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TACTICAL UNMANNED AERIAL VEHICLES IN A PROPOSED JOINT INFRASTRUCTURE TO COUNTER THEATER BALLISTIC MISSILES

by

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March 1995

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Proliferation of tactical ballistic missile (TBM) systems throughout the Third World represents a serious threat to American national interests. As demonstrated during operation Desert Storm in Iraq, countering this threat is a very difficult problem. A joint, multi-level infrastructure to counter the TBM threat is vital to American security.

This thesis considers the joint infrastructure and tactics necessary to counter the TBM threat. During peacetime, infrastructure assets monitor TBM forces of potential adversaries noting: operating routines, command control and communication (C3) architecture, fixed launch sites and logistics and storage areas. If hostilities arise, the infrastructure expands with theater-level search assets and weapons systems to localize and destroy the enemy TBM force, especially mobile launchers, before they fire on friendly forces or civilians.

Emphasis is on use of tactical unmanned aerial vehicles (UAVs) to locate and positively identify mobile transporter erector launchers (TELs) during the early stages of hostilities. The model proposed uses a tactical UAV to search a segment of road for transiting TELs. Given length of road segment searched and search platform velocity, probability of the UAV over flying the TEL is calculated. Having overflown the TEL, probability of detection and recognition as a target of interest is calculated based on sensor characteristics and searcher flight profile.

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ABSTRACT

Proliferation of tactical ballistic missile (TBM) systems throughout the Third World represents a serious threat to American national interests. As demonstrated during operation Desert Storm in Iraq, countering this threat is a very difficult problem. A joint, multi-level infrastructure to counter the TBM threat is vital to American security.

This thesis considers the joint infrastructure and tactics necessary to counter the TBM threat. During peacetime, infrastructure assets monitor TBM forces of potential adversaries noting; operating routines, command control and communication (C3) architecture, fixed launch sites and logistics and storage areas. If hostilities arise, the infrastructure expands with theater-level search assets and weapons systems to localize and destroy the enemy TBM force, especially mobile launchers, before they fire on friendly forces or civilians.

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EXECUTIVE SUMMARY

This thesis considers the development of a joint infrastructure and tactics to counter the theater ballistic missile transporter erector launcher (TBM/TEL) threat. The infrastructure is intended to monitor the peacetime TBM activities of potential adversaries in much the same way Soviet submarine forces were closely monitored throughout the Cold War.

The joint infrastructure incorporates multiple levels of intelligence collection assets. Unmanned aerial vehicles (UAVs) can provide a variety of services within the infrastructure: localization and identification of TELs, precision targeting and real time battle damage assessment (BDA). Low cost, safety, endurance and survivability of UAVs make them ideal platforms for search and targeting missions deep within enemy territory, where most TBM facilities and TELs are found.

During peacetime, national collection assets such as reconnaissance satellites and high altitude endurance (HAE) UAVs collect intelligence on potential adversary TBM operating routines, command control and communication (C3) architecture, fixed launch sites and logistics and storage areas.

In the pre-hostility phase of a conflict, collection efforts are intensified to provide indications and warnings of enemy TBM/TEL activities. Theater-level assets such as the joint surveillance and targeting radar system (JSTARS) and the medium altitude endurance (MAE) UAV provide broad area coverage of TEL operating areas. Also during the pre-hostility phase of a conflict, if not sooner, unattended ground sensors (UGS) are placed along known or suspected TEL transit routes and near logistics and garrison areas.

Once hostilities erupt, the lower levels of the joint infrastructure are engaged to pinpoint and identify targets of interest cued by the aforementioned theater and national assets. These lower level platforms consist of tactical UAVs and combat air patrol (CAP) missions. Identified enemy TELs are destroyed by CAP (perhaps lethal tactical UAVs), or long range artillery, naval gunfire or other standoff weapons systems.

This thesis emphasizes use of tactical UAVs to locate and positively identify transiting TELs. Search for TELs logically begins along existing enemy road networks. A search model is proposed whereby a tactical UAV searches a segment of road for enemy TELs. The TEL may be transiting through the area or have just emerged from a shelter to fire a missile. Although the model considers only the case of a stationary TEL, it provides an approximate probability of detection for the case of a slow moving TEL.

The model determines how much of the road segment the UAV can search or "cover" while the TEL is exposed. This coverage factor is used to determine the probability the UAV flies over the TEL. For a coverage factor of 1.0, meaning the UAV searches the entire road segment once during the TEL exposure, the probability that the UAV flies over the TEL at least once is 0.75. If however, the UAV is only able to cover half of the search area while the TEL is exposed, the probability of at least one fly over is 0.45.

Having flown over the TEL, determining whether it is detected and recognized as a target of interest is calculated based on sensor characteristics and searcher flight profile. Incorporating the idea of a sensor fixed at some depression angle and field of view (FOV), the model simplifies detection probability by avoiding the necessity of scanning the search area. The target passes from the top of the sensor FOV to the bottom. The operator has numerous opportunities to view the target depending on search platform velocity.

The model demonstrates reasonable probabilities of detection given the target is within sensor FOV. The model further demonstrates that compared to manned tactical aircraft, UAVs, by flying lower and slower, are much less likely to overlook targets and as such offer an advantage in detection probability when searching over hostile territory.

I. INTRODUCTION

A. BACKGROUND

Tactical ballistic missile (TBM) systems continue to proliferate throughout the Third World and developing nations. Many nations unfriendly to the United States are in possession of such missiles. For a detailed discussion of TBMs operated by Middle Eastern and other developing nations see Navias, 1993.

The Persian Gulf War of 1991 demonstrated that even with advanced anti-TBM systems such as the Patriot, countering short range ballistic missiles in flight is a very difficult problem. The widely proliferated SCUD B missile represents 1960's Soviet technology and is a direct descendant of the German V-2. Updated versions of the SCUD and similar missiles produced in several countries, notably North Korea and China, have longer ranges, are more accurate and even harder to shoot down.

The Persian Gulf War saw American and allied forces threatened by TBMs launched from Iraq. Fortunately, the Iraqi SCUD variant missiles packed more bark than bite with one tragic exception being the direct hit on an American barracks in Saudi Arabia.

Once a TBM has been launched, lives and property are at great risk. As demonstrated by Conner, Ehlers and Marshall [Ref 1, p. 13], the expected number of missiles that penetrate friendly defenses and ultimately strike friendly military or civilian targets can be greatly reduced by locating and destroying the transporter erector launchers (TELs) before they launch their missiles.

B. STATEMENT OF THESIS

This thesis considers the development of a joint infrastructure and tactics to counter the TBM/TEL threat. The infrastructure is intended to monitor the peacetime TBM activities of potential adversaries in much the same way Soviet submarine forces were closely monitored throughout the Cold War.

The joint infrastructure incorporates multiple levels of intelligence collection assets. During peacetime, national collection assets such as reconnaissance satellites and high altitude endurance (HAE) UAVs collect intelligence on potential adversary TBM operating routines, command control and communication (C3) architecture, fixed launch sites and logistics and storage areas. In the pre-hostility phase of a conflict, collection efforts are intensified to provide indications and warnings of enemy TBM activities. Theater-level assets such as the joint surveillance and targeting radar system (JSTARS) and the medium altitude endurance (MAE) UAV provide broad area coverage of TEL operating areas. Also during the pre-hostility phase of a conflict, if not sooner, unattended ground sensors (UGS) are placed along known or suspected TEL transit routes and near logistics and garrison areas. Once hostilities erupt, the lower levels of the joint infrastructure are engaged to pinpoint and identify targets of interest cued by the aforementioned theater and national assets. These lower level platforms consist of tactical UAVs and combat air patrol (CAP) missions. Identified enemy TELs are destroyed by CAP (perhaps lethal tactical UAVs), or long range artillery, naval gunfire or other standoff weapons systems.

This thesis emphasizes use of tactical UAVs to locate and positively identify transiting TELs. Cueing for tactical UAVs is provided by theater level assets such as JSTARS, high/medium altitude endurance (HAE/MAE) UAVs or unattended ground sensors (UGS).

A search model is proposed whereby a tactical UAV searches a segment of road for transiting TELs. Given the length of road segment searched and velocity of the search platform, the probability of the UAV over flying the TEL is calculated. Having flown over the TEL, the probability of detection and recognition of the target is calculated based on sensor characteristics and searcher flight profile.

II. THE PROPOSED JOINT INFRASTRUCTURE TO COUNTER TBM

Just as the Navy developed a multi-level infrastructure to counter Soviet submarine forces, a joint infrastructure should be developed to counter the threat of TELs. In fact, the search for TELs has a great deal in common with anti-submarine warfare (ASW). LT Mattis provides a detailed analysis of similarities between the search for TBM/TELs and ASW [Ref 2, p. 11].

History shows that attack of missile launchers has not been effective in the past. According to a BMDO briefing, no German V-1 or V-2 rockets were destroyed on the launchers during WW II [Ref 3]. Desert Storm saw similar results in Coalition attempts to locate elusive Iraqi SCUDs. In all, approximately 1460 allied air missions were flown against Iraqi TBM capabilities. Nearly half of these missions expended ordnance against fixed sites or structures such as culverts and highway overpasses thought to be potential TEL hiding places. Approximately 215 of the strike missions, 15 percent of the total, supposedly attacked TELs. Despite Coalition efforts and claims made during the War, it is now believed that few if any Iraqi TELs were actually destroyed as reported. "...there is no indisputable proof of any TELs or MELs - as opposed to high-fidelity decoys, trucks, or other objects with SCUD-like signatures - having been destroyed by aircraft operating independently" [Ref 4, p. 340].

A. PLATFORMS SUPPORTING THE JOINT ANTI-TBM INFRASTRUCTURE

The proposed infrastructure in depth consists of several platforms each performing a portion of the task of monitoring, localizing, tracking and if necessary destroying TBM/TELs.

1. Overhead Assets

Successfully countering the TBM threat begins before hostilities erupt. The infrastructure must provide unobtrusive detection and tracking methods to monitor the TBM forces of potential adversaries during peacetime.

"Overhead" (satellite) reconnaissance provides peacetime intelligence on day to day operations of TBM forces, monitoring logistic facilities, training and firing areas and noting unusual activity such as dispersal of TELs from their garrisons. In addition, during hostilities satellites provide warning of enemy TBM launches. Overhead assets are expensive to deploy, operate and maintain, but have the distinct advantage of operating with impunity against Third World nations likely to attempt aggression against U.S. interests. Capabilities of overhead systems vary, but most are equipped with sensors unaffected by weather or darkness.

There are of course disadvantages to overhead assets. With the exception of geo-synchronous satellites, overhead systems revolve around the Earth. Depending on the period of revolution, a particular satellite may pass over a target of interest such as a TBM storage facility every few hours or only once every few days. Sensor resolution of satellite systems may be insufficient for precise identification of targets and may make overhead systems more susceptible to deception.

2. Unattended Ground Sensors (UGS)

Several varieties of unattended ground sensors (UGSs) are currently available. These sensors detect and attempt to classify and identify vehicles passing nearby. UGSs make use of many prominent target signatures, for example; seismic, acoustic, magnetic anomaly, optical and infrared.

Much research and progress into the use of UGSs has arisen in response to the Conventional Forces in Europe (CFE) treaty. An excellent source of information on UGS technology useful for detecting military vehicle movements is *Verification at Vienna* [Ref 5].

a. Location

Determining where to place UGSs is the first and most important step if they are to be used successfully. Negative search theory involves determining where to search by determining where not to search. Hair demonstrates that for the TEL search problem, the area requiring search can be drastically reduced by use of negative search theory. [Ref 6]

Because TELs make extensive use of highways and secondary roads, UGSs will be most successful if placed at intersections and along roadways connecting TEL logistic and rearming areas with known or suspected firing positions. An area of research not covered in this thesis is to treat the road system as a network and the problem of UGS placement as a minimum flow network problem.

b. Emplacement

UGSs may be air dropped or hand placed depending on the situation. Placement accuracy required depends on the type of sensor used. Optical sensors of course must have their lenses pointing in the right direction. Optical sensors must also be positioned close enough to the road to maintain sufficient resolution for target identification. Seismic sensors also have special placement requirements. Seismic sensors are affected by geological features of the area being searched. To accurately determine the number of vehicles, their approximate type and velocity, several seismic sensors should be used, paying close attention to their relative placement from each other. Klinger and Malek recommend three seismic sensors be placed in an equilateral triangular pattern with one sensor at the edge of the road and the other two set off from the road approximately 20 meters [Ref 5, pp.185-192].

c. Communication

The use of detection algorithms and neural filtering networks within UGSs allows them to discriminate between possible target and non-target signatures. Only detections fitting signature profiles of likely targets of interest are reported by the sensors. Most UGSs report target detection via satellite or line of sight VHF. Eliminating non-target reporting saves the UGS valuable battery power and reduces the likelihood of counter detection.

