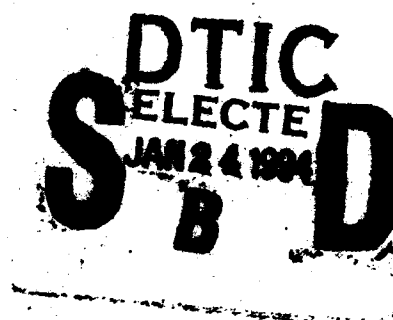


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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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THESIS

**AN ANALYSIS OF MULTIPLE SENSOR SYSTEM PAYLOADS
FOR UNMANNED AERIAL VEHICLES**

by

John F. Keane

September 1993

Thesis Advisor:
Second Reader:

Michael G. Sovereign
Richard E. Rosenthal

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UNMANNED AERIAL VEHICLES**

by

John F. Keane

**Lieutenant Commander, United States Navy
B.S., Virginia Military Institute, 1980**

**Submitted in partial fulfillment
of the requirements for the degree of**

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL

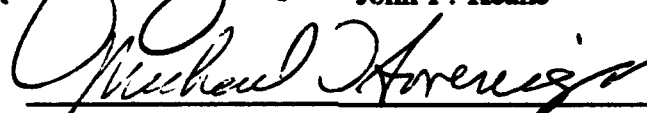
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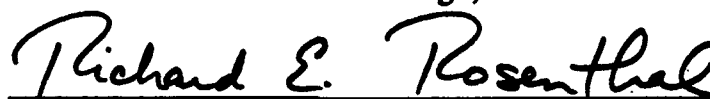


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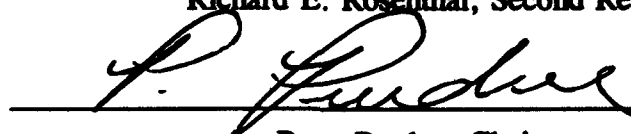
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ABSTRACT

Unmanned Aerial Vehicles (UAVs) presently under consideration by the Program Executive Officer for Cruise Missile Projects and Unmanned Aerial Vehicles (PEOCMPUAV) will be equipped solely with electro-optical (EO) sensors. This thesis provides a comparative analysis of the mission effectiveness between UAVs equipped with EO sensors and those equipped with a multiple sensor system payload.

A historical review of UAV development and employment is provided so that the reader may gain some insight into past UAV shortcomings in the hopes that they might be prevented in future systems. A typical Reconnaissance, Surveillance and Target Acquisition (RSTA) mission scenario is defined and a comparison made between UAVs equipped with EO sensors and those equipped with multiple sensor system payloads. The measure of effectiveness used for this comparison is the time required by the UAV to search 100 percent of an assigned area. The physical and operating characteristics of available sensor systems are discussed in detail.

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EXECUTIVE SUMMARY

Unmanned Aerial Vehicles (UAVs) presently under consideration by the Program Executive Office for Cruise Missile Projects and Unmanned Aerial Vehicles (PEOCMPUAV) will be equipped solely with electro-optical (EO) sensors. They will be required to perform a variety of missions, among them Reconnaissance, Surveillance and Target Acquisition (RSTA). These UAVs will be incapable of providing timely area coverage when tasked to perform such missions in large areas of uncertainty (AOUs). To address that deficiency, this thesis provides a comparative analysis of the mission effectiveness between UAVs equipped with EO sensors and those equipped with a multiple sensor system payload.

In future maritime engagements, organic manned surveillance aircraft may not always be available to the Strike Warfare Commander (STWC) or Anti-Surface Warfare Commander (ASUWC), as indicated by the recent deployment of the USS Theodore Roosevelt without S-3Bs and their Inverse Synthetic Aperture Radar (ISAR). RSTA missions provide a Surface Action Group (SAG) commander with valuable information concerning enemy surface activity within his area of responsibility. They allow him to keep abreast of changes in an enemy's force structure and bring his own forces to bear on threat sectors of immediate concern to him. Such missions may be tasked against fixed or mobile targets regardless of the availability or accuracy of cuing data.

A historical review of UAV development and employment is provided so that the reader may gain some insight into past UAV shortcomings in the hopes that they might be prevented in future systems. A typical RSTA mission scenario is defined and a comparison is made between UAVs equipped with EO sensors and those equipped with multiple sensor system payloads. The measure of effectiveness used for this comparison is the time required by the UAV to search 100 percent of an assigned AOU. A UAV equipped with multiple sensors such as moving target indicator (MTI) radars, synthetic aperture radars (SAR), electronic support measures (ESM) and infrared (IR) can cover an entire assigned search area in a fraction of the time required by a UAV equipped with a single optical sensor. This leaves more time available for target identification and classification, and frees the UAV to perform secondary missions if time and fuel permit. A UAV equipped with such a sensor suite is more capable of providing the SAG commander with timely area coverage, valuable situational awareness and a broader extension of the SAG's weapons and sensor systems and, ultimately, it's sphere of influence. The physical and operating characteristics of these sensor systems is discussed in detail.

