one direction then on some portion of the curve less than 100% of the target will be covered (blue). The narrow green portion of the graph indicates where the proper number of pixels covers the target for good Prob. ID and the target is 100% covered. The yellow portion of the graph indicates where the target is not covered with enough pixels. To overcome these issues on limited TFOV and less than required number of pixels on the target numerous looks at the target will be required. The diffraction limit is about 7 μrad for a 30 cm aperture.

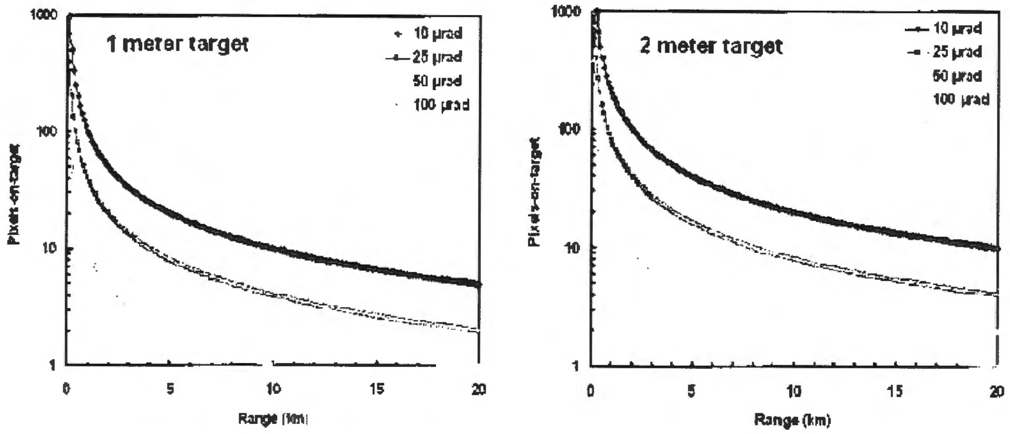


Figure 21: Probability of detection, classification, and identification for a 1 meter target and a 2 meter target

Figure 22 shows the detection, classification, and identification range as a function of altitude. Here, for a threat flying at 2 kft, and with typical system operating parameters, identification can be performed to nearly 25 km range, classification out to about 14 km range, and identification out to 10 km range. The system parameters are given in Table 4 while target parameters are given in Table 5.

Table 4: System parameters

Parameters	Values
Wavelength (µm)	1.54
Optics diameter (cm)	30
System F-number	10
Pixel pitch (µm)	25
Number of pixels	64 x 64
Pulse energy (mJ)	2 to 16
Divergence (mrad)	0.1

Table 5: Target parameters

Parameters	Values
Small UAV	
Aspect changes with look angle	
Length (m)	2
Wingspan (m)	2
Height (m)	0.5
Cross section (m^2/sr)	0.3

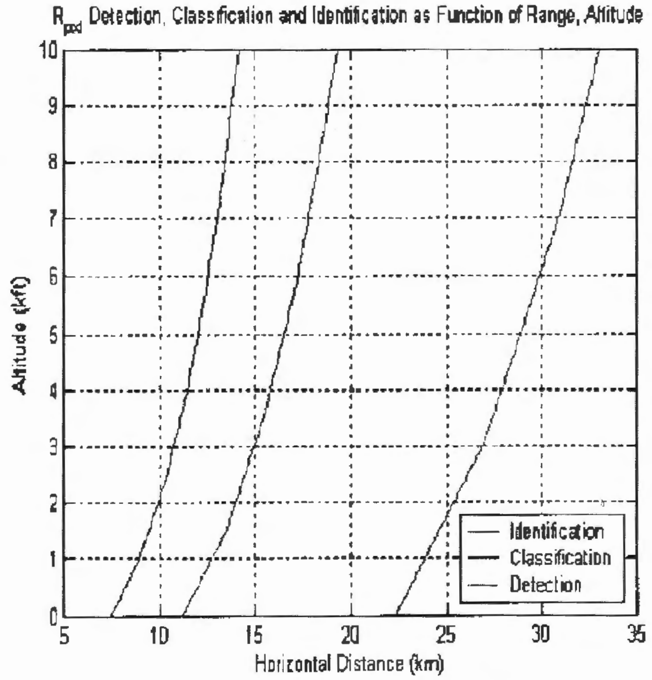


Figure 22: Detection, classification, and identification range

Signal to noise, Figure 23 and detection probability performance, Figure 24, is shown for a target cross sections of 0.3 m2 for a 100 μrad divergence and a 30 cm aperture. Here, a 0.3 m2 target can be detected to 20 km with 2 mJ pulse energy. An 0.98 probability-of-detection occurs at 17 km. To achieve more than 0.98 probability-of-detection requires a pulse energy of 4 mJ, still within acceptable limits.

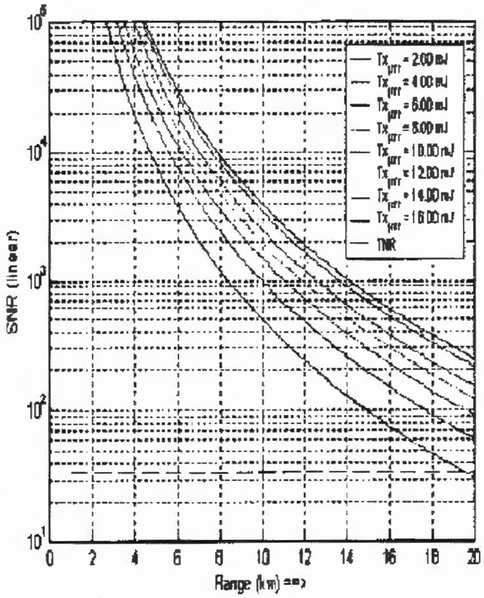


Figure 23: Sensor signal-to-noise performance for system and target values listed in Table 4 and Table 5

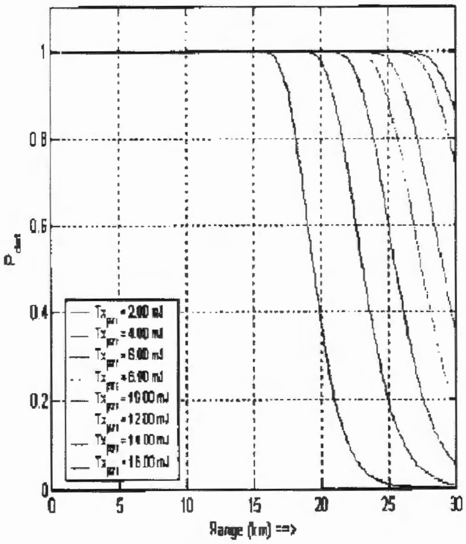


Figure 24: Sensor probability of detection performance for system and target values listed in Table 4 and Table 5

3.7.2 Optical Augmentation

Optical Augmentation (OA) is a very attractive method to locate optical objects. It provides a tremendous gain in detection relative to the target cross section without OA. A 1 m2 target has a $d\sigma d\Omega$ of about 0.03 m^2, while a corresponding OA cross section of the same size is 105 m^2; a gain of 3,500. Hence, OA can provide tremendous gains in target detection. However, if the target does not have any optics, or if the optics are out of band to the laser, OA will not work.