3. Joint Surveillance and Targeting Airborne Radar System

Joint surveillance and targeting airborne radar system (JSTARS) was used successfully in Desert Storm to cue Pioneer UAVs as well as combat air patrol (CAP) fighters to locations of suspected Iraqi military activity such as transiting TELs.

JSTARS is primarily designed to detect moving targets. Resolution of JSTARS moving target indicator (MTI) radar however may be insufficient to allow classification or identification of certain targets of interest. For instance, JSTARS can detect a column of moving vehicles, but may not be able to classify them as military targets or identify the specific vehicle type. A spotlight mode of the MTI radar is capable of the resolution necessary for target classification, but use of this mode is generally undesirable because wide area coverage is lost while spotlight mode is in use.

JSTARS provides theater level all weather coverage of enemy movements. Low-resolution radar video, recorded for playback in flight or post mission, provides vital intelligence to the JFC and allows cueing for immediate response by tactical assets. JSTARS suffers some disadvantages however. A limited number of these very expensive platforms are available. As a result, gapped coverage is very likely. Also, JSTARS currently has problems with "blind spots" as a result of specific target aspects, terrain masking and forestation.

4. Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles come in many varieties, and are discussed in detail in the following chapter. UAVs useful in the anti-TBM infrastructure include:

1. High Altitude Endurance (HAE) UAVs.
2. Medium Altitude Endurance (MAE) UAVs.
3. Tactical UAVs.

As is detailed in the next chapter, HAE UAVs provide broad area coverage and cueing for lower level systems. MAE UAVs provide a quick response asset for localization and classification of targets detected by overhead, HAE or JSTARS systems. MAE systems, like most UAVs, are inexpensive, have low probability of intercept/detection by enemy forces and do not place friendly personnel at risk. Tactical UAVs provide the means to positively identify targets cued by the aforementioned systems as well as performing targeting including laser designation for delivery of precision guided munitions. Tactical UAVs may dwell in the immediate target vicinity during the targeting and ordnance delivery phases of anti-TEL operations and provide immediate battle damage assessment (BDA) to the Theater CINC and JFC.

5. Miscellaneous Search Platforms

Other platforms, some of which are normally reserved for national level defense support missions, may be incorporated into the anti-TBM infrastructure. These assets include:

1. Defense Support Program (DSP). Originally deployed to warn against Soviet ICBM and SLBM launches against the U.S., detecting missiles during their boost phase by sensing infrared radiation, DSP satellites were used during Desert Storm to detect Iraqi SCUD launches.
2. COBRA BALL (RC-135S). Another national asset designed to detect and track ballistic missiles, COBRA BALL aircraft are in limited supply and do not currently deploy to support theater level operations although this capability exists. The multi-spectral sensor technology used by COBRA BALL could be added to other theater assets.
3. RIVET JOINT (RC-135V/W). A theater asset that collects, analyzes, reports and exploits enemy command control communication and intelligence (C4I) capabilities.
4. U-2R, RF-4, AWACS and E2-C aircraft all have capabilities useful for the anti-TBM mission especially during open hostilities.

[Ref 7, pp. 21-23]

B. JOINT INFRASTRUCTURE COMMAND CONTROL COMMUNICATION AND INTELLIGENCE (C4I)

Several interface systems and data/communications networks are incorporated into the proposed anti-TBM C4I effort including: [from Ref 7 and Ref 8, chapt. 11,]

1. Contingency Airborne Reconnaissance System (CARS). CARS is a theater level battlefield management asset that provides near-real-time processing, exploitation and rapid dissemination of multi-sensor intelligence data collected by airborne platforms

and possibly UGSs. Currently CARS processes data primarily from U-2 aircraft although it can be expanded to do the same for RC-135 "Rivet Joint", JSTARS and UAV platforms.

2. Enhanced Tactical Radar Correlator (ETRAC).

3. Joint Service Image Processing System (JSIPS)

4. Joint Deployable Intelligence Support System (JDISS). JSIPS connects national intelligence collection assets with theater and tactical level assets.

5. Joint Worldwide Intelligence Communication System (JWICS). JDISS/JWICS is a C4I system to support the information needs of the JTF commander with connectivity to the Theater CINC.

6. TROJAN SPIRIT II Communication System.

7. Modernized Integrated Exploitation System (MIES). MIES, part of the Army Tactical Exploitation of National Capabilities (TENCAP) architecture, exploits radar imagery processed by ETRAC.

8. Theater Air Control System (TACS). A modular, mobile command and control (C2) system used by the deployed Joint Force Air Component Commander (JFACC).

9. Tri-Service Tactical Communications (TRI-TAC).

10. Tactical Information Broadcast System (TIBS).

11. Tactical Digital Information Links (TADIL).

CARS, JSIPS, ETRAC and MIES are primarily intended to support service components of a JTF.

TRI-TAC, TROJAN SPIRIT II, TIBS and TADIL provide theater wide voice and data C4I connectivity among all platforms within the joint infrastructure. The TRI-TAC and TROJAN SPIRIT communication networks provide voice and data link connections between platforms in the field and the JFC. TIBS broadcasts all-source intelligence information over SATCOM, providing timely, correlated, multi-level targeting and air situation data [Ref 7, p. 24]. TADIL consists of several separate data link systems.

TADIL-A/Link 11 connects mobile air, land and surface platforms such as AWACS, JSTARS and Naval C2 equipped nodes. TADIL-B/Link 11B is primarily for land platforms such as the Air Force Control and Reporting Center (CRC) and USMC Tactical Air Operations Center (TAOC). TADIL-J/Link 16 provides jam resistant secure voice and data link surveillance for AWACS and JSTARS as well as other land, air or sea based C2 nodes. [Ref 7, p. 19]

At the theater-level, interface between JSTARS aircraft and UAVs is being improved through use of a common ground station.[Ref 8, chapt. 11]

C. JOINT ANTI-TBM INFRASTRUCTURE PROPOSED INTEGRATION

Figure 1 depicts three levels; national, theater and tactical, within the proposed joint anti-TBM infrastructure. The HAE UAV may be considered a national or theater level asset. During peacetime, SIGINT/imaging satellites provide non-obtrusive reconnaissance and intelligence gathering against potential adversaries worldwide. HAE UAVs supplement the overhead intelligence collection effort on a regional or theater level. Operating at extreme altitudes and with low radar cross sections, HAE UAVs are immune to intercept by Third World and developing nations.

Figure 2 is a notional layout of the interfaces and C4I links between various platforms within the joint infrastructure. Solid lines connecting boxes within Figure 2 represent data flow and are annotated with the type(s) of data that the platform provides. Dashed lines represent voice communications. The heavy lines connecting the TIBS and JDISS/JWICS networks with the CARS, ETRAC nodes are meant to indicate the heavier data flow rates between these networks. Voice links for the UAV platforms are actually connections between the ground control sites (GCS) and the rest of the infrastructure. One-way data links between UGS and other platforms indicate the possibility of placing receivers aboard UAVs, JSTARS and CAP aircraft, allowing them to receive and process UGS data much the way P-3s process sonobouy data in the ASW problem. Radar imagery data is passed via TROJAN SPIRIT II or TADIL, from the platforms and is distributed to CARS, ETRAC, MIES and JSIPS for processing. Processed imagery and reports are disseminated via TIBS and or the JDISS/JWICS networks.

National Level	SIGINT/Imaging Satellites, DSP COBRA BALL HAE UAVs
Theater Level	MAE UAVs Unattended Ground Sensors JSTARS RIVET JOINT
Tactical Level	Tactical UAVs CAP aircraft Spec Ops Forces Misc Weapon Systems (NGF, artillery)

HAE UAVs may be considered a national or theater level asset

Figure 1: Levels of the proposed joint anti-TBM infrastructure

The anti-TBM mission begins when an overhead satellite or HAE UAV detects a target of interest. Sensor information may be passed to CARS, routed through JSIPS for processing, and disseminated via TIBS or JDISS/JWICS. Cued MAE UAVs and or JSTARS aircraft attempt to further classify and identify the target, reporting contacts via TROJAN SPIRIT II or TRI-TAC communications networks to JDISS/JWICS. Imagery data may be processed by ETRAC and MIES as necessary. Near-real-time target status information is available to the JTF and Theater CINC via TIBS and JDISS/JWICS. Tactical UAVs and or CAP aircraft are cued to investigate targets that cannot be ruled out as non-TELs. The tactical UAV proceeds to the target vicinity and attempts localization and identification. Chapter IV details a UAV tactic useful for localization and identification of TELs. The UAV Ground Control Station (GCS) relays target position to the appropriate forces for cueing TAC Air assets, MLRS or naval gun fire upon the TEL.

The tactical UAV remains in contact with the target, possibly providing laser designation for precision guided munitions. The UAV will loiter in the target vicinity to perform immediate BDA after ordnance delivery has occurred.

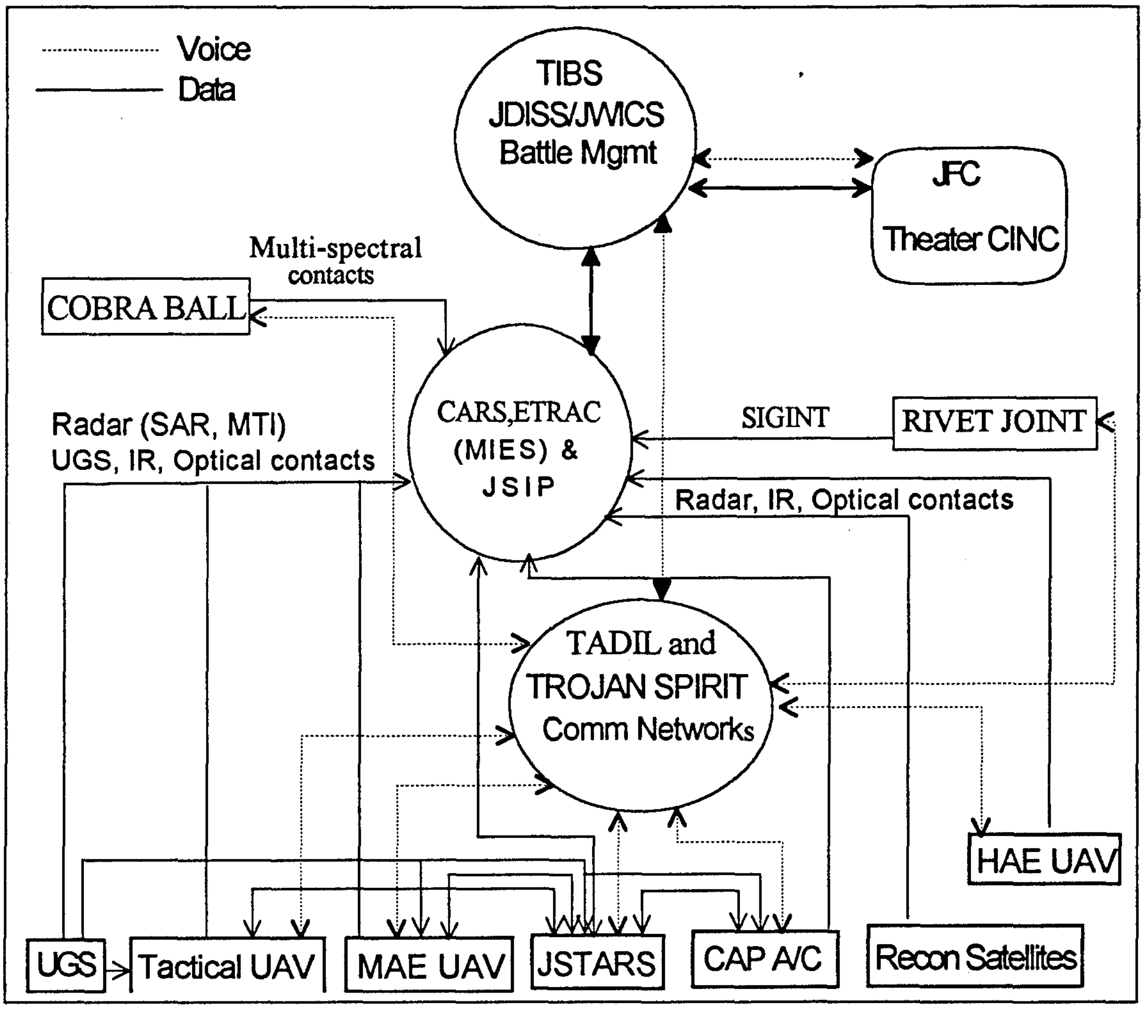

Figure 2: Notional platform integration and C4I of the joint anti-TBM infrastructure

III. USE OF UNMANNED AERIAL VEHICLES TO LOCATE TARGETS

While Unmanned Aerial Vehicles (UAVs) are certainly not capable of performing every aviation mission, there are missions for which they are ideally suited. Searching for mobile tactical ballistic missiles may be one of these missions. This chapter explores using UAVs in the search mission and provides background information of current UAV systems in use or development.