The thesis presents a mathematical optimization model capable of selecting from those systems previously described. UAVs presently under development are capable of carrying multiple sensor payloads. Because they are smaller in size than manned platforms, UAVs have only a limited amount of space in which to carry these systems. The model discussed in this thesis selects a sensor payload from data link, radar, ESM, and IR systems based on the utility or perceived value of the individual sensor in a

RSTA mission scenario. Sensor systems are selected based upon their weight, volume, power consumption and unit cost. Additionally, the model considers the sensor's target identification capability and false alarm rate when determining the optimum payload. Values for sensor system utility, identification capability and false alarm rate were derived using the method of the Analytical Hierarchy Process (AHP) and Expert Choice software. They were verified using the method of paired comparisons.

The optimum sensor system payloads are selected and the best alternatives to EO sensors for performing RSTA missions in a hostile environment are recommended under a range of budgets. The model was run for the next generation of Short Range UAV (SR-UAV) having a 15 ft³ payload cavity, a 1000 W electrical generator and capable of carrying a payload weighing 200 pounds.

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I. BACKGROUND

As a world power, the United States will continue to maintain global interests and must be able to influence political events through credible military presence and power projection capabilities. In the face of steadily decreasing overseas basing and a shrinking military budget, the United States must maintain the ability, in concert with allied forces, to execute timely sustained combat operations across the spectrum of conflict. These capabilities will be instrumental in maintaining regional stability in the transition to a new post cold war world order.

In future conflicts, littoral power projection will be the U.S. military's primary warfighting priority. The ability to affect events in a green water scenario will be the key to successful regional stability operations.

War scenarios presently under consideration by the Joint Chiefs of Staff include both low- and high-intensity conflicts in littoral regions. U.S. military forces would most likely be employed in these scenarios to conduct both pre- and post-strike aerial reconnaissance in support of strikes by joint coalition forces over hostile territory.

Aerial reconnaissance is essential for effective strike planning. However, reconnaissance missions expose aerial vehicles to threats during intense ingress and egress near the target area. A relatively low-altitude fly-over is often required to obtain the detailed tactical imagery needed to identify targets or assess battle damage.

Therefore, in such instances where timely critical intelligence data is required, Unmanned Aerial Vehicles (UAVs) can provide support with no risk to human life.

A. PURPOSE OF THE THESIS

UAVs presently under consideration by the Program Executive Office for Cruise Missile Projects and Unmanned Aerial Vehicles (PEOCMPUAV) will be equipped solely with electro-optical (EO) sensors. They will be required to perform a variety of missions, among them Reconnaissance, Surveillance and Target Acquisition (RSTA). These UAVs will be incapable of providing timely area coverage when tasked to perform such missions in large areas of uncertainty (AOUs). To correct that deficiency, this thesis provides a comparative analysis of the mission effectiveness between UAVs equipped with EO sensors and those equipped with a multiple sensor system payload.

The remainder of Chapter I provides a historical review of UAV development and employment so that the reader may gain some insight into past UAV shortcomings in the hopes that they might be prevented in future systems. Chapter II defines a typical RSTA mission scenario and provides a comparison between UAVs equipped with EO sensors and those equipped with multiple sensor system payloads. The measure of effectiveness used for this comparison is the time required by the UAV to search 100 percent of an assigned AOU. Chapter III describes the physical and operating characteristics of various sensor systems capable of enhancing UAV on-station performance. In Chapter IV the reader is introduced to a mathematical model capable of selecting from those systems previously described in Chapter III. Chapter V

provides a summary of the analysis. Throughout this thesis, the author relies heavily on his experiences as a Patrol Plane Tactical Coordinator onboard Maritime Patrol Aircraft and as a mission planner on both Patrol Wing and Battle Group Staffs.

B. UAV DEVELOPMENT

The use of Unmanned Aerial Vehicles (UAVs) to support the on-scene commander has a long history. In the 1890's, U.S. Army researchers stationed at Madison Barracks in New York experimented with an early aerial reconnaissance system - a camera hung from a large kite [Ref. 1:p. 21].