Reflectivity is not given for focal planes (or most optical systems). Therefore, it is assumed that the fill-factor (ff), being the fraction of area with detectors has a low reflectivity (~0.1) and the remaining area (1-ff) has the reflectivity of the material. In most cases the material index is 3 – 4, so the reflectivity is 0.34. Now, ff may vary from 25% to 90%, therefore, a value of 75% is selected for the ff, giving a reflectivity value of 0.16. The diameter of the collecting optics has been found to range between 13mm and 150mm. The collector size affects both area and solid angle of return, the latter through diffraction effects. A13mm aperture is selected as a worst case for both area and solid return angle. This also assumes normal incidence on the optic, area being reduced off axis.

Figure 25 shows how the OA cross section increases as a function of aperture diameter. Note that even for small apertures, the cross section can be very high.

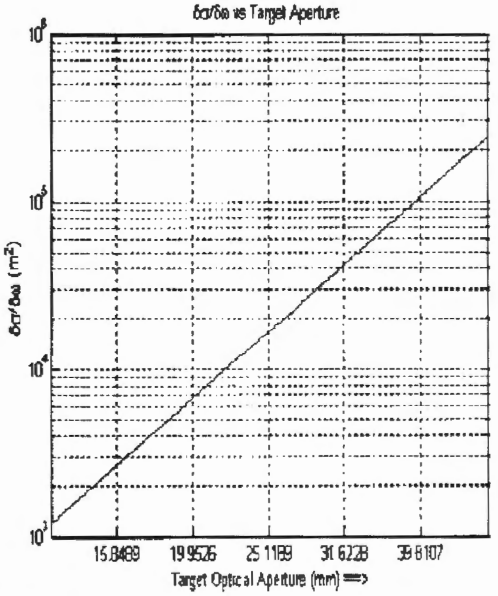


Figure 25: Optical Augmentation performance in terms of cross section as a function of target aperture diameter

- **Optical augmentation (OA) uses target optics to increase the apparent cross section**
  - Enhancing the visibility of small signature targets
- **To work, OA has three requirements**
  - Target must be located by search beam
  - Search beam must be in FOV of target optics
  - Search beam must be in passband of target optics
- **OA limited by**
  - Precision of target optics
  - Environment
    - **Target jitter in atmosphere**
  - Atmospheric distortion
    - **This is most important**

3.7.3 Technology development

Counter UAV requires development of key critical component and system technologies. Here, short pulse lasers able to achieve range resolution of less than 1 meter are required. These lasers must operate with pulsewidths of about 3 ns. As the number of pixels will determine prime laser power, average powers in the 20 to 40 W class are required. Also, the lasers must be eyesafe. Phased array lasers show promise to achieving high peak power output, modest average power, short pulses, with a scalable architecture, and the potential for phased array beamsteering.

Focal plane arrays will require a significant amount of development in both the detector and ROIC. Evolution to angle-angle-range sensors are required to achieve 3D imagery. Within the FPA area, both linear and Geiger mode APDs must be examined. A technology roadmap is shown in Figure 26 that shows the progression of technology development for angle-angle-range LADAR sensors as well as compact DEW with deep magazine capability.

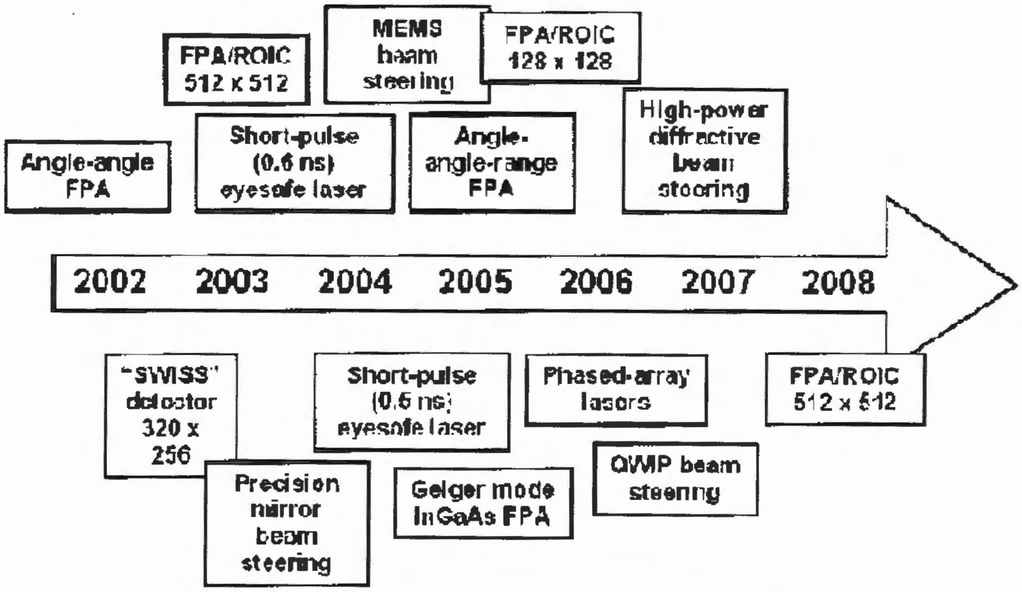


Figure 26: Technology roadmap for sensor and DEW technologies

3.8 Field Tests

3.8.1.1 Configuration

A live fire opportunity was presented where BAE Systems was afforded the opportunity to collect absolute and relative data on a threat UAV. This effort was conducted at Ft. Bliss the week of 9 February 2004. An assortment of instrumentation was assembled from the BAE Systems Jam Lab facility and transported to Ft. Bliss for the collection. This instrumentation included: 1) a calibrated, banded radiometer; 2) an integrating MWIR camera; 3) a staring MWIR camera; 4) a visible camera, and; 5) an LWIR Microbolometer camera. A laser rangefinder was taken as well, but, die to its low operating power, only provided limited results.

The equipment was calibrated and tested at BAE Systems facility prior to shipping to ensure proper operation. At the test site, data was taken of both static and dynamic UAVs, in all bands. Upon completion of the field trials, the data was analyzed and the results presented here. Static measurements were performed to measure absolute radiance from the target with a calibrated, banded, radiometer. In this capacity, absolute radiance was measured in the three primary mid-wave missile IR seeker bands.

Prior to beginning data collection a blackbody reference source was placed at the same distance as the threat. This ensured accurate calibration of the radiometric instrumentation during the data collection. Changing solar conditions caused by the sun's transit and clouds obscuring sunlight can compromise the fidelity of data collected. Thus, re-calibration is performed incrementally to ensure all instrumentation is operating properly. The blackbody permits calibration at the beginning and end of a test hence, ensuring the calibration did not change during the entire series.