A. USING UAVS TO SEARCH FOR TBM/TELS

UAVs have both advantages and disadvantages compared to alternative platforms. These are discussed in the following paragraphs.

1. Advantages

a. Safety

Unlike conventional aircraft, UAVs do not place aircrewmen at risk of enemy anti-aircraft fire. "In that same war (Vietnam) America lost more than 2,500 manned aircraft, about 5,000 of her airmen were killed, and nearly 90 per cent of *all* US servicemen taken prisoner were pilots and crewmen [Ref 9, p. 7]." Similarly, during the Persian Gulf War, the vast majority of coalition prisoners captured by the Iraqis were aircrew personnel.

During the post-Vietnam era, Americans have become less willing to accept sacrifice of lives without a justification tied directly to American security interests. Near-real-time news coverage and perhaps a greater national cynicism towards government mean support for US military involvement in foreign countries quickly starts to wane once Americans begin taking casualties. Therefore, commanders of future conflicts should employ unmanned sensors whenever possible to ensure that they can both accomplish the mission and minimize the risk of unnecessary casualties.

b. Survivability

With the exception of the very expensive stealth aircraft, modern piloted aircraft are manufactured from metal and other materials that are easily detected by radar. The average pilot with flight gear weighs approximately 200 lbs. Adding a human pilot to an aircraft requires the addition of a cockpit that increases the airframe size by at least 10 cubic feet. Instrumentation necessary for manned flight adds more weight and volume to the aircraft. Jet powered aircraft make considerable noise and often generate a readily detectable infrared signature.

In contrast, most UAVs suitable for the TBM/TEL search mission are relatively small aircraft, many weighing only a few hundred pounds. They are generally constructed of low density materials such as wood, fiberglass and plastics that result in a very low radar cross section and often allow them to sustain a high level of ground fire with minimal damage. They generally use small, piston driven engines that reduce noise and infrared signatures.

Survivability of UAVs is well documented. The following quotes appear in Munson [Ref 9, p. 7].

> This...target was...flown against the concentrated gunfire of the (British) Home Fleet during an exercise in the Mediterranean. For two hours, every gun in the fleet tried in vain to destroy the lone, slow and fragile target, but it was recovered safely.

> Thousands of rounds of radar-directed fire from a sophisticated air defense gun, as well as hundreds of rounds of fifty caliber, were expended on an unmanned vehicle flying well within range. The unmanned vehicle flew on without a scratch.

Munson goes on to explain that the significance of these quotes, in addition to providing testimony of the survivability of UAVs, is that the quoted incidents occurred 47 years apart, the first in January 1933, and the latter in 1980.

c. Cost

Even the most expensive UAVs are economical compared with the cost of a modern manned aircraft. The majority of tactical UAVs in current use around the world that may be suitable for the anti-TEL mission cost on the order of a few tens of thousands of dollars each.

d. Endurance

One of the requirements for an airborne search platform, whether searching over land or water, is endurance. The search for TELs may necessitate extremely long missions and will undoubtedly take place on the enemy's home terrain where an aircrew would have to deal with the constant threat of detection by hostile forces. Combining the stress of flying behind enemy lines with the long mission endurance requirements, unmanned search platforms have a distinct advantage over manned platforms. UAV ground control sites (GCS) are generally located in relatively safe rear areas. GCS crews can be rotated so that a well rested observer is always at the console monitoring the search area. Free of the worry of being shot down, UAV controllers and observers can concentrate on the search mission.

Technology exists for much greater endurance in UAVs than is currently available, on the order of 120 hours (5 days) or longer. As greater flight endurance becomes a reality, the usefulness of UAVs and their advantage over manned aircraft for search missions is enhanced.

e. Targeting and Battle Damage Assessment (BDA)

Although current UAVs are all non-lethal in that they do not carry ordnance themselves, they are a valuable targeting asset. They may remain in the target vicinity during and immediately after delivery of munitions by other means such as tactical air strike, artillery or naval gunfire, to provide immediate BDA. This gives warfare commanders vital intelligence and aids in determining if a target has been neutralized or requires further attack.

2. Disadvantages

a. Range

Current tactical UAVs are generally constrained to line of site operation between the UAV and GCS. Relaying telemetry data and commands between the UAV and GCS via satellites is possible, but adds to cost, complexity, size and weight of the UAV system.

b. Endurance

The high and medium altitude endurance UAVs described in the next section, as their names imply, are designed for extended endurance missions. Tactical UAVs on the other hand, generally have limited endurance. For instance the Pioneer UAV has a limited endurance of six to nine hours although most missions do not exceed five hours [Ref 9, p. 59].

c. Air Space Violation

TELs operate almost exclusively within the confines of their own country. To be effective in the anti-TEL mission, tactical UAVs, whose sensors typically have relatively short effective ranges, must operate over enemy territory. During open hostilities this is not a problem, UAV operations are incorporated into the joint air plan. If UAVs are to play a role in the peacetime infrastructure, monitoring potentially hostile TBM forces and aiding the intelligence preparation of the battlefield (IPB), they must be able to conduct the mission while operating in international airspace. It should be possible for high altitude UAVs with sensitive, long range sensors operating against coastal threat nations bordered by oceans or seas to remain outside the recognized border in international airspace and peer into the target nation interior. Another possibility is UAVs operating at extremely high altitudes, essentially in low-Earth orbit (also international airspace). Developing UAV systems able to operate at such extreme altitudes and with sensors capable of target classification from such altitudes is very expensive.

d. Positioning Inaccuracies for Targeting Mission

Figure 3 from Holman [Ref 10] depicts some of the weaknesses in UAV targeting efforts. The method currently in use provides satellite positioning information to the UAV via the global positioning satellite (GPS) system. The UAV derives altitude information from an onboard barometric altimeter. In the targeting role, the UAV illuminates the target with a laser designator for precision guided munitions. The cumulative errors associated with GPS, barometric altitude inputs and possible small error in laser ranging results in an aimpoint location accuracy of approximately 200 meters. This circular error probable (CEP) is considered insufficient for targeting precision guided munitions [Ref 10, p.20].

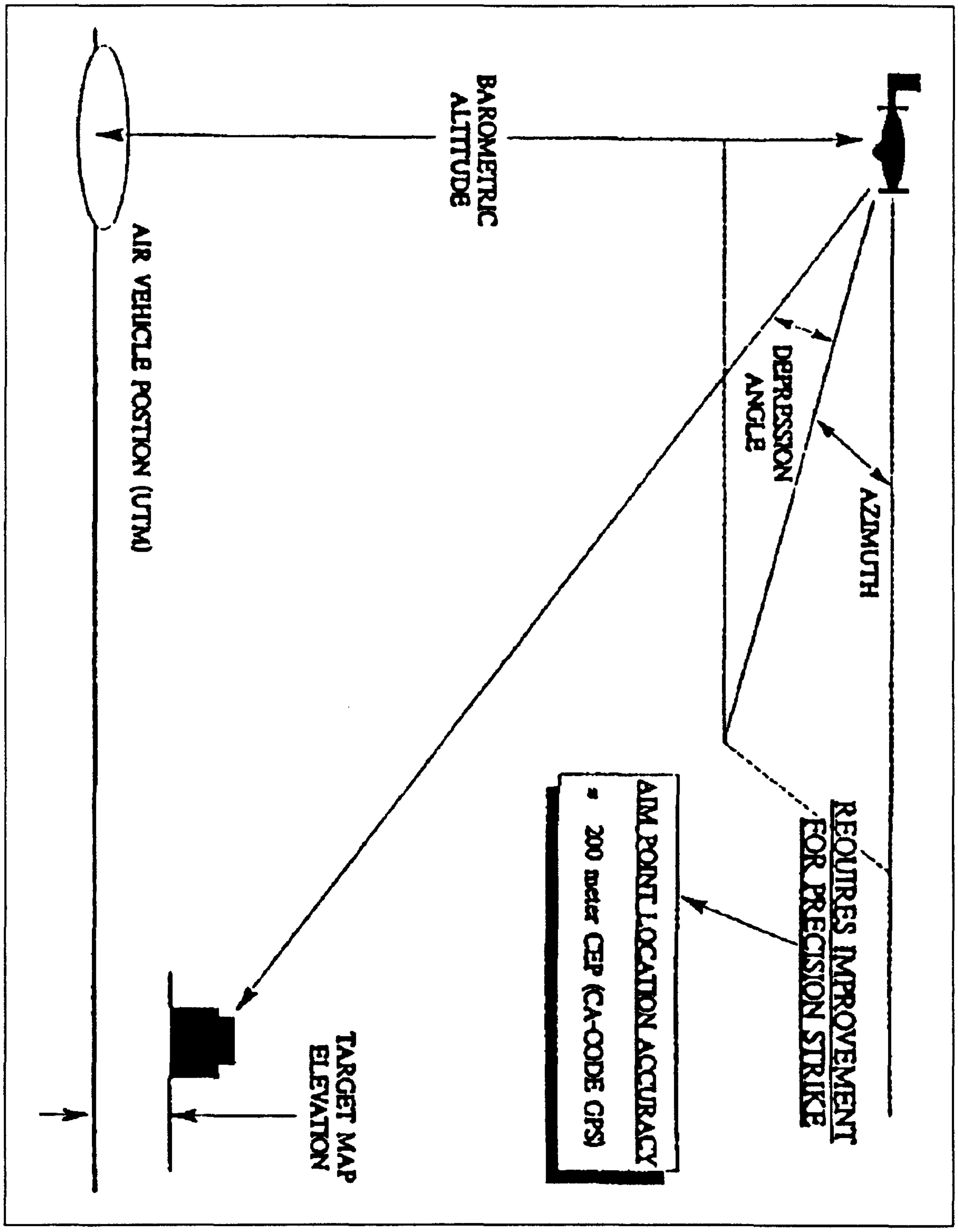

Figure 3: Aim Point Location Triangulation (From Ref 10, p. 20)

B. UAVS IN CURRENT USE

1. Mazlat/AAI Pioneer

The Pioneer UAV, made famous during Operation Desert Storm, was a joint development of Mazlat of Israel and AAI Corporation of Baltimore, Md.

The Pioneer is 14 feet long, has a wingspan of 16.9 feet and weighs up to 419 lbs at take off. [Ref 11]

Constructed mostly of fiberglass and fabric, with aluminum wing spars and tail boom supports, the Pioneer has a very low radar cross section (RCS). The low RCS, coupled with its small size, make the Pioneer hard for an enemy to detect.