1. The World Wars

The history of unmanned aircraft started shortly after the first manned flight. The invention of the radio and internal combustion engine led to attempts at combining the two in a wood and paper aircraft controlled by a pilot on the ground. As early as World War I, experimentation began with an unmanned aircraft designed by Charles F. Kettering and Orville Wright. A conventional biplane, known as the Kettering Bug, had a 15 ft wingspan and carried a 180 lb bomb a distance of 40 mi at 55 mph. Conditions on the European battlefields were ideal for such a system: enemy anti-aircraft weapons were heavily concentrated, Germany had air superiority in certain sectors, and there was an extremely static battlefield situation over 470 miles of front. However, the war ended less than a month after the fourth test flight [Ref. 2].

For the most part, research and development between 1917 and 1959 was confined mainly to lethal UAVs, the most famous being Germany's V-1 buzz-bomb and

air-launched *Mistel* which consisted of a scrapped JU-88 bomber packed with explosives carried under an FW-190 fighter. The FW-190 flew the JU-88 over the target area and dropped it like a bomb. Approximately 250 *Mistels* were assembled between 1943 and 1945 for a last ditch *Luftwaffe* offensive.

Throughout World War II, the U.S. Army Air Force under General H.H. Arnold made an attempt to develop a somewhat similar system to the *Mistel*. Old B-17, B-24, and PB4-Y aircraft were stripped of armament and fitted with command receivers and 10 tons of explosive. The aircrew consisted of a pilot and a radio operator. Once airborne, the crew bailed out, and control of the aircraft was taken over by a second aircraft. The system was abandoned after two accidents in three flights. Joseph P. Kennedy, Jr., the brother of President Kennedy, was killed while working on this program [Ref. 3] .

The main drawback of the radio-controlled plane was that it was piloted from a distance by a pilot who could not see the target from the remotely controlled plane's perspective. The controller also had to keep in view both the target and the remotely controlled aircraft, making him vulnerable to enemy anti-aircraft fire. Another kind of pilotless aircraft, the drone, avoids these problems. Drones are simple, pre-programmed aircraft, and once launched, are beyond control. A drone can take-off and autonomously fly a route, changing altitude and direction according to a pre-programmed mission schedule. It cannot, however, identify local bad weather and fly around it.

2. U-2 Reconnaissance Over the USSR

Due to concern over the political fallout that would inevitably develop if a U-2 were to be shot down over Soviet airspace and its pilot captured, the Air Force started modifying a target drone for photographic reconnaissance missions, three and a half years after the United States began overflying Russia. On 1 May 1960, U-2 pilot Francis Gary Powers was shot down over Russia, ending all chances of a Paris summit meeting between President Eisenhower and Premier Khrushchev. President Eisenhower announced the discontinuation of all U-2 flights over the USSR. This was a time when charges of a "missile gap" dominated the press, the nations first spy satellite would not become operational for another 18 months and work on the high flying SR-71 was not yet begun. At the height of the Cold War, the United States had just lost its main source of intelligence behind both the Iron and Bamboo Curtains. Work began in earnest on an unmanned reconnaissance vehicle that could penetrate hostile airspace and bring back accurate photographic intelligence. That work intensified when, two months after Powers was captured in Russia, an American RB-47 bomber converted for electronic eavesdropping missions was shot down over the Barents Sea. After six hours in frigid waters, two of its five crewmen were taken prisoner by the Soviets [Ref. 3]. They were held for seven months until released as a gesture of good will just four days after the inauguration of President Kennedy [Ref. 4:p. 87]. As a result, a production contract for a reconnaissance version of the *Firebee* standard target drone was awarded to Teledyne Ryan in 1962 under a program called *RED WAGON*.

3. The Cuban Missile Crisis

On 27 October 1962 President Kennedy demanded that the Soviet Union dismantle its missile bases and remove its nuclear warheads from Cuba. That same day, Soviet SA-2 missiles in Cuba shot down a U-2 , killing its pilot Maj Rudolph Anderson, Jr. With the Cuban Missile Crisis at its peak, the United States needed photographic confirmation that the Soviets had either removed their missiles or refused to do so. Only two U-2s were immediately available to continue the Cuban overflights. Because only two of the Ryan UAVs had been built and their operational testing not yet completed, RF-8A aircraft were used to image Cuba. The Cuban Missile Crisis demonstrated a need for a concerted UAV development effort by the U.S. military. By the August, 1964 Tonkin Gulf Incident, UAVs were finally ready for wartime service [Ref. 3] .

4. Operations Over Mainland China

In 1964, while deployed to Kadena Air Base, Okinawa, the Strategic Air Command's 100th Strategic Reconnaissance Wing launched Teledyne-Ryan AQM-34 drones from DC-130 Hercules aircraft flying along the coast of Mainland China. These UAVs penetrated Chinese airspace and obtained high-quality photographic imagery of military facilities and troop movements, and were later recovered on the surface of the South China Sea. In 1965, the Chinese held a news conference during which they displayed a downed U.S. pilotless reconnaissance aircraft. This was the first opportunity the American public had to observe a UAV performing missions too dangerous or politically sensitive to be undertaken by manned aircraft. UAV operations

against mainland China were suspended by President Nixon in the early 1970s as a result of improved relations between the two countries [Ref. 1:p. 31].