Both the threat and calibration source are seen in Figure 27 that depicts the threat and calibration source located in close proximity. To facilitate data collection, and to permit precise measurement, the threat was mounted on a tripod and indexed at 10 degree intervals, Figure 28.

Figure 27: Threat mounted on test stand with blackbody calibration source in background

Figure 28: Threat mounted on test stand to facilitate accurate indexing

Assembly and check-out of the UAVs are shown in Figure 29 and Figure 30. Proper operation is verified prior to launch.

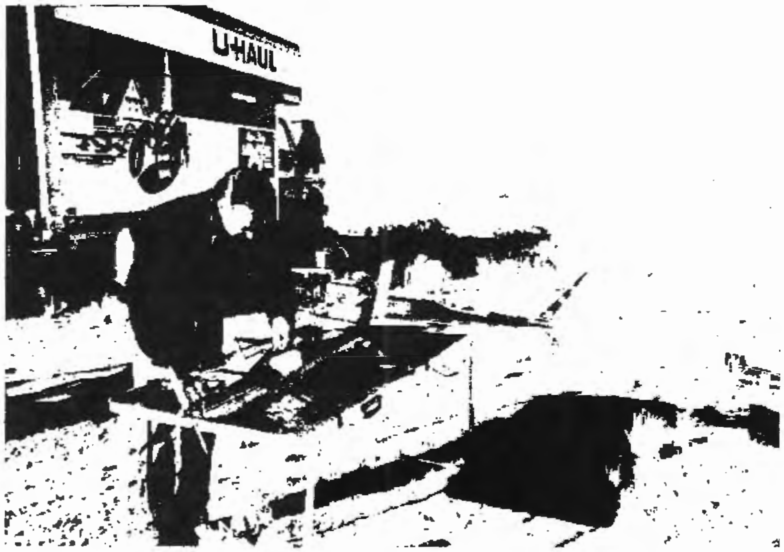


Figure 29: Assembly of threat prior to flight

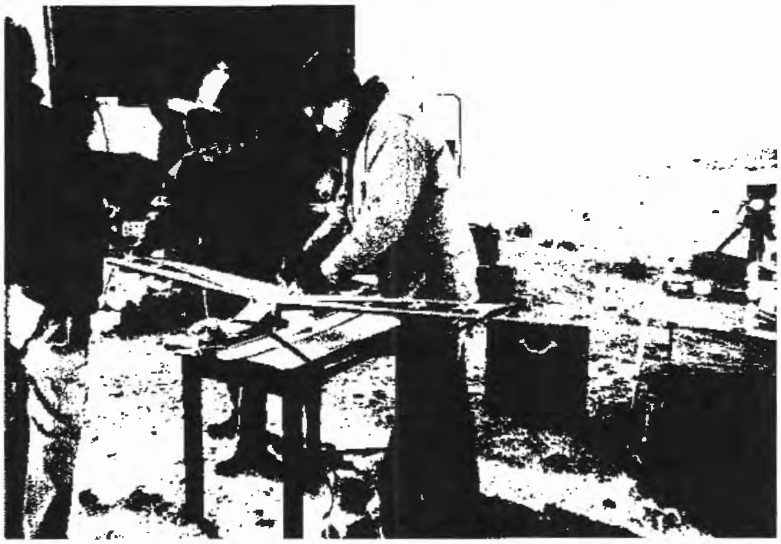


Figure 30: Threat is checked for proper operation

Threat launch is usually accomplished by having an operator run along the ground and throw the threat into the wind. During one day, due to stagnant air conditions, the UAVs have to be launched from a bucket truck as shown in Figure 31 and Figure 32.

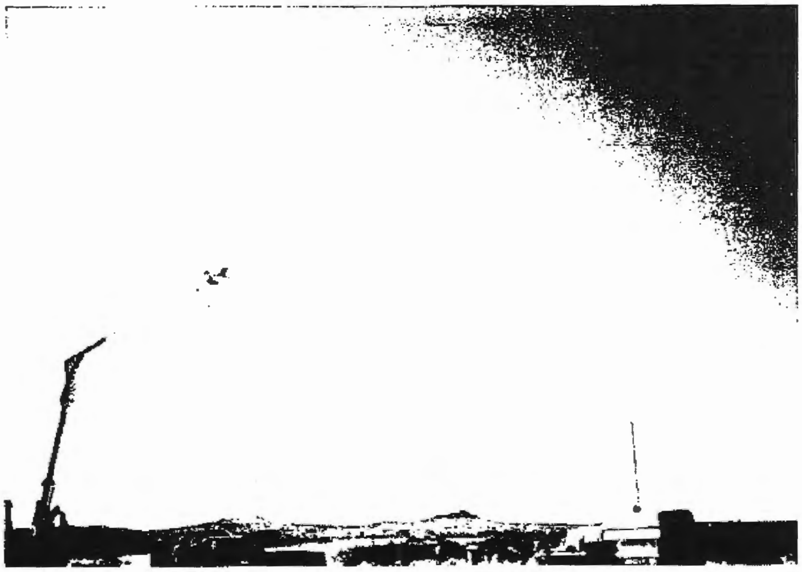


Figure 31: Threat held by operator in bucket prior to launch

Figure 32: Threat takes flight after release by operator

The BAE Systems instrumentation was mounted on a tripod with a tilt-pan head to facilitate tracking. All instrumentation was contained in the back of a cargo truck to facilitate operation and to provide shelter. Two photos of the BAE Systems instrumentation showing the calibrated 3-band radiometer, 3 to 5 μm MWIR camera, visible video camera, and the 8 to 12 μm Microbolometer camera are shown in Figure 33 and Figure 34..