In over 300 sorties during Desert Storm, Pioneer UAVs logged approximately 1000 flight hours. Although all Pioneer missions were conducted at altitudes below 5000 feet, well within range of all anti-aircraft guns, infrared missiles and even small arms fire, only one Pioneer was shot down by the Iraqis. [Ref 8, p. 2-2]

2. Medium Altitude Endurance (MAE)

Medium altitude endurance UAVs are currently under development to satisfy requirements delineated in the MAE mission needs statement (MNS). MAE UAVs are to have at least 24 hours of on station endurance. Their radius of action is to exceed 500 nautical miles from the forward line of own troops (FLOT). MAE UAVs are expected to operate at low to medium altitudes below 25,000 ft. They will carry a variety of sensors and communications equipment to pass along gathered intelligence data. To attain the desired level of connectivity with the joint worldwide intelligence communication system (JWICS), MAE UAVs utilize the TROJAN SPIRIT II communications system that provides C, X, and Ku band UHF (line of sight and satellite) and VHF communications. [Ref 8, p. 3-8]

The system currently flying that is most promising for use in the anti-TEL mission is the Tier II MAE called the Predator. The Tier II program provides funding for 10 Predator aircraft and three ground stations. As of the summer of 1994, three Predators delivered thus far have flown over 30 hours in a single flight. [Ref 12, p. 7] Predator carries a multi-payload electro-optical and infrared (EO/IR) platform called SKYBALL®, developed by the Versatron Corp. SKYBALL is gyro-stabilized and contains two high resolution color TV cameras; one capable of 10X zoom with 20 degree wide angle or 2 degree narrow field of view (FOV), the second is a 900 mm fixed focal length "spotter scope" for viewing at extreme distances. SKYBALL's infrared imager has six selectable fields of view ranging from one degree for long range, to 38 degrees for landing. The infrared camera delivers "TV-like" images in nearly all visibility conditions. SKYBALL also has a laser range finder (LRF) capable of measuring distance to targets up to 10 km away with an accuracy of 5 meters. [Ref 12, pp. 30-31] Predator also employs SAR capable of one foot resolution from an altitude of 15,000 ft [Ref 13, p. 19].

The MAE concept of operations (CONOPS) envisions their use for cued reconnaissance/survelliance missions directed by the Theater CINC or JFC satisfying the need for theater level urgent collections. MAE UAVs, with long dwell time and sophisticated sensor and communications suites, are particularly well suited to the mission of searching for TELs. Rutherford states that MAE UAVs such as Predator, "...will provide key small-area surveillance either through its own pre-programmed autonomous search routines or by being cued by other companion assets [Ref 13, p. 19]."

Cueing for MAE operations can come from several sources including; high altitude endurance (HAE) UAVs discussed next, JSTARS and overhead systems. Once the MAE has classified and perhaps identified the target, it can be further investigated by low altitude tactical UAVs such as Pioneer, or manned aircraft and then targeted and destroyed. Figure 4 depicts the MAE CONOPS.

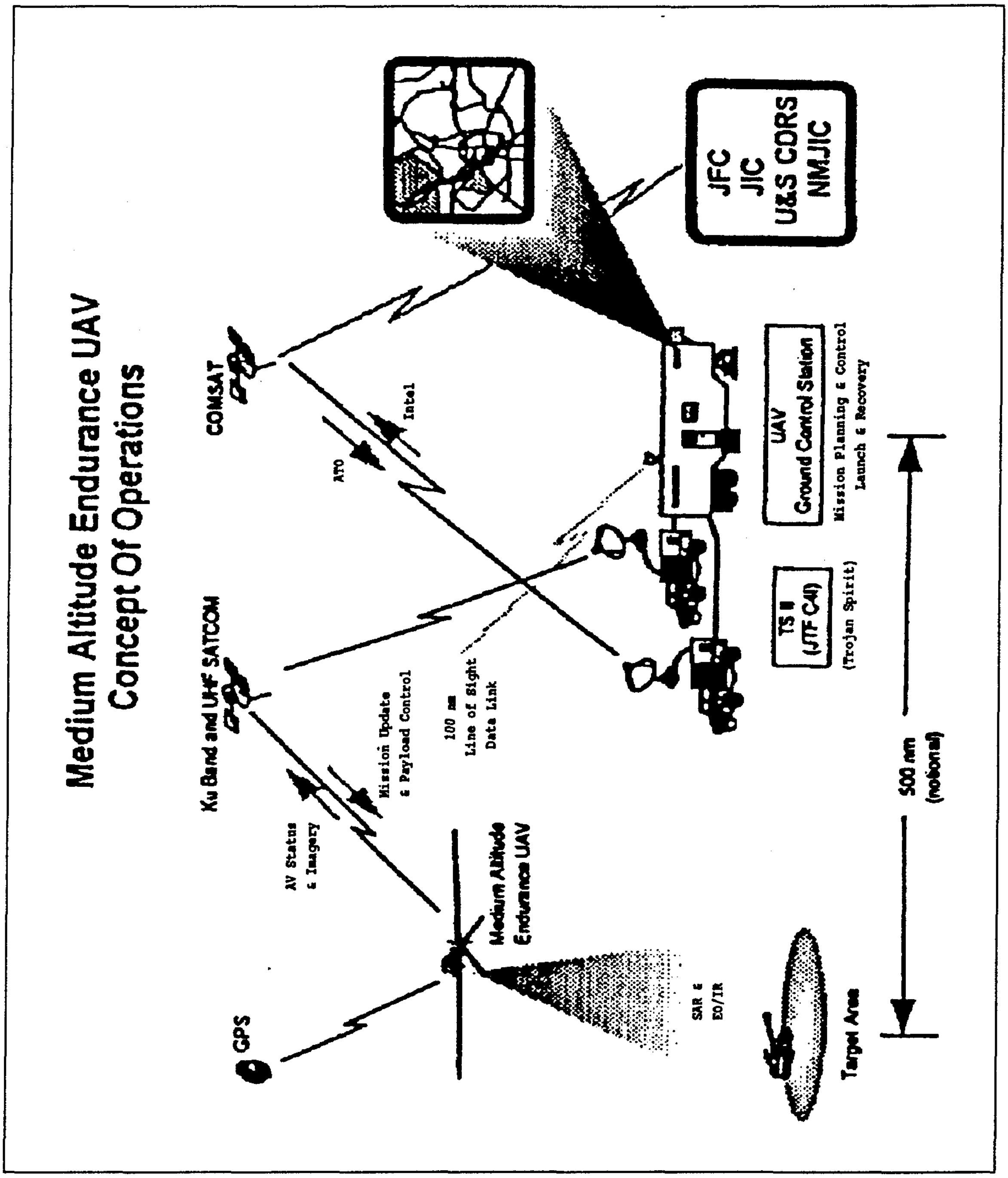

Figure 4: MAE CONOPS (From Ref 13, p. 19)

3. High Altitude Endurance (HAE)

A number of HAE programs have been undertaken over the last several decades. Most of these systems were apparently overly ambitious and proved unable to achieve specified mission requirements with existing technology and were thus canceled before becoming operational.

Desert Storm reiterated the need for a high altitude system providing broad area coverage and sustained point surveillance. "The initial requirement is to search over 136,000 km^2 per day and provide 1900 point targets per day for pre and post strike reconnaissance [Ref 8, p. 3-8]." HAE systems are to have a minimum endurance of 24 hours at a distance of 5600 km and will operate at altitudes of approximately 60,000 ft and above.

The primary sensor used aboard envisioned and developmental HAE systems is synthetic aperture radar (SAR) capable of down-linking directly, or via satellite, to the JFC via JWICS.

An advantage of HAE over MAE UAVs in the theater-level collection role especially during hostilities is that the altitudes HAE systems operate at makes them much less susceptible to interdiction by Third World nations. They may know the system exists and is located over their country, but they lack the means of shooting it down. Another advantage of HAE is longer endurance. Systems under development include some making use of solar power that allows for nearly limitless on station endurance. Such solar powered HAE UAVs therefore make development of an infrastructure to continuously track TBM capabilities of potentially hostile Third World nations much more feasible.

Two disadvantages of HAE UAVs are low resolution and cost. Low sensor resolution makes it difficult to classify potential targets from high altitude and increases the error rate. HAE UAVs are relatively expensive, up to several million dollars each.

C. SUMMARY

UAVs are much less expensive to deploy than satellites and much cheaper to build than conventional aircraft. Wide proliferation of TBMs means the infrastructure to track them during peace time requires a large number of diplomatically acceptable systems that can monitor the TBM forces of potential adversaries without threatening their national sovereignty. High altitude UAVs may be able to supplement existing "overhead" surveillance assets for the peace-time monitoring role. Such assets provide indications and warnings of a potential adversary's intentions regarding deployment of TBM forces.

When hostilities do arise, UAVs continue to play a central role in the anti-TBM mission. MAE UAVs supplement theater level assets such as JSTARS, providing broad area coverage of the battlefield. Because of the high value of platforms such as JSTARS, they generally loiter over friendly areas to minimize the risk of becoming targets of enemy anti-air defenses. MAE UAVs may penetrate deep within enemy territory to provide coverage beyond the range of JSTARS sensors.

Tactical UAVs likewise may penetrate and loiter over enemy air space, localizing TELs and providing targeting for precision guided munitions and real time BDA.

The next chapter discusses a localization search tactic for employing tactical UAVs against transiting TELs.

IV. THE SENTRY SEARCH MODEL

As the name implies, the Sentry Search model involves searching back and forth along a segment of terrain, much like a sentry walks his post, back and forth.

The first important assumption of the Sentry Search model is that TELs will utilize hard surfaced and secondary roads to transit between their logistics and firing areas. The sentry will search segments of such roads deemed likely to be used by TELs.

From past experience it is known that although TELs are capable of off road travel, they generally make use of existing road networks whenever possible. Using the existing highway system allows the TEL to move quickly while minimizing the chance of mechanical breakdown.

The TEL crew wishes to get into firing position as soon as possible to minimize counter detection, and therefore travels at high speed from their logistics areas or shelter to their firing position. Firing positions are assumed to be within a short distance of a hard-surfaced or secondary roadway. [Ref 6]

Upon firing their missile, the TEL crew suspects there is a high likelihood they have been detected and they therefore egress the firing area quickly. Again, roadways offer the best opportunity for the TEL to escape quickly.

Knowing that TELs transit to and from firing and logistics areas via roadways reduces the area that must be searched to locate them before they fire their missiles. Hair demonstrates that the search area can be dramatically reduced by correlating TEL transit patterns and topological restrictions with the terrain being searched [Ref 6].

Sensor sweep width is not a factor if the TEL operates within a short distance of the road being searched. We assume that this distance is within the sensor sweep width.

A. THE MODEL FOR A STATIONARY TARGET

The sentry, a UAV, is assigned to fly back and forth along a segment of road. The sentry flies at a constant velocity v back and forth along a segment of road of length L. We assume that TELs arrive according to a stationary Poisson process. Under this assumption, the point along the road at which the TEL appears is uniformly distributed. Sentry position along the road segment at the time of TEL appearance is denoted by u, also uniformly distributed. The TEL is assumed to remain exposed for a fixed period of time t. The sentry is assumed to operate such that gapped coverage of the search area does not occur.

In the amount of time t the TEL is exposed, the sentry, traveling at a constant speed v, covers a distance equal to vt. Thus, an upper bound on the proportion of road segment L that the sentry covers during a TEL exposure is (vt)/L. Figure 5 lays out the basic scenario where 0 indicates one end of the road, and L the other. Point a is at (L - vt). The distance between points a and b is equal to one half the distance covered by the sentry during TEL exposure; i.e. b = L - vt/2. Recall that the location of the searcher along the road when the TEL appears is designated u.

Depending on sentry starting position and assuming the sentry makes no more than one round trip (two road lengths) of the road segment during t, three possibilities exist: the sentry may fly over the TEL once, twice or not at all.