5. Buffalo Hunter Operations in Southeast Asia

During the next eight years, over 5000 American airmen lost their lives in Southeast Asia because their airplanes were shot down or crashed due to malfunctions. The Strategic Air Command's 100th Strategic Reconnaissance Wing flew more than 3435 unmanned reconnaissance missions over North Vietnam, China and Laos, with an attrition rate of less than ten percent. They performed photo-reconnaissance, damage assessment, electronic eavesdropping, jamming, chaff dispersal, and propaganda leaflet dispersal missions [Ref. 5:p. 162].



Figure 1 Teledyne Ryan's Buffalo Hunter reconnaissance drone [Ref 6:p. 110].

UAVs provided photographic imagery deep within enemy territory without risking their controllers to possible death or capture. They collected targeting data for the ROLLING THUNDER bombing campaign over North Vietnam [Ref. 3]. The

attrition rate faced by U.S. Air Force and Navy aircrews during the war in Southeast Asia led to the first employment of UAVs in a combat environment. Over 2500 Buffalo Hunter photo-reconnaissance missions were flown over North Vietnam with an overall attrition rate of 4%. Photo reconnaissance missions were flown at very low altitudes. Seven such missions were flown for pre-strike planning in support of the rescue mission against the Son Tay prison compound located just 22 miles outside of Hanoi. Two were shot down by North Vietnamese gunners and four suffered mechanical failures [Ref. 6:p. 81].



Figure 2 Buffalo Hunter reconnaissance photo of Son Tay prison 1968 [Ref 6:p. 110].

Additional UAV missions included electronics intelligence (ELINT) collection, radar jamming, and chaff deployment [Ref. 1:p. 31]. Because Buffalo Hunter missions were flown at such low altitudes, they were able to provide excellent photo-reconnaissance in support of SR-71 high-altitude missions and immediate post-strike battle damage assessment. Lack of a night vision capability forced all missions to be flown during daylight hours. Navigation inaccuracies made it difficult to accurately place the UAV where it was needed, with a resulting mission success rate of 40-60%. Additionally, because Buffalo Hunter carried no data link for timely data dissemination, the time needed to process and analyze the intelligence data collected during a mission reduced its value [Ref. 2].

6. Israeli Bekaa Valley Operations

One of the most spectacular operations of modern warfare is the combined arms effort of the Israelis against the Syrians in Lebanon's Bekaa Valley in June 1982. Prior to the operation, Israeli *Mastiff* and *Scout* UAVs overflew an area known to be heavily defended by Syrian-manned Soviet-built SA-6 SAM sites and collected electronic and photographic intelligence later used to develop the Israeli SEAD (Suppression of Enemy Air Defenses) plan. The Syrian air defenses had been dug in for over a year in the Bekaa Valley, so their positions were known to a high degree of accuracy. Additionally, the Syrian lack of a strong emissions control (EMCON) policy allowed the Israelis to record the exact radar frequencies for future jamming, targeting and programming of anti-radiation missiles.

The first phase of the Israeli attack was meant to stimulate the Syrian defenses. *Mastiff* and *Scout* UAVs previously used to verify and locate Syrian radars relayed their information to Boeing 707 and Lockheed E-2C command and control aircraft. Air-launched *Sampson* and ground-launched *Delilah* decoy drones flew attack aircraft profiles, forcing the Syrians to launch most of their available SAMs prior to the actual arrival of the first wave of Israeli aircraft.

During the second phase of the attack, *Mastiff* UAVs were used for gunfire support services against these same SAM sites. Using the ELINT information provided by earlier UAV sorties, F-4 Wild Weasel aircraft launched *Shrike* and *Standard* anti-radiation missiles destroying the SA-6 fire control radar antennas. With the battle damage assessment information provided by on-station UAVs, the Israeli tactical commander was able to order follow-on strikes.

Additionally, the same UAVs employed in the attack against the SAM batteries loitered overhead Syrian airfields and relayed imagery of Syrian Mig-21s and -23s taking off to the airborne tactical commander [Ref. 7]. The entire engagement lasted ten minutes, the final results of which were 17 of the 19 SAM sites destroyed without the loss of a single Israeli attack aircraft.

7. Honduras

Located between Nicaragua and El Salvador, San Lorenzo, Honduras was the site of a forward operations base between November 1984 and April 1986, from which six *Skyeye* UAVs were deployed in anti-guerilla reconnaissance missions. These operations demonstrated the need to cue the system to the approximate position of

potential targets due to the narrow field of view of the infrared sensor. Additionally, because these missions were conducted in a mountainous region, and the UAVs were equipped with line-of-sight data links, the typical flight profile called for higher than normal altitudes over the target area, greatly reducing imagery resolution.