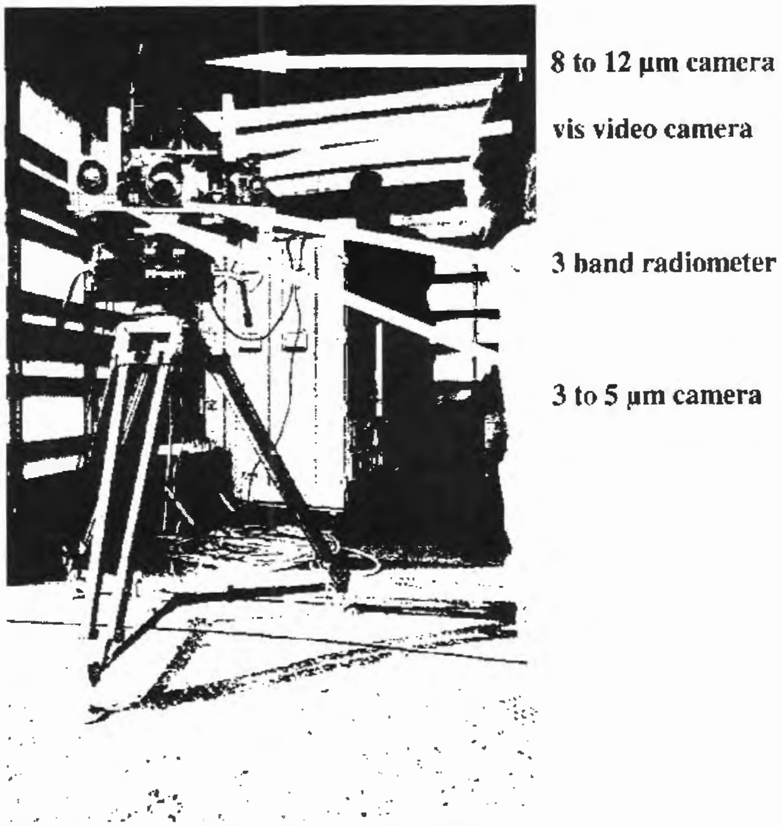


Figure 33: BAE Systems data collection instrumentation

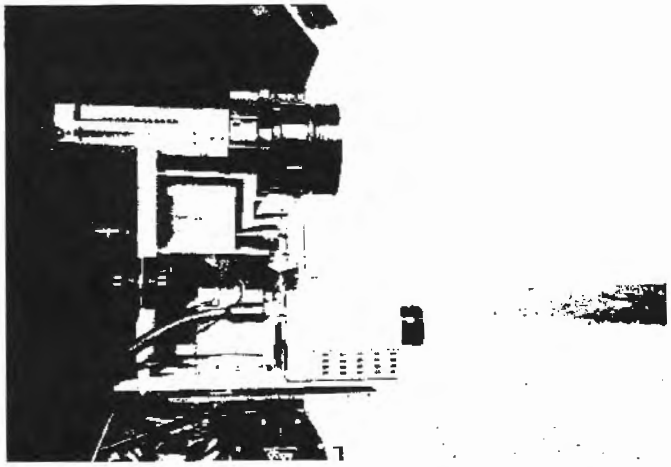


Figure 34: Side view of BAE Systems instrumentation

3.8.1.2 Absolute radiance measurements

Absolute radiometric measurements of the UAV were made in the three radiometer bands to determine the amount of emission within each band. The UAV was mounted on the test stand and operated at full throttle; a short "warm-up" period was observed to ensure the engine and exhaust came to normal operating temperature. The threat was indexed every 10 degrees to ensure complete circumferential coverage.

A calibration source was located at the same distance as the threat and referenced to ensure calibration. Also, since the background conditions constantly change due to cloud, and solar transit, a constant calibration ensures accurate measurements.

- **Radiometer was calibrated to blackbody source**
  - Source located at same distance as threat
  - Done to cancel path differences
- **Radiometer calibrated for radiance in**
  - Band I
  - Band II
  - Band IV

Results of the radiometric measurements in mW/sr are shown in Figure 35 for Band I, Figure 36 for Band II, and Figure 37 for Band IV. Also, since the 8 to 12 µm Microbolometer camera worked so well detecting and tracking the threats, the radiance for this device in the 8 to 12 µm LWIR region was extrapolated from the Band IV data and is shown in Figure 38.

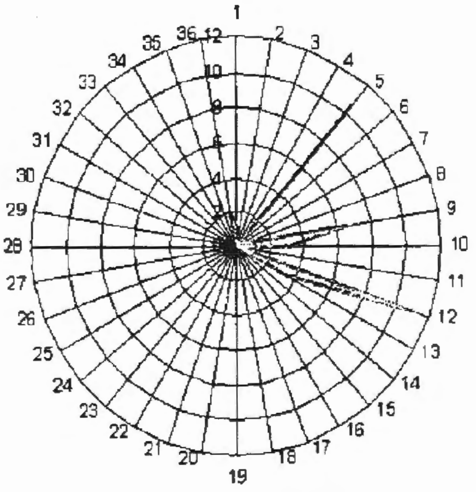


Figure 35: Band I radiometric data

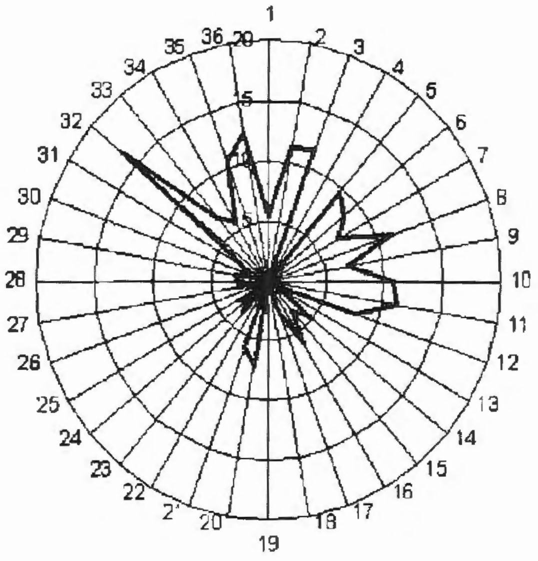


Figure 36: Band II radiometric data

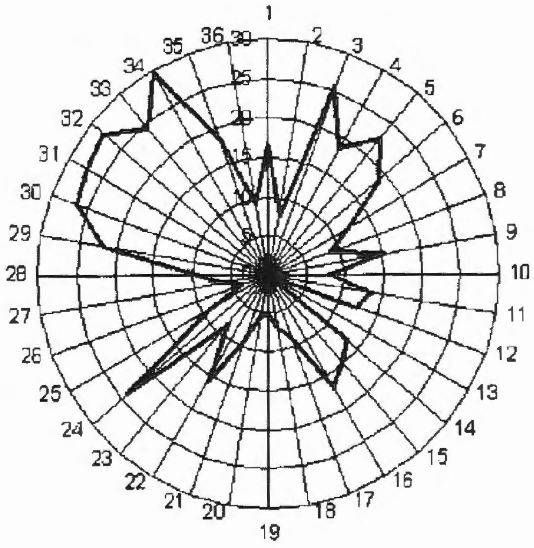


Figure 37: Band IV radiometric data

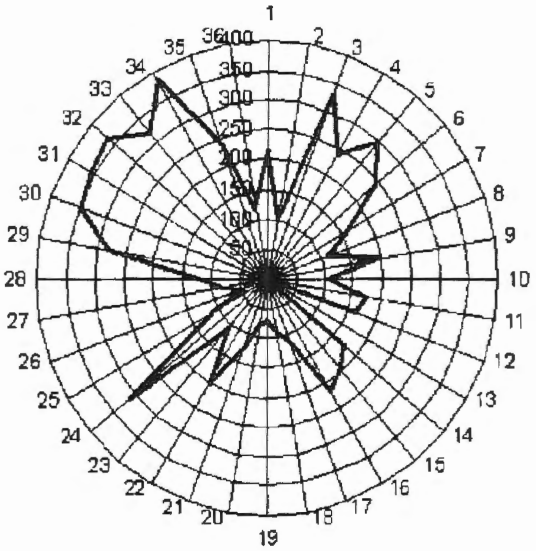


Figure 38: 8 to 12 µm LWIR radiometric data

Maximum radiance and the specific angle where this occurred was now determined and is shown in Table 6. Note that the greatest radiance in Bands II and IV, and the LWIR occurred at roughly 340 degrees. This was where the engine exhaust was located.