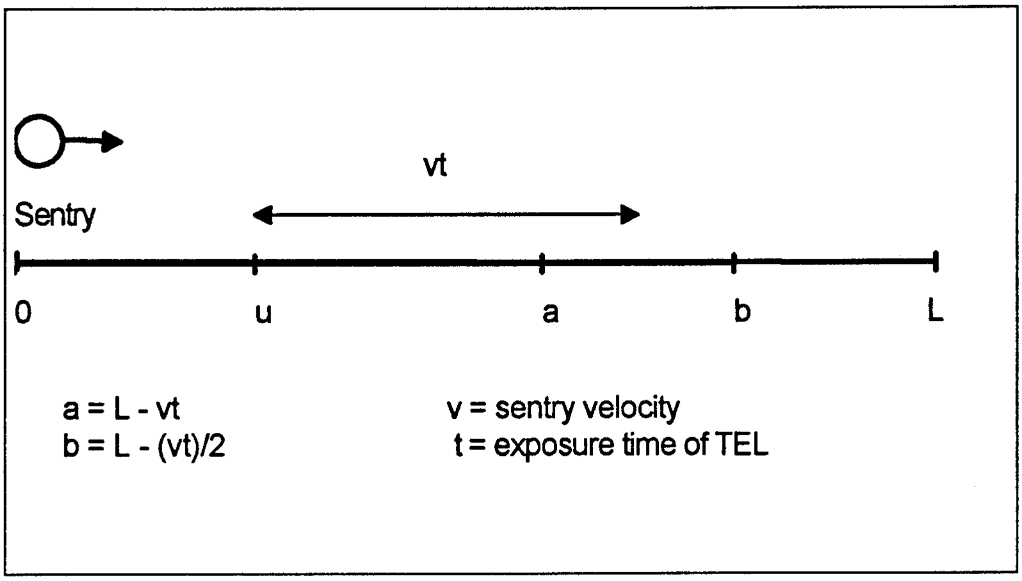

Figure 5: Schematic of the Road for the Sentry Search model

1. Probability the sentry flies over the target only once

In Figure 6, sentry starting point along the road is such that the sentry does not reach the end of the assigned search segment during TEL exposure.

Let $P^{(1)}$ (F.O.|u) denote probability the sentry flies over the TEL once, given it is at point u when the TEL appears. Define T to be the position where the TEL appears Since no turn is required of the sentry if $0 < u < L - vt$,

$$P^{(1)}(F.O.|u) = P(u \leq T \leq u + vt)$$

$$= (vt)/L \quad \text{for } 0 < u < a.$$

Changing the scale by letting $z = u/L$, and $x = (vt)/L$, the above becomes

$$P^{(1)}(F.O.|z) = x \quad \text{for } 0 < z < 1\text{-}x. \qquad (1)$$

Note that x is the fraction of the road that can be flown over by the UAV during the exposure time of the target. This x is called the coverage factor.

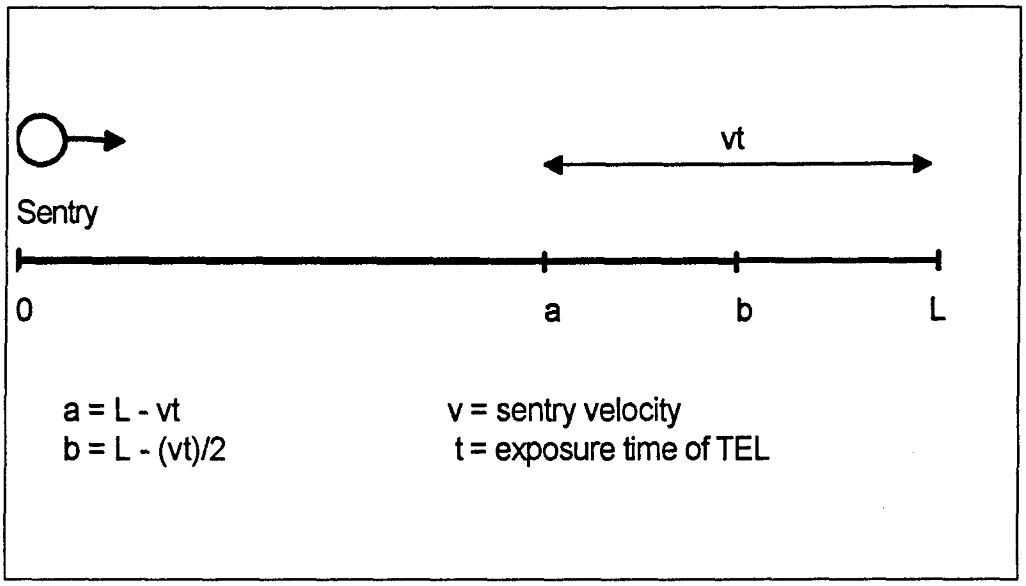

Figure 6: Sentry does not make a turn during TEL exposure

In Figure 7, $a < u < b$ where $a = L - vt$, $b = L - (vt)/2$. The sentry makes a turn during TEL exposure t. Probability that the sentry flies over the TEL once during t is:

$$P^{(1)}(F.O.|u) = P(u \leq T \leq L + a - u),$$

$$= [2(L - u) - vt] / L \quad \text{for } a < u < b.$$

Substituting as before gives,

$$P^{(1)}(F.O.|z) = 2(1 - z) - x \quad \text{for } 1-x < z < 1-x/2 . \quad (2)$$

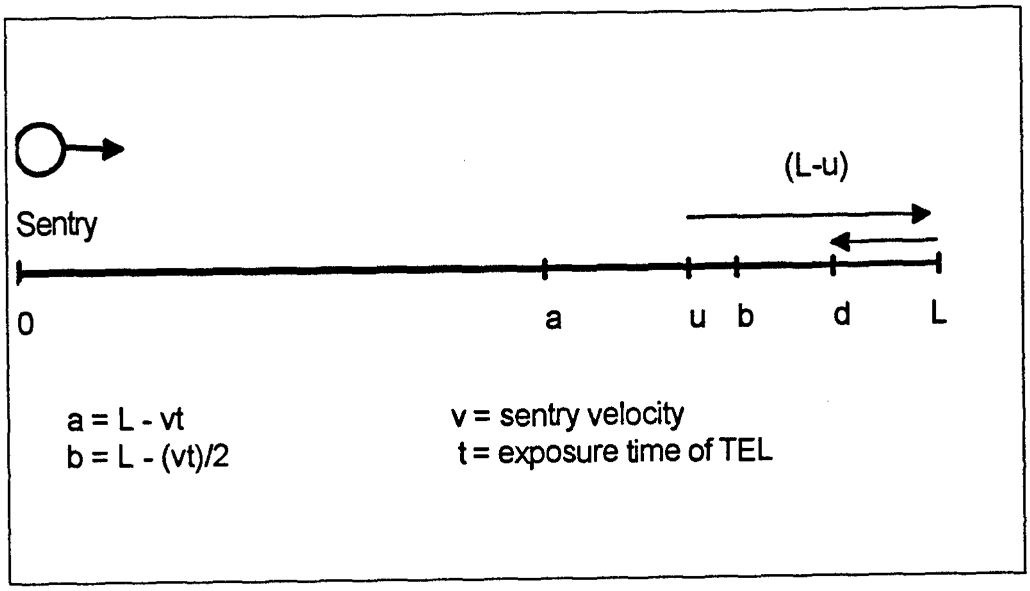

Figure 7: Sentry starting position u such that a < u < b

Lastly, if sentry starting position is as depicted in Figure 8:

$$P^{(1)}(F.O.|u) = P(2L - vt - u \leq T \leq u)$$

$$= (u - (2L - vt - u))/L \quad \text{for } b < u < L,$$

$$P^{(1)}(F.O.|z) = 2z - 2 + x \quad \text{for } 1\text{-}x/2 < z < 1. \qquad (3)$$

Integrating over z removes the condition, leaving the probability of one fly over.

$$P^{(1)}(x) = \int_0^{1-x} x\,dz + \int_{1-x}^{1-x/2} (1-2z-x)\,dz + \int_{1-x/2}^{1} (2z-2+x)\,dz, \text{ or}$$

$$P^{(1)}(x) = x - x^2/2. \qquad 0 \leq x \leq 2 \qquad (4)$$

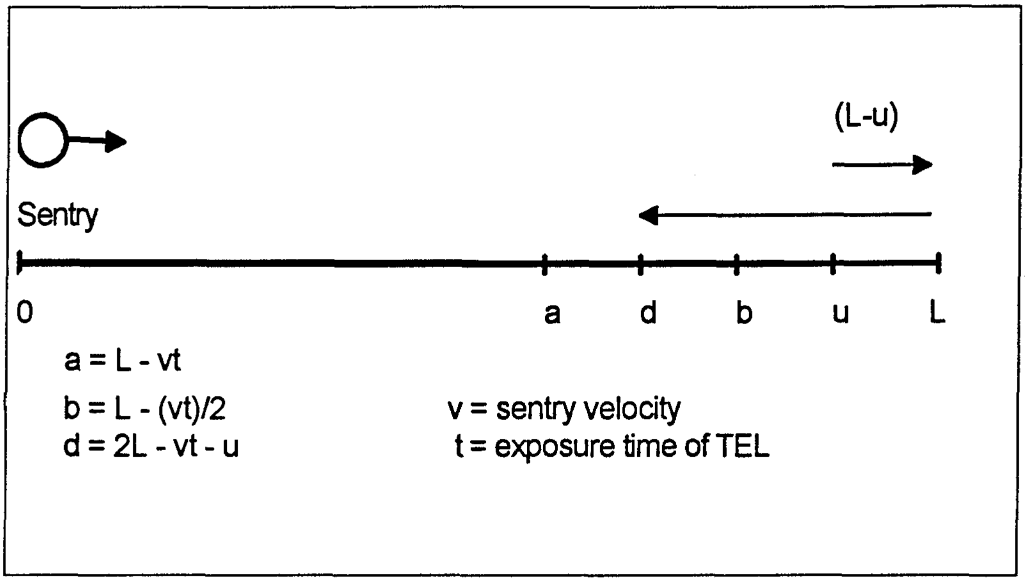

Figure 8: Sentry starting position u such that $b < u < L$

Probability of the sentry flying over the TEL once ($P^{(1)}$) is shown graphically by Figure 9.

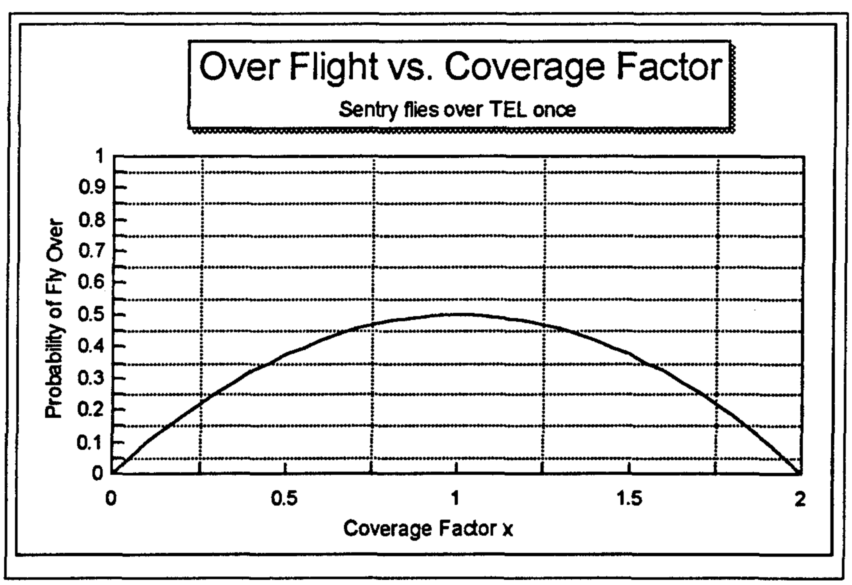

Figure 9: Probability of single over flight $P^{(1)}$ versus coverage factor

2. Probability the sentry flies over the target twice

Derivation of the probability the sentry flies over the target twice is similar and complementary to the previous derivation of probability of one fly over. $P^{(2)}(F.O.|u)$ denotes probability of twice flying over the target given the sentry starting position is at u. Referring again to figures 6, 7 and 8 yields the following equations:

$$P^{(2)}(F.O.|u) = P(u \leq T \leq L - (u + vt))$$

$$= 0 \quad \text{for } 0 < u < a, \qquad (5)$$

since in this case, from Figure 6, no portion of road segment L is covered twice.