8. Operation Desert Storm

The U.S. Navy, U.S. Marine Corps and U.S. Army operated with the *Pioneer* UAV system during Desert Shield/Desert Storm Operations in 1990-1991. Two battleships were equipped with the *Pioneer* for the Navy in addition to three Marine Corps units and one Army unit. Over 530 sorties and 1680 flight hours were flown in the Southwest Asia Theater. After Desert Storm commenced, nearly 330 sorties and over 1000 flight hours were flown in theater, with at least one *Pioneer* airborne 24 hours per day. Twelve *Pioneer* UAVs were destroyed in the war, two of which are classified as combat losses [Ref. 8:p. 26].

The *Pioneer* UAV System provided day or night reconnaissance, surveillance, targeting, gunfire spotting services, and battle damage assessment through continuous real-time video downlink to a controlling station where system operators monitored and recorded air vehicle imagery with little risk to themselves.

In addition to follow-up battle damage assessment, the battleships provided naval gunfire support against electronic warfare sites, command centers, and anti-aircraft artillery sites. The UAV provided the battleship the ability to accurately fire on targets and spot every round fired, resulting in reduced weapons expenditures. These platforms were then free to engage secondary targets and targets of opportunity.

Initially, the Marine and Army UAV units were tasked to collect intelligence against Iraqi troop concentrations along the Saudi-Iraqi border. Despite the fact that inclement weather prevented their use during the first two days of the ground war, *Pioneer* was used to locate and direct counter-battery fire on Iraqi artillery positions, armored and mechanized units, missile and anti-aircraft emplacements, and support battle damage assessment for artillery batteries and coalition air strikes. Additionally, they were used to map Iraqi minefields and bunkers, allowing the Marines to pass through and around these defenses in darkness, capture key command sites without warning and speed the advance into Kuwait City. Marine and Army units provided target identification and cuing for J-STARS aircraft against potential operational areas that indicated Iraqi activity.

Other innovative approaches in using the *Pioneer* UAV to support the battlefield commander were developed and introduced into the conflict. Marine Corps task force commanders received *Pioneer* video in their command vehicles and directly assessed the Iraqi response to the ground assault during the march on Kuwait City. The Army tasked *Pioneer* reconnaissance missions to pre-determine flight paths for Apache helicopters.

The use of *Pioneer* to collect battlefield management data under adverse conditions and in a potentially high threat environment without placing air or ground personnel in harm's way precluded the potential loss of life or additional prisoners of war during the Desert Shield/Desert Storm operations. The *Pioneer* UAV operated with little danger of detection or threat either while flying or operating over hostile forces.

Their employment eliminated the risks associated in using manned aircraft to collect required intelligence data or follow-up battle damage assessment. The small size and detection characteristics of the Pioneer allowed the UAV to sit over hostile areas and observe activities with minimal risk [Ref. 9:p. 6].