Table 6: Maximum radiance at angle

Band	Angle	Radiance
Band I	120	10.7 mW/sr
Band II	320	16.5 mW/sr
Band IV	340	29.5 mW/sr
LWIR	340	383.6 mW/sr

Note that the radiance in the LWIR is significantly higher than in any of the other bands. The following conclusions conclude that to had detection at 20 km ranges, and active system approach is required.

- **Very low Band I radiance**
  - Expected with a target of this type
- **Low radiance Band II and Band IV radiance**
  - Highest radiance at engine exhaust

- **Moderate radiance in LWIR**
  - Expected at the low NEDT
  - This band did acquire and track the threat to 2.5 km ranges

The target in the visible and LWIR are shown in Figure 39 and Figure 40, respectively.

Figure 39: Threat on test stand in visible

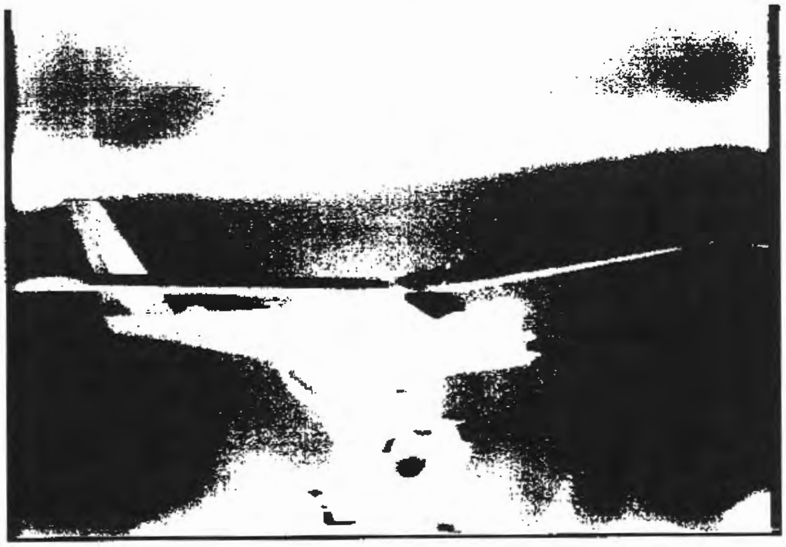


Figure 40: Same threat on test stand in LWIR

3.9 Countermeasures

3.9.1.1 Introduction

Threats are typically slow moving, typically moving at tens of meters/second, but, present a very small cross section. To be effective, a countermeasure must defeat the threat by causing physical damage which causes operation to cease, or damage on-board sensors so they cannot perform their function. Two countermeasures were evaluated here: 1) directed energy weapons (DEW) consisting of lasers and high power microwaves, and; 2) sensor jamming using optical scattering and reflection (OSAR) techniques. Note that if the UAV payload does not consist of optical based systems, then OSAR jamming will not function. Hence, DEW to sufficiently damage the vehicle to terminate is flight is the best option.

- **Threats typically slow moving**
  - Propeller driven
  - Typically tens of m/sec
- **Small cross section requires very precise pointing and tracking**
  - Sub mrad accuracy
  - Small CEP
  - Jitter from both platform and beam motion
    - Must account for bias from both of these
- **Countermeasures considered defeat small UAV threats**
  - Directed energy
    - HEL, HPM
  - Sensor jamming
    - OSAR, damage

3.9.1.2 Directed Energy

High energy lasers are very attractive as countermeasures. They are powerful, highly directable, and can cause catastrophic damage to the target. However, beam divergence and boresight issues require compensation for turbulence induced aberrations, scintillation, refractive index changes, and beam wander. Hence, to be practical and over the 10 km engagement range, some type of aberration compensation is required.

- **Will require atmospheric aberration compensation**
  - Compensate for turbulence induced distortions
  - Provide fine aimpoint correction
- **Maximize energy-on-target and minimize atmospheric loss**
  - To diffraction limit
  - Scattering and absorption prime losses
- **Maximize laser energy on target**

  - Decrease in beam divergence
  - Minimize atmospheric loss
  - Increase pointing accuracy
- **Decrease energy variance on target**
  - Maximize effectual energy
- **Capability for sequential multiple target engagement**

In operation, the LADAR detects and identifies the threat. The DEW is pointed in the threat direction and fine aimpoint control is affected through the LADAR; in this capacity, constant range, bearing, and angle information is updated into the fire control solution. Upon engagement, the DEW must follow the threat, keeping power concentrated. Finally, the LADAR will continue to monitor the progress of the engagement, hence, providing assessment of kill.

The functional capability for the DEW sequence is shown in Figure 41 where there is a large volume high speed **Search to Detect, identify, and confirm threats. This is performed at** standoff range using an angle-angle-range, 3D, flash LADAR sensor. Once the threat is confirmed, an operator-in-the-loop will make the decision to engage. Note that when available, this function can be performed using ATR.

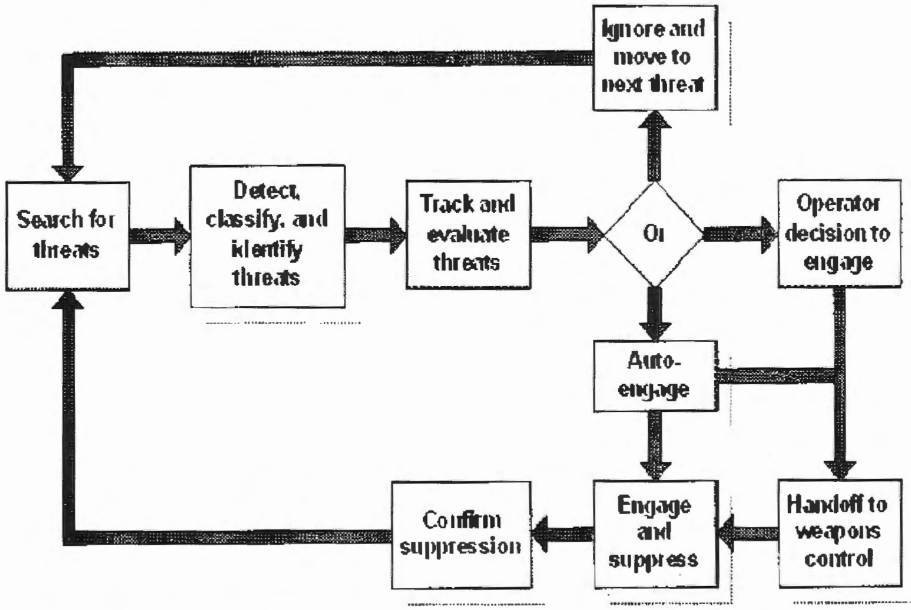


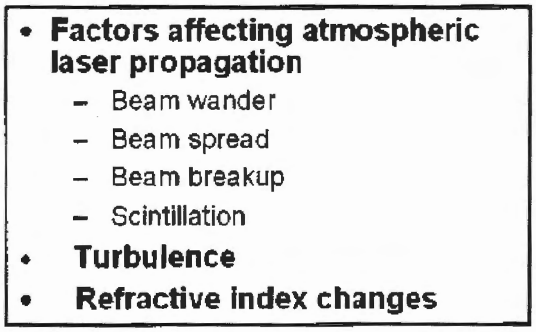
Figure 41: Block diagram of DEW operation and sequence

Aberration compensation is essential to HEL DEW application. Hence, over the 10 km engagement path, some sore of correction is required. Factors affecting laser propagation are shown in Figure 42.