Next,

$$P^{(2)}(F.O.|u) = P(2L - vt - u \leq T \leq L)$$

$$= (L - (2L - vt - u))/L \quad \text{for } a < u < b, \text{ or}$$

$$P^{(2)}(F.O.|z) = z + x - 1 \quad \text{for } 1\text{-}x < z < 1\text{-}x/2. \qquad (6)$$

Lastly if, as in Figure 8, sentry starting position u is such that $b < u < L$,

$$P^{(2)}(F.O.|u) = P(u \leq T \leq L)$$

$$= (L - u)/L \quad \text{for } b < u < L, \text{ so}$$

$$P^{(2)}(F.O.|z) = 1 - z \quad \text{for } 1\text{-}x/2 < z < 1. \qquad (7)$$

Again, integrating over z removes the condition, leaving the probability of two fly overs:

$$P^{(2)}(x) = \int_0^{1-x} 0dz + \int_{1-x}^{1-x/2} (z+x-1)dz + \int_{1-x/2}^{1} (1-z)d\ ,$$

$$P^{(2)}(x) = x^2/4, \qquad 0 \leq x \leq 2. \qquad (8)$$

The probability the sentry flies over the target at least once, P(x), is the sum of equations (4) and (8) and is thus:

$$P(x) = x - x^2/4, \qquad 0 \leq x \leq 2. \qquad (9)$$

The probability of no fly over taking place is the difference between 1.0 and equation (8) and is therefore,

$$P^{(0)}(x) = 1 - x + x^2/4, \qquad 0 \leq x \leq 2. \qquad (10)$$

The probability the sentry flies over the TEL twice is depicted in Figure 10.

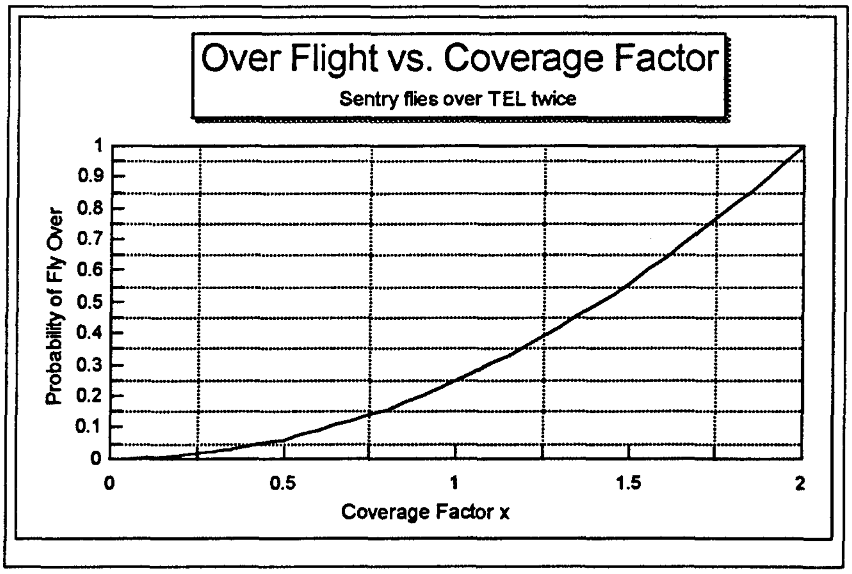

Figure 10: Probability sentry flies over TEL twice, $P^{(2)}$, versus coverage factor

B. MEASURE OF EFFECTIVENESS AND SENSITIVITY ANALYSIS FOR THE SENTRY SEARCH MODEL

The probability that the sentry flies over the TEL at least once, P(x), provides a good measure of effectiveness for the model. From Figure 11, the probability of at least one fly over is approximately 0.60 when 75% of the search track is covered during TEL exposure and approaches 1.0 as coverage factor approaches 2.0. From Figures 9, 10 and 11, when coverage factor equals 1.0, P(x) = 0.75; sentry flies over the TEL once with probability 0.5, twice with probability 0.25 and not at all with probability 0.25.

At coverage factors below 1.0, P(x) and coverage factor are approximately linearly related. For instance, increasing coverage factor from 0.75 to 1.0 brings a 25% improvement in P(x) from 0.60 to 0.75. As coverage factor increases beyond 1.0 however, improvements in P(x) require greater than proportionate increases in coverage factor. The next 13.33% increase in P(x), from 0.75 to 0.85, requires a 25% increase in coverage from 1.0 to 1.25.

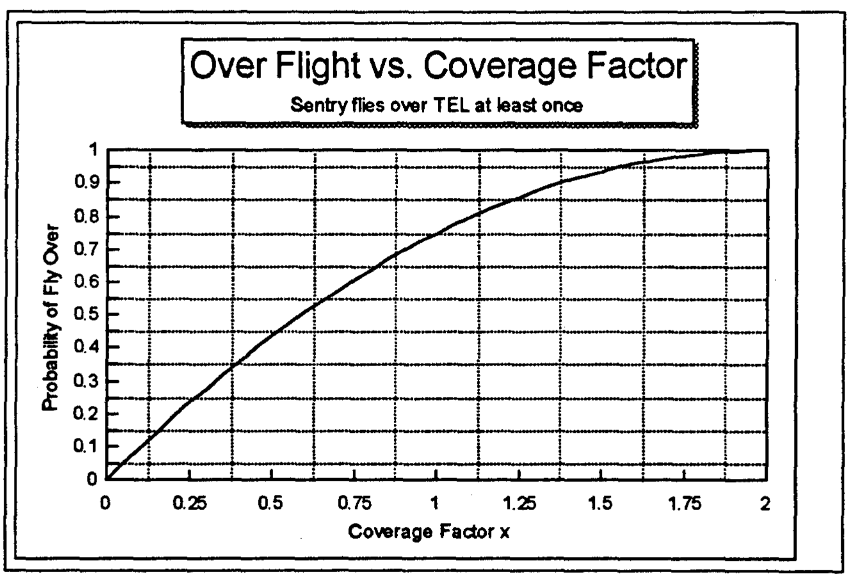

Figure 11: Probability sentry flies over TEL at least once Vs coverage factor

C. SUMMARY

The probability that the sentry flies over the TEL is directly related to coverage factor, i.e., the fraction of the road length that can be flown over by the UAV during a target exposure time. Coverage factor is therefore influenced by length of road segment L, TEL exposure time t and search velocity v. For tactical UAVs, search velocity is normally in the range of 100 kts. Length of road segment assigned to the sentry is influenced by anticipated TEL exposure time. TEL exposure time is therefore the determining variable in estimating coverage factors. Forecasting TEL exposure time requires accurate intelligence of enemy capabilities. The level of intelligence required is only attainable through extensive monitoring prior to hostilities. This necessity further supports the establishment of a joint anti-TBM infrastructure.

With probability of the sentry flying over the TEL calculated, the next step is to determine the probability that sensors aboard the sentry actually "see" the TEL. For the Sentry Search model, flying over the TEL is analogous to having the target within sensor field of view. The next chapter considers the probability of gaining visual or infrared detection given a fly over has occurred.

V. VISUAL AND INFRARED DETECTION

Whether the search is conducted by a manned aircraft or a UAV, the target must be seen (detected) and recognized as a target before anything can be done to neutralize it.

Koopman defined detection as, "That event constituted by the observer's becoming aware of the presence and possibly of the position and even in some cases the motion of the target.... " [Ref 14, p.13] Hartman, expounding on Koopman's definition says, "Detection means that an observer decides that an object in his field of view has military interest." Hartman further defines recognition as allowing discrimination among finer classes of targets. [Ref 15, p. 4-2]

For tactical UAVs conducting the Sentry Search tactic, the primary search sensors are onboard television (visual) and infrared cameras that relay information back to the ground control site (GCS).

This chapter discusses factors influencing detection and recognition by means of visual and infrared sensors. It is demonstrated that UAVs may have a significant advantage over manned tactical aircraft in detecting and recognizing targets of interest, especially when an enemy anti-air threat exists.

A. VISUAL SEARCH

The term visual search refers to use of the human eye to detect targets viewed directly or with the aid of a camera. Much work has been done to determine the full capabilities of human vision. Vision under normal daytime lighting conditions centers on the foveal region of the eye, an area approximately 1.5 mm in diameter on the retina. For distant objects, vision takes place along an axis of approximately five degrees about the center of the fovea [Ref 16, p. 24]. This small area of visual acuity means the eye must scan about to "see" an entire area. Jones describes an experiment that determined that during the course of a second, the axis of vision changes about eight degrees as the eye scans the area being searched. While the foveal axis is shifting, vision does not take place. [Ref 16, pp. 23-29] Figure 12 summarizes human visual performance based on results of this experiment. Under this model, vision is not continuous, consisting instead of "glimpses" or fixations. Glimpses occur at a rate of approximately three per second with each glimpse lasting approximately 1/4 of a second [Ref 14, p. 47].

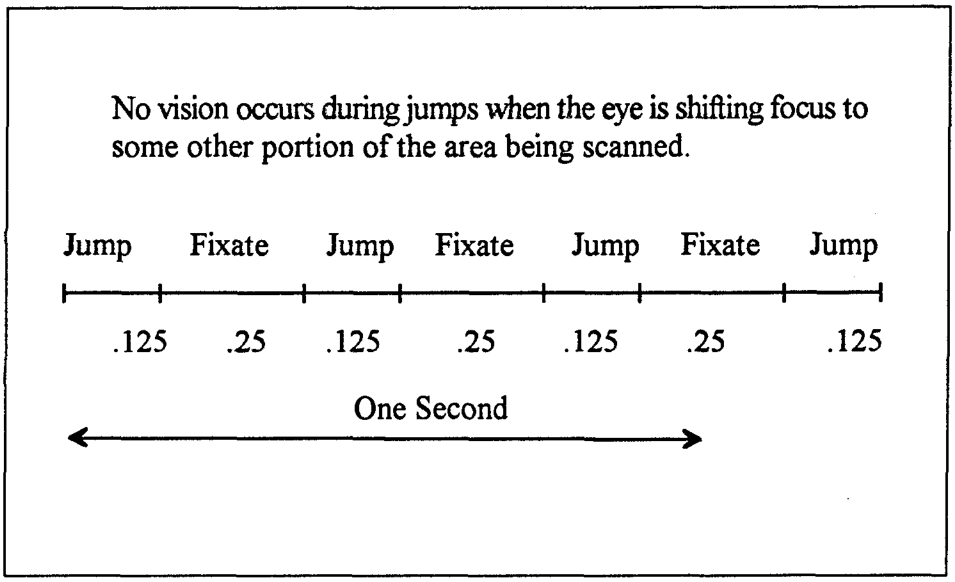

Figure 12: Visual performance during a one second interval (After Ref 16, p. 29)

The probability of visual detection depends on several factors.

- Size of the area glimpsed by the search sensor.

Figure 13 depicts how search altitude, sensor depression angle and sensor field of view (FOV) impact the size of the area glimpsed.

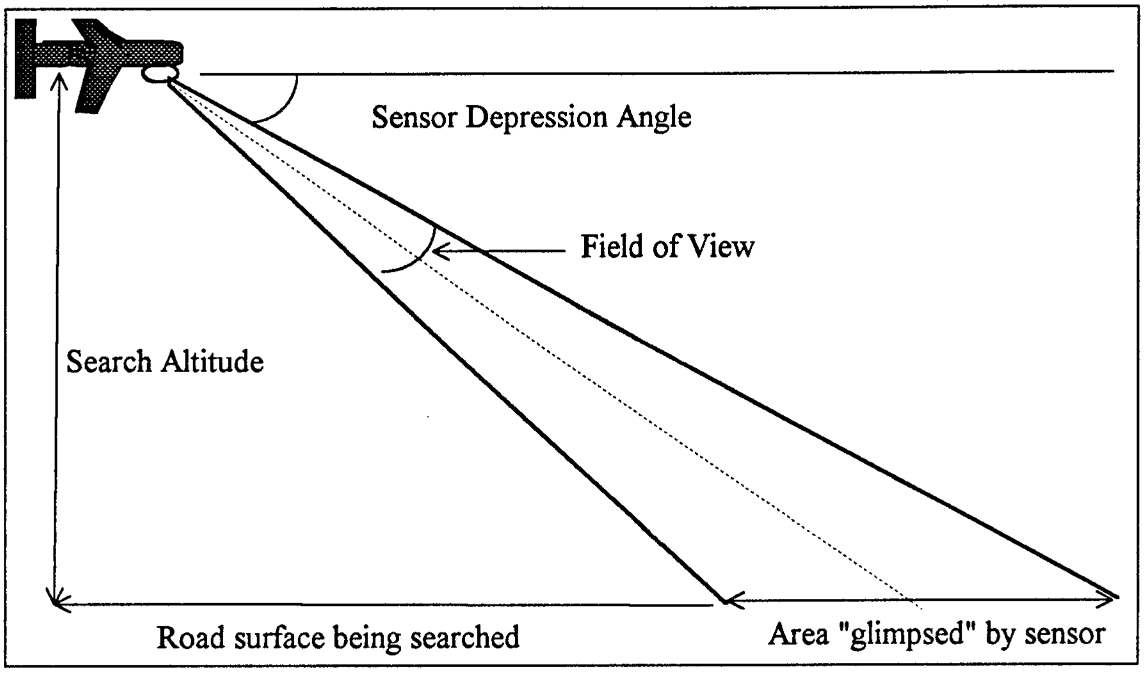

Figure 13: Example of forward looking sensor field of view

Table 1 shows how the area within search sensor FOV changes with altitude using the MKD-200 camera of the PIONEER UAV with wide angle FOV (17^{O} x 23^{O}).