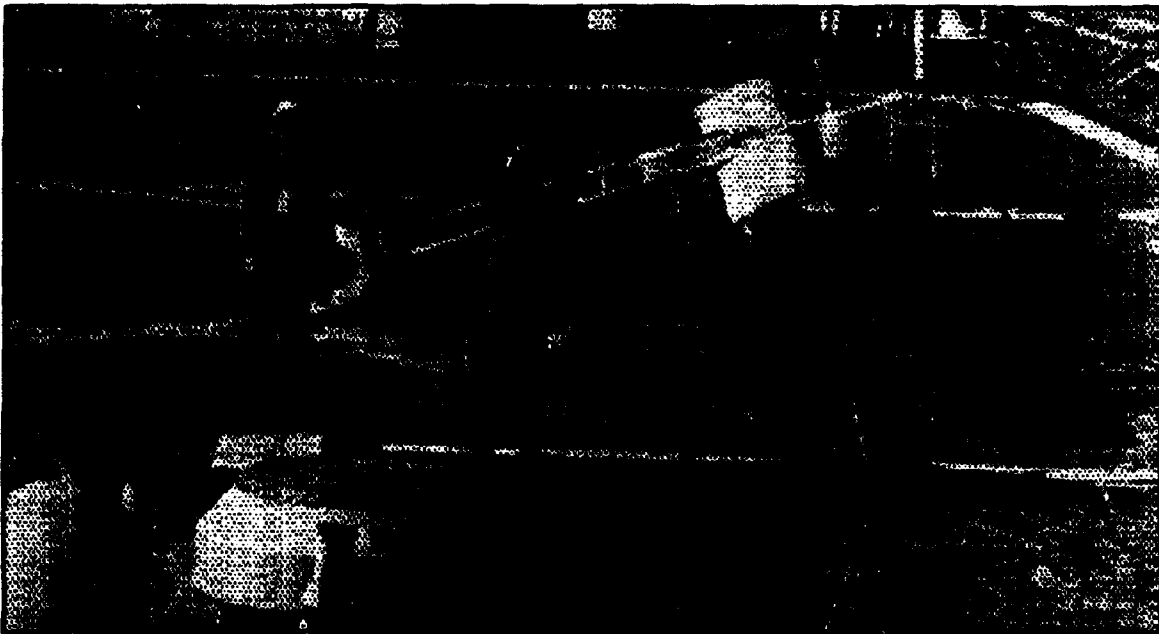


Figure 3 Pioneer flight operations onboard a U.S. battleship in the Persian Gulf [Ref 9:p. 17].

A list of UAV shortcomings in the Gulf Conflict was put together primarily from the services' experience with the Pioneer. At the top of the list were complaints that there were too few UAV systems and the equipment to support them was too cumbersome to be moved easily [Ref. 10:p. 44]. Throughout both Desert Shield and Desert Storm, UAVs averaged a sortie rate of only 13.25 sorties per vehicle. Marine aviators flying close air support and battlefield air interdiction operations (CAS/BAI)

missions were not able to capitalize on UAV information because it was out of date by the time it reached them [Ref. 11:p. 59].

During the war, the U.S. Air Force could muster only 1.5 squadrons of RF-4Cs from reserve-component units. A few weeks after Iraq's invasion of Kuwait, Marine Corps RF-4Bs were decommissioned. Due to the shortages, manned reconnaissance aircraft were assigned as many as 30 targets in a single mission - the norm is four or five [Ref. 12:p. 38].

C. SUMMARY

The employment of UAVs in twentieth century military operations has a long and varied history. Since the 1960's they have been particularly useful in performing covert missions against targets where airframe survivability is questionable.

Had Teledyne Ryan's Buffalo Hunter reconnaissance drones been equipped with electronic data links, their intelligence data would have been more timely. An infrared capability would have allowed reconnaissance missions to be flown at night thereby minimizing UAV vulnerability and increasing the availability of reconnaissance missions. Additionally, these UAVs were not equipped with a navigation system that could accurately place the aircraft over the intended target area [Ref. 13].

Israeli operations in the Bekaa Valley demonstrated for the first time the versatility of such a platform in a hostile environment and the tactical significance of proper employment of these platforms and timely dissemination of UAV intelligence data.

Anti-guerrilla operations in Honduras, while confirming the usefulness of electronic data links, demonstrated that line-of-sight command and control equipment are ineffective in mountainous regions where mission profiles are flown at low altitudes to enhance imagery resolution. Additionally, when infrared or visual sensors are the sole or primary search sensors, the cuing data required to plan Reconnaissance, Surveillance, and Target Acquisition (RSTA) missions must be accurate enough to fly the UAV to the target's approximate location. In order to accomplish this, accurate navigational equipment and timely coordination with national sensors is required. Missions employing optical sensors are better suited to immobile targets such as command bunkers.

Desert Storm proved to be the culmination of thirty years of American UAV research and development. Forty Pioneer UAVs deployed to South West Asia from 16 January to 27 February flew over 1680 flight hours in 530 sorties with a 5% combat loss rate. An additional fourteen air vehicles were damaged during the Gulf War as a result of operator error, engine/airframe failure, gunfire, and electromagnetic interference [Ref. 14:p. 106].

Organic manned surveillance aircraft may not always be available to the Strike Warfare Commander (STWC) or Anti-Surface Warfare Commander (ASUWC), as indicated by the recent deployment of the USS Theodore Roosevelt without S-3Bs and their Inverse Synthetic Aperture Radar (ISAR). RSTA missions may not always be flown against only relatively fixed targets. Future missions may be planned to search relatively large areas against mobile targets. For such missions accurate cuing data may

not be available and therefore, infrared sensors may not prove adequate as the primary search sensor. Wide area surveillance sensors such as radar and electronic support measures (ESM) will be required if full area coverage is to remain the mission planner's goal.

Incorporation of improved sensors and electronic data links can enhance UAV RSTA mission success. Future UAVs must be capable of successfully searching an area for enemy targets, whether they be designated targets of interest or targets of opportunity. Inclusion of an infrared imaging sensor will allow the UAV to covertly identify contacts while an imaging radar will allow the system to do so from a safe distance outside the envelope of the target's weapon systems.