- **Optical waves experience distortion as they propagate through the atmosphere**
- **Distortions caused by**

  - Temperature variations
  - Solar heating of the atmosphere
  - Turbulent motion of the air due to winds and convection
- **Classic example**
  - Shimmering images when looking over a desert
- **Laser beam divergence and boresight issues**
  - Beam periodically moved off target due to turbulence
  - Image dancing and blurring

The Figure 43a shows an aberrated beam after passing through the atmosphere and Figure 43b is its corrected counterpart.



- **Factors affecting atmospheric laser propagation**
  - Beam wander
  - Beam spread
  - Beam breakup
  - Scintillation
- **Turbulence**
- **Refractive index changes**

Figure 42: Factors affecting beam propagation through the atmosphere

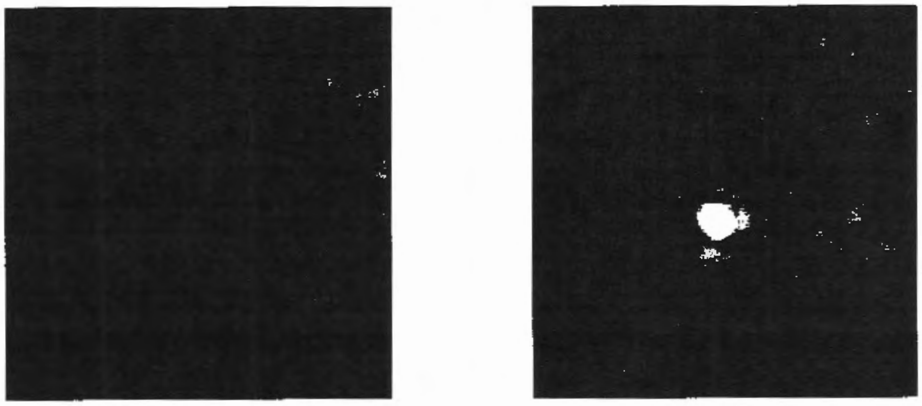


Figure 43: Aberrated beam (left) and corrected beam (right)

3.9.1.3 Beam Wander

Figure 44 shows increase in "bucket" over transmitter diameter to turbulence strength over a propagation path of 10 km. Constant turbulence strength, C_n^2, of 10^{-14} is assumed. At smaller aperture sizes conjugation fidelity and energy-on-target decrease. Hence, there is a dependence upon turbulence variation along propagation path. Turbulence closer to platform is easier to correct than an aberrator of similar strength near the target. Turbulence jitter is inversely proportional to beam diameter and altitude.

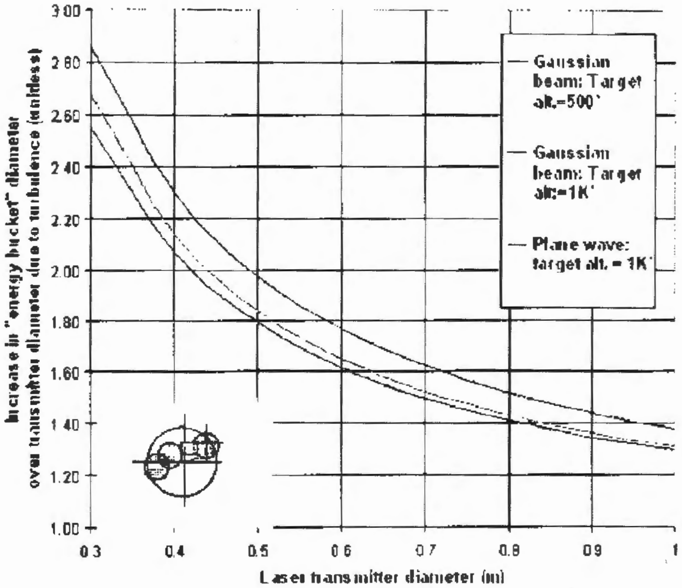


Figure 44: Laser transmitter diameter vs. Beam wander at 10 km

Aberration compensation improves DEW performance greatly as shown in Figure 45, without aberration compensation, and Figure 46, with aberration compensation. Without compensation, for turbulence strength of 10^{-15}, roughly 10% of the energy is available on target. With compensation, for the same conditions, roughly 80% of the energy is delivered to the target.

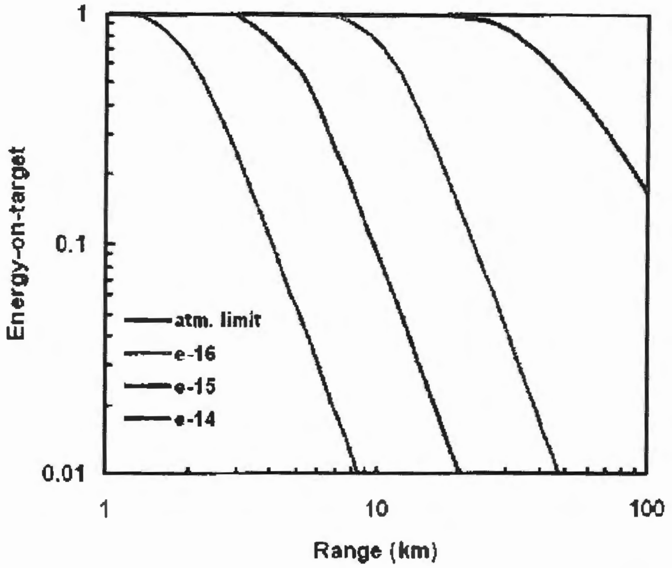


Figure 45: Energy-on-target without aberration compensation

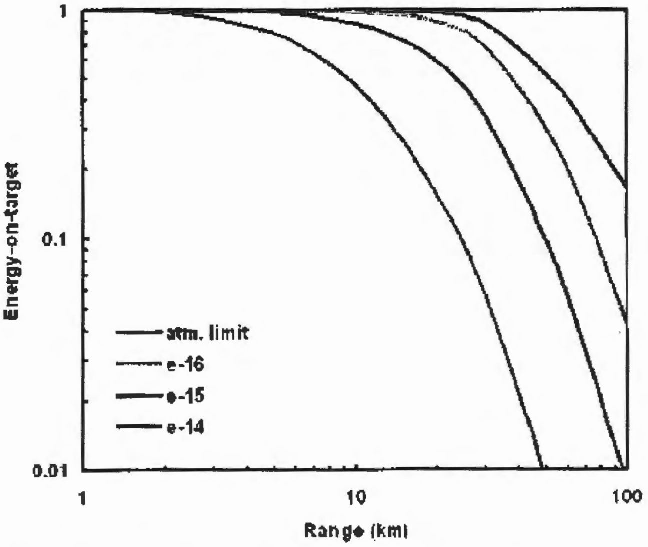


Figure 46: Energy-on-target with aberration compensation

The enhancement factor is shown in Figure 47 for turbulence strength of 10^{-15}. Here, at a range of 10 km a gain of about 10 is seen.