Altitude (AGL) in ft	Swath Width (ft) 17 x 23 FOV
1,000	407
2,000	814
3,000	1,221
4,000	1,628
5,000	2,035
6,000	2,442
7,000	2,849
8,000	3,255
9,000	3,663
10,000	4,070

Table 1. Visual swath widths for MKD-200 camera (After Ref 11)

Figure 14 expounds upon the data of Table 1, showing how search altitude and sensor depression angle affect area glimpsed using the MKD-200 camera. Lines in the Figure depict the length of the area glimpsed for the three selectable FOV settings available on the MKD-200. Search altitudes between 500 and 2500 ft were chosen as an example of typical glimpse areas to be expected from UAVs conducting the Sentry Search tactic.

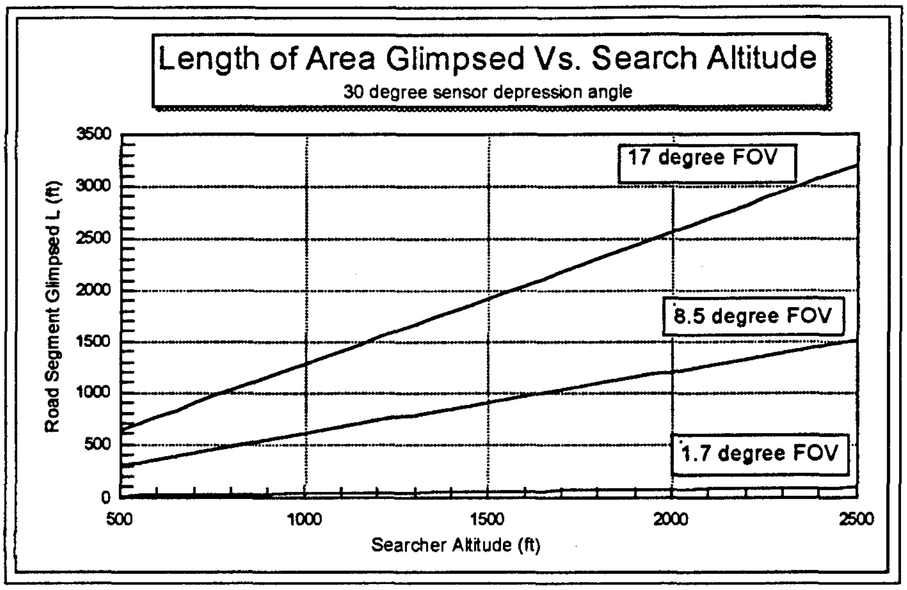

Figure 14: Length of area "glimpsed" versus search altitude and sensor FOV for the MKD-200 camera used aboard the PIONEER UAV with a 30^0 depression angle

- Number of glimpse opportunities as target passes through sensor FOV.

Once size of the area glimpsed is known, the number of glimpses possible of that area is determined. The number of glimpses possible (n) depends upon the length of area glimpsed, L, and searcher velocity v. Number of glimpses possible is found by dividing L (ft) by v (ft/sec), and multiplying by 3 glimpses per second.

$$n = (3L)/v \qquad (11)$$

- Single glimpse probability of detection and recognition.

The single glimpse probability of detection, g, is a function of several factors: target to background contrast, size of the target, relative motion, lighting ect.... [Ref 17]

- Search sensor depression angle and resolution.

At any depression angle where the search area is not viewed straight on, objects on the far end of the area glimpsed are at the lowest resolution. Optimum search altitude and depression angle are therefore dictated by sensor resolution capabilities. Operator confusion arises from the sense that the entire area displayed is being searched when in fact only some portion of the area on the display is under the required resolution. This is not a problem for the Sentry Search model since eventually the entire road segment passes through the high resolution portion of the display. Problems arise however when using search patterns involving non-fixed sensor scanning. Fahlstrom and Gleason recommend the addition of a "detection horizon" line to sensor screens. [Ref 18, p. 43] The detection horizon is the point beyond which objects are not sufficiently resolved for classification or identification.

1. The Discrete Glimpse Model of Visual Detection

The discrete glimpse model begins by assuming each glimpse consists of an independent Bernoulli trial. Define g_i as the probability of success (detection) on the ith glimpse. Considering all glimpse probabilities, $g_1 = g_2 = \ldots = g$, where g is some value between zero and one, detection probabilities can be calculated.

Let N be the number of glimpses required to detect the target. The probability of detecting the target on the nth glimpse is:

$$P(N = n) = ,$$

$$= g(1-g)^{n-1} . \qquad (12)$$

Equation (12) follows a geometric distribution. The mean and variance of the number of glimpses required for detection are:

$$E[N] = 1/g ,$$

$$Var[N] = (1-g)/g^2 .$$

Detecting the target within the first n glimpses will occur with probability

$$P(N \leq n) = ,$$

$$= 1 - (1 - g)^n ,$$

$$= 1 - (1 - g)^{3L/V}. \qquad (13)$$

Figure 15 shows the detection probability as a function of velocity v for various values of g and the stated L. Recall that the area glimpsed, L, is a linear function of sensor altitude, FOV and depression angle. The length of area glimpsed, L, is held constant. Six values of g, the single glimpse probability of detection, were chosen, ranging from 0.01 to 0.10. Even with a seemingly low single glimpse probability of detection i.e. g = 0.04, at velocities in the range of 100 knots (common to UAVs), the probability of visually detecting a target is approximately 60 percent. To interpret the value g, recall that E[N] = 1/g, so if g = 0.04, E[N] = 25 glimpses. Thus the expected time to notice that a target is present for this g is approximately 8 seconds.

Figure 16 demonstrates the result of changing FOV from 17^0 to 8.5^0 holding sensor depression angle constant. For this 50% reduction in FOV, L decreases by 47% from 1281.5 to 604.5 ft. The probability of detection at g = 0.04 decreases to approximately 37 percent.

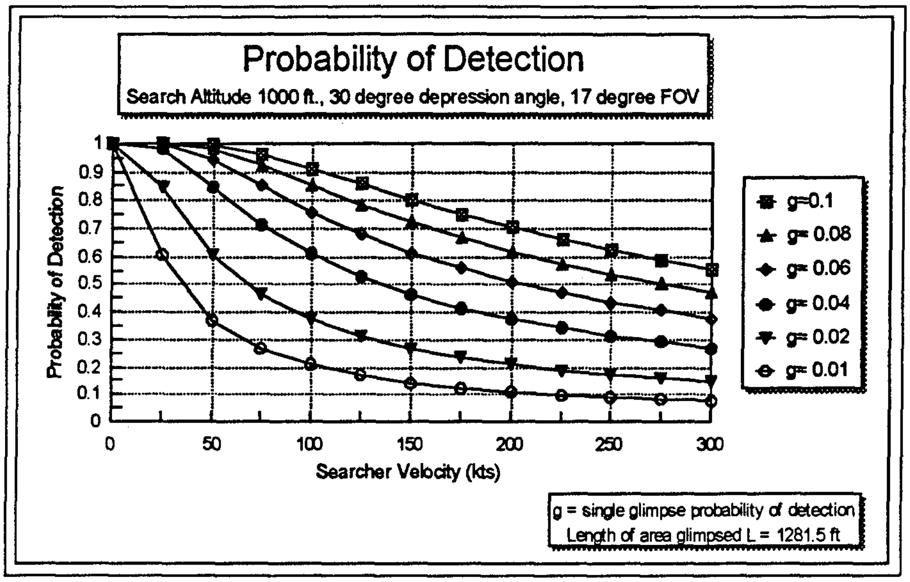

Figure 15: Probability of detection with 17^0 FOV

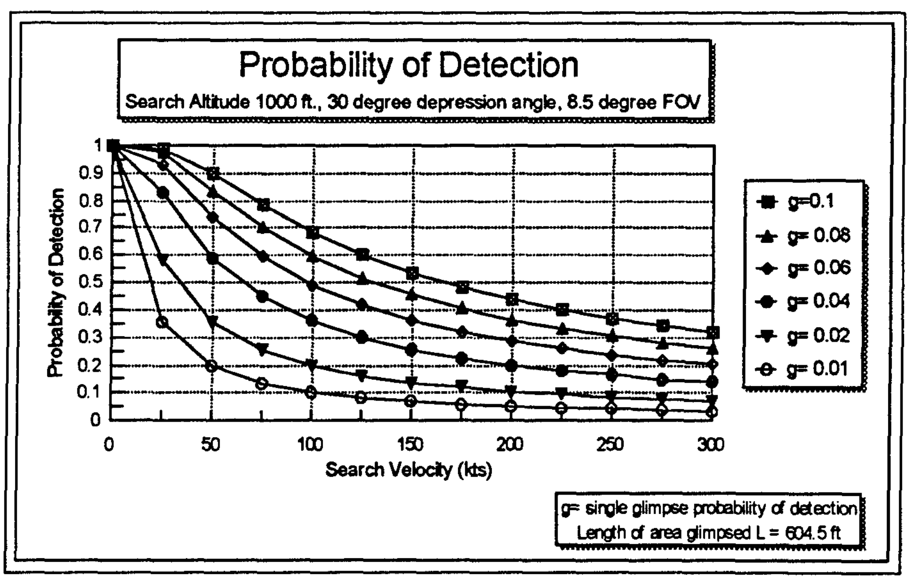

Figure 16: Probability of detection with 8.5^0 FOV

2. The Continuous Looking Model of Visual Detection

Under the assumptions of the Sentry Search model, TV and or infrared sensors aboard the UAV do not scan, but merely "look" ahead of the UAV at some depression angle as it flies along above the road. The UAV operator concentrates the search along the road, so very little visual scanning is required. A continuous looking model may adequately represent such situations where the operator's gaze is fixed.

Hartman discusses a continuous looking model based on a detection rate function D(t). For simplicity, he assumes D(t) = D, a constant, i.e., one detection per hour. The probability of detecting a target in a short time interval is proportional to the length, Δt, of the interval:

$$P(\text{detect in } [t, t + \Delta t]) = D(t)\Delta t \qquad (14)$$

Time periods are assumed to be independent under both the discrete and continuous equations. Over a long time period T, where $T = N\Delta t$, the independent Bernoulli trial assumptions of the glimpse model can be used:

$$P(\text{detect in time interval } T) = 1 - P(\text{fail to detect N times})$$

$$= 1 - (1 - D\Delta t)^N$$

$$= 1 - (1 - D\,(T/N))^N .$$

In the limit as N approaches infinity, the equation becomes equivalent to:

$$P(\text{detect in time interval } T) = 1 - e^{-DT}. \qquad (15)$$

Equation (15) represents the cumulative distribution function (CDF) of the exponential distribution. The exponential distribution is the continuous analog of the discrete geometric distribution, and according to Hartman, is the one most frequently used to model time required to detect a target. [Ref 15]

Pollock describes a detection rate function proportional to the angle subtended by the target as measured from the observer. As depicted in Figure 17, his example involves a target of area A observed from a height h and a slant range of r from the observer to the target. If the size of the target is small relative to h and r, the angle subtended is approximated by $Ah/(h^2 + r^2)^{3/2}$.