II. MISSIONS

Future generations of Unmanned Aerial Vehicles (UAVs) will be required to provide near real-time Reconnaissance, Surveillance and Target Acquisition (RSTA) support to include Battle Damage Assessment (BDA) to tactical commanders day or night and in periods of inclement weather. The system will incorporate the concept of modular mission payloads. Only those sensors required to perform the immediate task will be carried by the UAV. Electro-optical (EO) sensors are the chosen sensors for the baseline version UAV.

Follow-on growth missions include Naval Surface Fire Support (NSFS), Electronic Countermeasures (ECM) and Anti-ship Missile Defense (ASMD). With these growth missions comes newer sensor systems to be carried by the UAV as the need arises.

This chapter presents an overview of the baseline RSTA mission scenario. A cued area search in littoral waters is used to show the dilemma faced by mission planners when tasked to plan RSTA missions with limited sensor payload support.

A. OPERATIONAL OVERVIEW

The primary purpose of the UAV in a normal RSTA mission is to extend the effective ranges of a ship's weapons and sensor systems. As a force multiplier, they will increase the number of air assets available to a ship, giving the ship's Commanding Officer the capability to search a broader area around his platform

thereby focusing his own ship's firepower directly in the area of interest. This will enable him to act more independently of search assets requiring long and uncertain tasking cycles.

UAVs will allow ships without organic air assets such as the Arleigh Burke class DDG-51, which will be the main component of future surface forces, to perform long range RSTA missions independently of other units. This could include long duration barrier operations in littoral regions. Even those ships with an organic helicopter onboard will be able to generate accurate situation and targeting data against multiple threats simultaneously using both the UAV and its LAMPS helicopter, thereby increasing the size of its radius of influence. The UAV could also act as a targeting platform for armed LAMPS helicopter strikes against small gunboats and combatants.

B. RSTA MISSION

The factors effecting the success of RSTA missions include, but are not limited to, availability, accuracy and timeliness of cuing data, target mobility and proximity to the UAV launch platform, threat condition and the size of the area to be searched with the sensors available. Active sensors such as radar provide the search platform with a means of effectively covering a large area in relatively short time due to its increased range over conventional optical sensors. However, because they are active, these sensors act as beacons to any hostile unit in the vicinity of the assigned search area. Passive sensors such as infrared (IR) and electronic support measures (ESM)

enable the air vehicle to assume a covert posture. Due to the shorter ranges of IR compared to radar, and the fact that ESM requires a willing cooperative target to activate its emitters, the time required to search an area of uncertainty (AOU) using passive sensors is considerably greater than that of active sensors.

Accuracy of the target data base and threat condition are factors which effect the choice of sensor to be employed throughout the search phase of the mission as discussed below.

1. Fixed Targets

When the approximate locations of targets are known, the mission can be planned to image limited areas of interest. These might include airfields, lines of communication, or any fixed area where pre-strike intelligence is required. Missions planned against such targets are well suited for optical sensors, especially when a covert posture is required prior to the arrival of strike aircraft.

2. Cued Search

Collateral information from other intelligence sources may be used to cue the UAV and to limit the size of the search area. An ESM system collocated with an onboard imaging sensor provides a powerful combination for detecting and accurately locating emitting targets, as well as providing situation awareness.

Accuracy of the cuing data and size of the AOU play a major role in determining the primary search sensor.

3. Area Search

The area search method is employed when the target area is not defined due to lack of pertinent cuing information. The search consists of parallel and slightly overlapping tracks, and continues until a target is imaged or until the assigned area is covered. Although time-consuming, this type of area search provides a reference data base for use in follow-on mission planning.

4. Targeting and Battle Damage Assessment (BDA)

UAVs are a natural choice for assignment as stand-off targeting aircraft (SOTA). During conflict, mobile targets present a difficult targeting problem, especially during periods of inclement weather and in areas consisting of formidable terrain. When these conditions are encountered, accurate target position and status cannot be determined using conventional imaging sensors such as IR. ESM systems may indicate the presence of mobile air defenses accompanying enemy forces, but provide only approximate locations.

Moving Target Indicator (MTI) radars can indicate speed and direction, but alone are not sufficient to allow a complete analysis of the enemy's force structure, to include electronic order of battle (EOB) and force composition. Once targets cease moving, other sensors must be employed to provide intelligence data. One such sensor which proves ideal for this situation would be an imaging radar such as Synthetic Aperture Radar (SAR) or Inverse Synthetic Aperture Radar (ISAR). The UAV could be cued by its onboard ESM sensor to relative target position, targets localized by the MTI radar, and the high resolution capabilities of

the imaging radar can determine how the units are deployed, locate them accurately, and supply this information for targeting to a strike package, even in inclement weather. The UAV could then loiter over the target area providing battle damage assessment through the use of its onboard optical sensors.