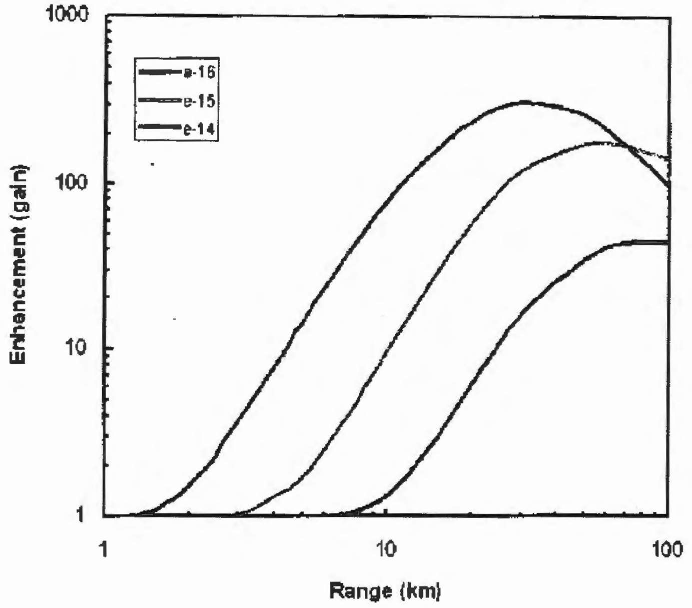


Figure 47: Enhancement factor shows significant gain for effectual energy on target

3.9.1.4 Countermeasure Effectiveness

Figure 48 and Figure 49 show the effectiveness of DEW to accomplish various sensor and material effects. Typically, sensor blinding (OSAR) requires the lowest amount of intensity, typically from microwatts to milliwatts of intensity. Nest is sensor damage, which requires milliwatts to watts of intensity. Last is material damage which requires watts to many watts. The drivers in DEW are typically the sensor architecture, sensor material, or threat material. Some sensors, due to their architecture, are more vulnerable than others to laser illumination. Also, damage to sensor material varies widely, again, depending upon the sensor material. Finally, material damage is the most difficult mechanism and varies widely depending upon the material.

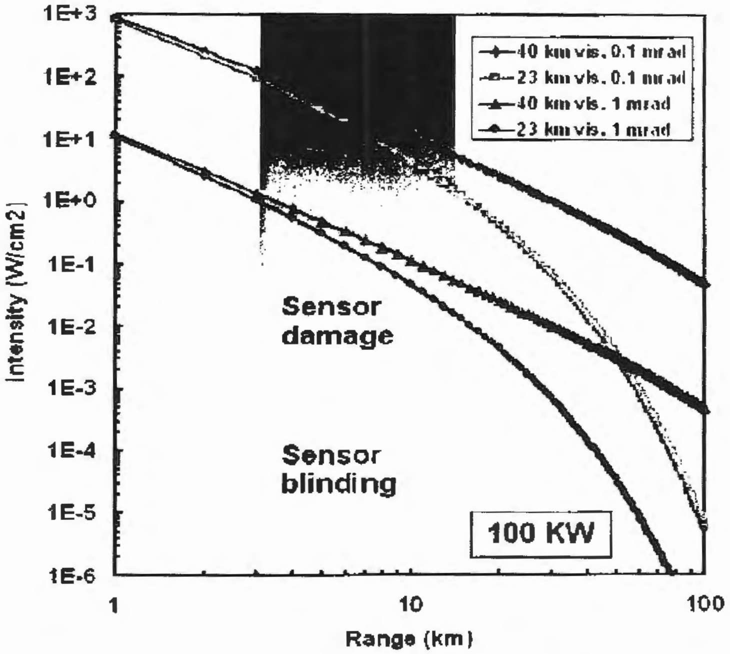


Figure 48: DEW countermeasure effectiveness at 100 KW levels

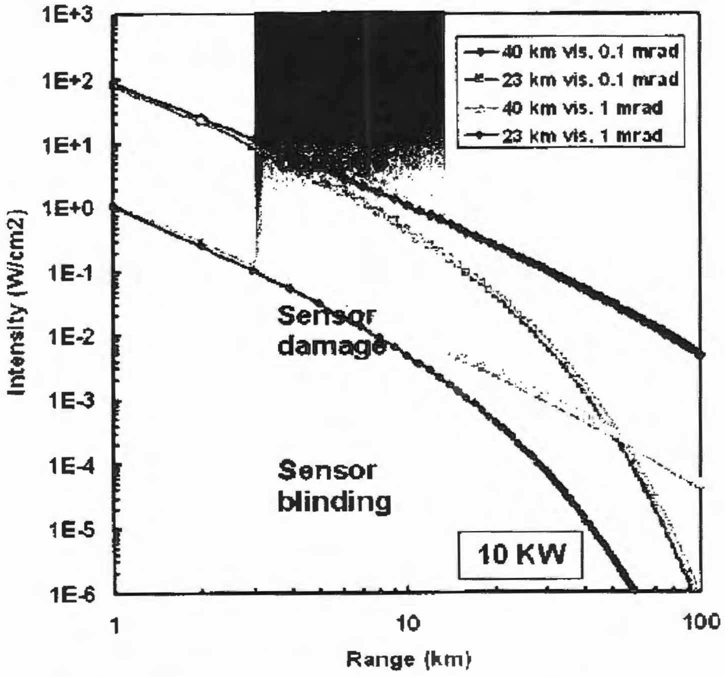


Figure 49: DEW countermeasure effectiveness at 10 KW levels

3.9.1.5 Optical Scattering and Reflection (OSAR)

OSAR is a very powerful technique for defeating optical sensors. Typically, depending upon the intensity of the laser pulse, a sensor is either blinded or damaged to the point it can no longer function. Figure 50a and Figure 50b show OSAR and how sensor performance is degraded. In the Figure 50a, the trees and pylon are clearly visible. In Figure 50b, OSAR effects prevent the scene from being viewed.

- **Optical Scattering and Reflection**
  - Known as OSAR
  - Used with great effect in certain jammers
- **Threat sensor blinded by intense laser light**
  - Looses ability to see
    - Temporary or permanent depending upon intensity
  - Threat sensor damage possible at high intensity

Figure 50: Scene photograph (left) and same scene photograph with OSAR

3.9.1.6 Close Proximity Countermeasures

Proximity countermeasures are effective in the sense that a vehicle can maneuver to the threat area and effect localized countermeasures. Typically, OSAR or high power microwaves can be delivered in this manner. A vehicle, such as the Class II OAV would intercept the threat UAVs and affect the countermeasures. In this manner, the countermeasure platform would carry the countermeasure sources required. A LADAR and camera on board the countermeasure vehicle would provide feedback to an operator-in-the-loop as to effectiveness and confirm defeat. A depiction of proximity countermeasures enlisting an OAV-type platform is shown in Figure 51.