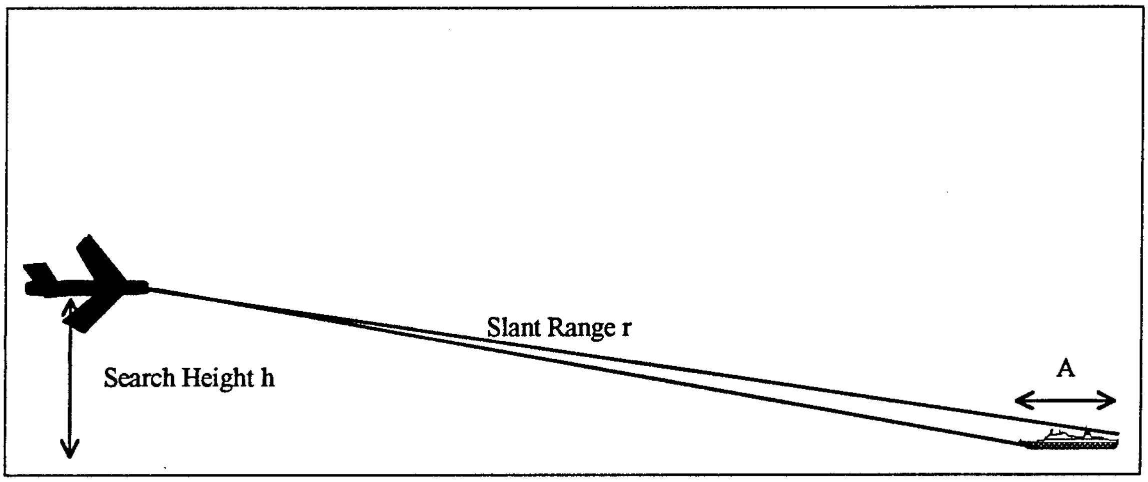

Figure 17: Relationship of h, r and A in Pollock detection rate model

The single glimpse detection function resulting from this relationship of h and r is then:

$$g(h) = ch/(h^2 + r^2)^{3/2}, \qquad (16)$$

where c is a constant that includes A. [Ref 19, p. 256]

For models where the search is conducted from nearly overhead of the target, r and h are approximately equal. Under this assumption, equation 16 becomes:

$$g(h) = c'/h^2 , \qquad (17)$$

where $c' = c/\sqrt{8}$.

Equation 17 is very useful when comparing the probability of detection from different altitudes. Such a comparison of the probabilities of detection for tactical UAVs versus manned tactical aircraft operating at different altitudes is the subject of the following section.

3. Comparison of TAC Air and UAV Probabilities of Detection

Manned aircraft conducting search missions over hostile territory typically fly much higher and faster than UAVs to avoid enemy air defenses. We now demonstrate that UAVs have a higher probability of detection by virtue of their more thorough search at lower altitudes and velocities.

Recall that the area glimpsed, L, is a linear function of search altitude, sensor FOV and sensor depression angle. Holding sensor depression angle and FOV constant, a manned TAC Air platform, flying at a higher altitude glimpses a proportionally larger area than a lower flying UAV. Merely glimpsing a larger area however does not improve the probability of detection because, as discussed earlier, the single glimpse probability of detection, g, is related to the inverse of the square of search altitude.

The number of glimpses possible, n, is a function of both area glimpsed, L, and search velocity v. Since L is linearly related to search altitude, if increases in altitude and velocity are of equal magnitude, for example altitude and velocity are both quadrupled, the number of glimpses remains constant.

A numerical example is used to clarify the relationships of altitude and velocity to the probability of detection. Assume a UAV searches from an altitude of 5,000 ft at a velocity of 100 kts and a TAC Air platform searches from 20,000 ft at 400 kts. Holding depression angle constant for the two platforms, and assuming the UAV and TAC Air sensors each have a visual FOV approximately equal to that of the MKD-200 camera, from Table 1 their respective areas glimpsed are 2035 ft and 8140 ft. Because altitude and velocity of the TAC Air asset are both four times those of the UAV, as mentioned, the number of glimpses is the same for both platforms, and for this example n equals 37.

From Equation 17, the TAC Air asset, searching from four times the altitude of the UAV, has a single glimpse probability of detection equal to 1/16th that of the UAV.

Using equation 13, the probability of not detecting the target, denoted $P_{ND}(N > n) = (1 - g)^n$, provides a basis to compare detection probabilities for TAC Air assets and UAVs. We begin by multiplying g in the equation by 16.0 for the case of the UAV because as determined, relative to the TAC Air platform, the UAV has a single glimpse probability of detection 16 times larger. The probability of not detecting the target using the UAV is therefore $P_{ND}(N > n) = (1 - 16g)^n$, versus $P_{ND}(N > n) = (1 - g)^n$ for the TAC Air platform.

Plotting the ratio of non-detections by TAC Air assets versus non-detections by UAVs against varying values of g is depicted in Figure 20. From Figure 18 it is apparent that the UAV by virtue of its ability to search from a lower altitude and velocity is much less likely to overlook the target. For instance, with a single glimpse probability of detection of 0.024, the TAC Air asset, flying four times higher and faster to avoid enemy air defense, is 10 times as likely as the UAV to overlook the target on any given glimpse. With g 0.028 however, the TAC Air asset is 100 times more likely to overlook the target on a given glimpse.

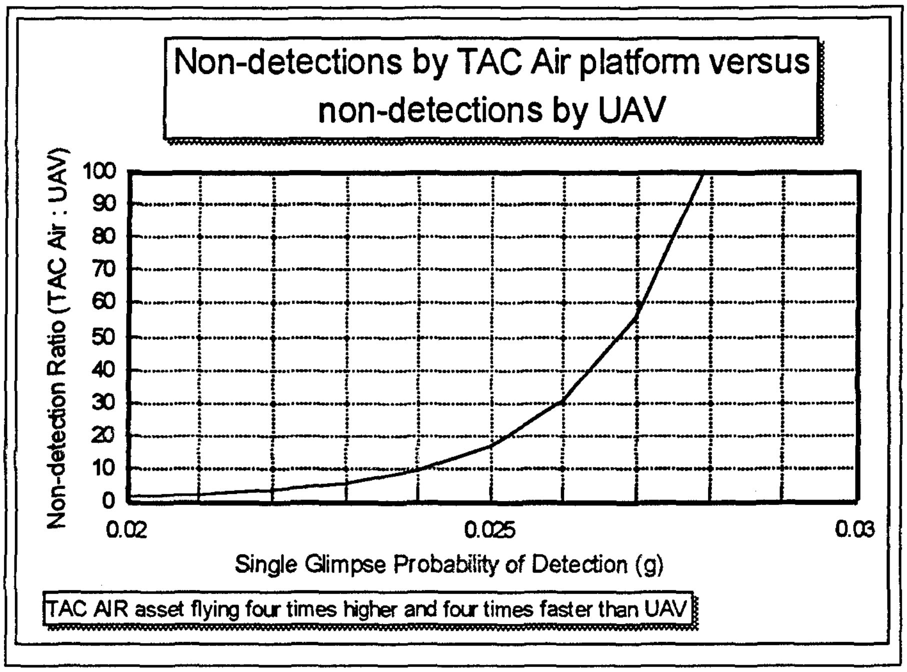

Figure 18: Ratio of non-detections for TAC Air versus UAV platforms

B. INFRARED TARGET DETECTION

Experience has shown that TEL activity often takes place at night. For this reason, infrared detection plays an important role in the search for TELs whether by piloted aircraft or UAVs.

Table 2 displays the swath width of the MKD-400 Infrared system aboard the PIONEER UAV under various combinations of search altitude and FOV.

Altitude (AGL) in feet	IR Swath (ft) 2 x 3 degree FOV	IR Swath (ft) 7.2x10.7 FOV	IR Swath (ft) 16.7x2 FOV
1,000	52	187	443
2,000	105	374	886
3,000	157	561	1,329
4,000	210	748	1,772
5,000	262	935	2,215
6,000	314	1,122	2,658
7,000	367	1,309	3,101
8,000	419	1,498	3,544
9,000	471	1,683	2,990
10,000	524	1,870	4,430

Table 2. Swath widths for MKD-400 IR system (from Ref 11)

Clearly, swath widths for the infrared system used aboard PIONEER are smaller than those of the optical camera. Infrared systems are effective day and night. Even with the smaller swath width, infrared is a powerful tool for target detection due to the increased target to background contrast.

C. OTHER DETECTION METHODS

Many new "smart" sensors have been developed and are discussed extensively in the literature, particularly in publications of the Society of Photo-Optical Instrumentation Engineering (SPIE).

Late generation automatic sensors exploit target signatures in the infrared as well as optical portions of the light spectrum. Automatic optical sensors typically rely on pattern recognition algorithms. As the sensor scans the search area, it attempts to match what it is "seeing" with geometric patterns fitting the intended target profile. While automatic infrared detections are much easier, without precise thermal imaging profiles, it remains difficult for the sensor to distinguish a TEL from a semi-tractor trailer or any other large "hot" object.

One new sensor showing promise is wavelength tunable video. A tunable filter provides multispectral imaging capability useful in scanning for known spectral signatures and spectral shifts. For instance, the engine alternator of a TEL may radiate on a specific wavelength. Wavelength tunable sensors can scan for that specific wavelength. Vegetation cut and used to camouflage a vehicle radiates at a different frequency than the vehicle attempting to hide behind it and also from the surrounding living vegetation. Wavelength tunable video sees right through such camouflage, making the vehicle stand out. [Ref 20, pp. 10-12]

D. SUMMARY

Visual detection depends on several factors, many of which are controllable by the searcher.

Even with very small single glimpse probabilities of detection, the discrete glimpse model predicts fairly high detection probabilities for tactical UAVs employing the Sentry Search tactic.

Under the continuous looking model, detections follow an exponential distribution assuming some constant detection rate. Detection rates may be related to the inverse of the square of search altitude.

UAVs are less vulnerable to enemy air defenses and may search from altitudes and velocities that maximize the probability of detecting the target. The ability to fly lower and slower over hostile territory gives UAVs a distinct advantage in probability of detection over manned aircraft.

Whether the search for TELs is conducted using manned aircraft or UAVs, ultimately, a human operator must detect, recognize and positively identify the target before it can be neutralized. Both infrared and television cameras are suitable for this task. New generations of smarter, artificially intelligent sensors show great promise for use aboard UAVs and may be particularly suited to autonomous UAVs operating without continuous human assistance and merely relaying contact information to friendly forces.

VI. CONCLUSIONS AND RECOMMENDATIONS

Tactical ballistic missiles pose an ominous threat to regional and world wide security. A joint anti-TBM infrastructure is as important to post-Cold War American security as the integrated ASW infrastructure has been throughout the last 50 years.

Western technological sophistication aids the task of global peace-time monitoring of TBM forces of potential adversaries. Innovations and improvements in sensor capability and endurance of UAV platforms and unattended ground sensors (UGSs) enables Theater CINCs and JFCs to closely monitor status of enemy TBM forces in the period preceding hostilities. Once hostilities erupt, UAV and UGS assets aid in rapidly pinpointing and destroying mobile TELs and the enemy TBM logistics infrastructure.

UAVs can provide a variety of services within the infrastructure: localization and identification of TELs, precision targeting and real time BDA. Low cost, safety, endurance and survivability of UAVs make them ideal platforms for search and targeting missions deep within enemy territory, where most TBM facilities and TELs are found.

Search for TELs logically begins along existing enemy road networks. The Sentry Search model considers the case of TELs appearing somewhere along a road segment. The TEL may be transiting through the area or have just emerged from a shelter to fire a missile. Although the model presented considers only the case of a stationary TEL, it provides an approximate probability of detection for the case of a slow moving TEL.

Merely having a TEL within sensor range does not guarantee detection. Although automatic detection algorithms show great promise, for the near future a human operator is still required to visually confirm target identity.

Sensor resolution and the rate at which images of the search area are presented to the observer are important factors in determining whether an operator visually detects and accurately identifies the target. The Sentry Search model, incorporating the idea of a sensor fixed at some depression angle and FOV, simplifies visual detection probability by avoiding the necessity of scanning the search area. The target passes from the top of the sensor FOV to the bottom. The operator has numerous opportunities to view the target depending on search platform velocity. The model presented demonstrates reasonable probabilities of detection given the target is within sensor FOV. Because of the influence of search altitude on the single glimpse probability of detection, UAVs, by flying lower and slower, offer an advantage over manned aircraft when searching over hostile territory.

Follow-on topics include expanding the Sentry Search model to include the full range of possible TEL to searcher relative motion. Another possibility is the use of linear programming to determine optimal coverage factors, search altitudes, velocities and sensor suite configurations. Development of a network interdiction model involving UAVs searching critical arcs and laying and monitoring UGS barriers along an enemy road network, are other possible areas of study.

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