- **Mount CM on UAV platform**
  - Consider class II OAV
- **Outfit with variety of CM**
  - OSAR jammers
  - HPM modules (FCG)

  - μ-munitions
- **Typical operation**
  - Base station LADAR provides range and bearing
  - On-board sensors provide guidance and navigation to intercept
    - Also provided localized information
  - Once in region of threat
    - Platform assesses situation
    - Effects CM
    - Monitors effects
    - Provides assessment

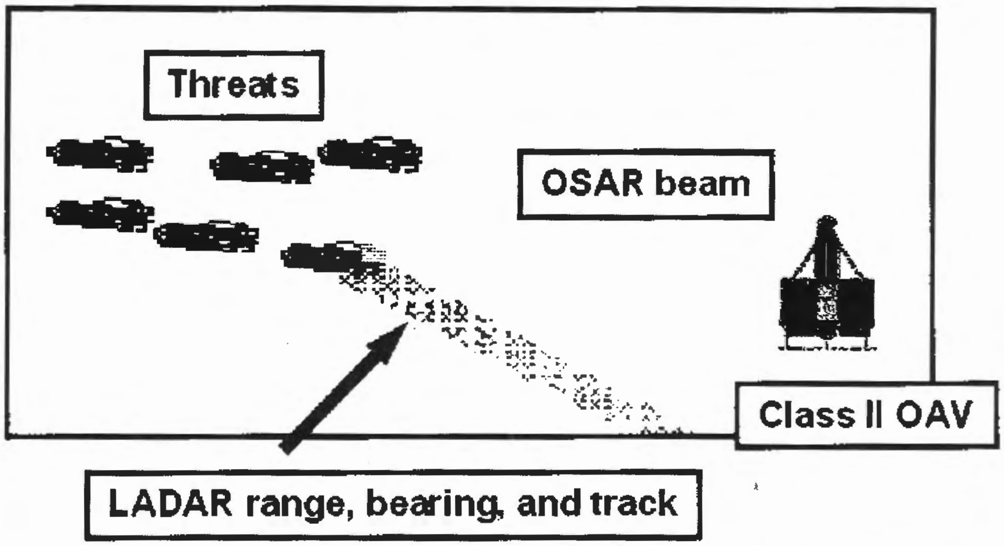


Figure 51: Depiction of proximity countermeasures engaging a fleet of hostile UAVs

3.9.1.7 High Power Microwaves

High power microwaves (HPM) is a viable DEW alternative. They possess many of the attributes as lasers, and can affect the same countermeasures. Also, HPM modules consisting of flux compression generations, soda can sized devices, can be delivered to the threat area and detonated. In this capacity, countermeasures would be affected to the threat localized region. HPM has the advantage of damaging or destroying the communication and navigation capability of the platform within a localized region. Also, HPM may be affected by a number of methods. Flux compression generators, explosive devices that generate tremendous, localized effects can be used at standoff distances. Also, BAE Systems UK has developed directable HPM weapons that can be used in close proximity to the threat. These devices are electrically powered, compact, and have a deep magazine capability. Output powers are in the GW region. Figure 52 shows how HPM may be used as a proximity countermeasure.

- **Speed-of-light all weather capability against hostile electronic systems**
- **Precision strike at selected CM levels**
  - Damage, destroy, degrade
- **Coverage of multiple targets**
  - Within same area
- **Highly directable**
  - Minimum collateral damage
- **Simplified pointing and tracking**
  - Cued from LADAR
- **Deep magazine**
  - Reasonable operating cost

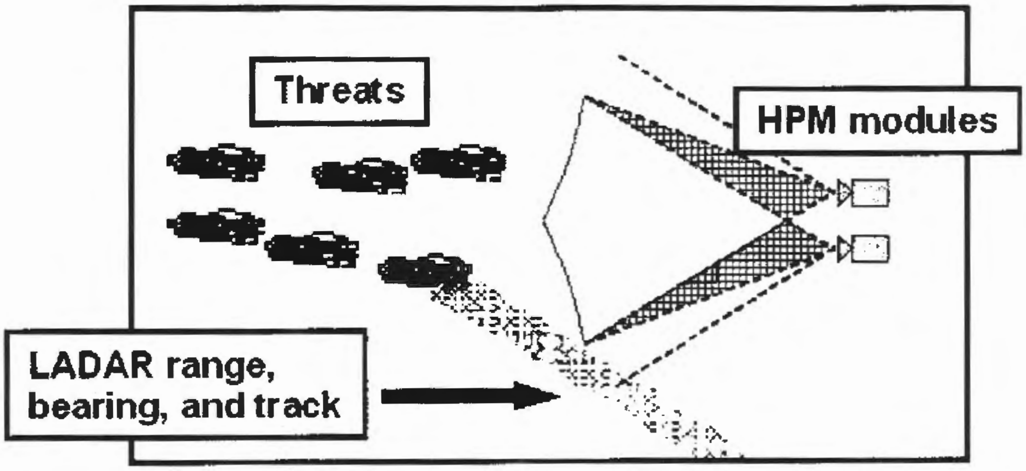


Figure 52: Depiction of proximity countermeasures using HPM engaging a fleet of hostile UAVs

3.9.2 Summary

The military have a need to protect their forces from hostile UAVs. A capability is required to perform a wide area search, detection, ID, and engagement and suppression of hostile UAVs at standoff distances.

These small, crude UAVs can be employed with optical and electronic payloads to disrupt the operations of forward-area operations by transmitting intelligence data about operations, assets, or troop deployments. Also, hostile UAVs equipped with small electronic jammers can disrupt forward-area operations.

Hence, the need exists for cost-effective, precision detection and CM capability against single and multiple threat UAVs.

Mission Payoffs include search, detect, engage, and suppress threat UAVs at standoff distances before they become a problem. The angle-angle-range LADAR imagery collected will permit high resolution imagery of multiple small signature fast moving targets. In this capacity, the advanced LADAR imagery will enable search, detection, identification and engagement of multiple targets using directed energy as the principal mechanism. The Directed Energy Weapon will require aberration compensation for turbulence correction and fine aimpoint control.

Key technologies required include advanced solid state lasers that provide short pulse (< 1 ns) operation, high peak and average powers, operate in the eyesafe region of the spectrum, and can include phased array lasers utilizing coherent combining of the arrays to achieve 100 KW operation. With respect to laser radar, focal plane array technology with independently addressable pixels providing both intensity and range information. Angle-angle-range sensors operating in both linear and Geiger mode, read out integrated circuits (ROIC) that permit fast readout on nsec or sub-nsec levels, and are low noise.