C. MISSION SCENARIO

Naval forces deploy as part of a Carrier Battle Group (CVBG), normally composed of a mix of cruisers, destroyers, frigates and support ships in addition to the carrier and its embarked air wing, and totalling as many as eleven ships. Initially, UAVs will be embarked in Spruance (DD-963) and Arleigh Burke (DDG-51) destroyers. Most likely scenarios in which the UAV would play a vital role involve Surface Action Group (SAG) operations without the support of a carrier.

In the past, SAGs have been supported by land-based Maritime Patrol Aircraft (MPA). However, with the recent reduction in the number of MPA squadrons and overseas deployment sites, this valuable RSTA asset may not be available to the SAG commander during future conflicts. The SAG commander needs an organic RSTA asset to be aware of activities in his battle space.

By far the most difficult RSTA mission which the SAG commander will be forced to plan and execute is that which is based on poorly defined or inaccurate cuing data - the broad area search. Certain non-organic cuing systems such as High Frequency Direction Finding (HFDF) nets produce large AOU's. As the size of the AOU increases, so does the time required to cover 100 per cent of the area. The

most common AOU inaccuracy faced by mission planners is caused by time-late intelligence data. For instance, a five hour old AOU with a semi-major axis of 15 nm and a semi-minor axis of 10 nm is received by the SAG commander from the Anti-Surface Warfare Commander (ASUWC) along with tasking to search the area with a coverage factor of 1.25. The center of the area is approximately 60 nm from the SAG and target speed is estimated to be 15 kts. This translates to a search area with semi-major axis of 90 nm and semi-minor axis of 85 nm. This combination of inaccuracy in cuing data and large AOU size can place a strain on RSTA asset availability.

The broad area search mission is discussed below for two cases: (i) a UAV equipped solely with an optical sensor, and (ii) a UAV equipped with a multi-sensor payload consisting of radar, ESM and IR systems. The first case was chosen because current planning for the baseline version of the next generation of UAV is to employ the concept of the modular mission payload. That is, the UAV will only carry a single sensor system, primarily electro-optical (EO), during RSTA missions. Should the assigned mission dictate the use of another sensor, for example radar, it will be necessary to swap payloads on deck either before or between missions.

The second case is based on the author's operational experience as a Tactical Coordinator in Maritime Patrol Aircraft, a mission planner on a Patrol Wing Staff and as ASUWC for a CVBG in the Mediterranean and Red Seas during Operations Desert Shield and Desert Storm. Its purpose is to compare onstation area coverage

between the modular mission payload and a multi-sensor payload such as those currently employed by manned RSTA assets.

1. Scenario

A CVBG has been operating in the Mediterranean Sea for the past five months and has detached a two ship SAG to operate in a littoral region in the vicinity of a small island chain where terrorist gunboat activity has been reported by counter-intelligence sources. These gunboats are believed to be equipped with Soviet-made surface search radars, hand-held Surface-to-Air Missiles (SAMs), small caliber anti-aircraft guns and grenade launchers. It is believed that they could conduct operations against SAG units either as one or in formations of as many as five units.

The ASUWC has passed an elliptical AOU with a semi-major axis of 50 nautical miles (nm) and a semi-minor axis of 30 nm to the SAG commander in which several gunboats are believed to be operating. Time-late on the locating data is one hour. When plotted, a large portion of the ellipse is located over land and within territorial standoffs of littoral nations. The mission planner has determined a 20 x 20 nm box located 30 nm to the north of the SAG's present position to hold the best prospects for detecting any possible gunboat activity.

Shipboard environmental prediction systems indicate an IR range of four nm and a radar range of 27.5 nm against a gunboat-size target. To minimize counter-detection, the assigned search altitude is 500 ft. ESM ranges at this altitude are predicted to be $41.25 \text{ nm} (1.5 \times 1.23 \times (\text{radar height})^{1/2})$. A standard ladder

search is assigned at a search speed of 60 knots (kts) to allow increased onstation endurance, high probability of detection and low false alarm rate in haze and traffic. Predicted onstation surface winds are from the west at 20 kts and a cloud layer exists at 1000 ft. A coverage factor of 1.25 is to be used to ensure 100 per cent coverage of the area with some overlap of the imaging swath. Coverage factor is defined as sweep width / track spacing, where sweep width is the predicted detection range of the search sensor.

The modular mission payload employed in the first case will consist solely of IR. In the second case, a multi-sensor payload consisting of MTI and SAR radars, and IR and ESM systems will be used to cover the same area. For the purposes of this thesis, the goal is 100 per cent coverage of the assigned area.

a. Optical Sensor Search

With a predicted IR detection range of four nm against a gunboat-size target, the resulting track spacing for a coverage factor of 1.25 is three nm. With westerly winds at 20 kts, the initial leg of the search pattern is 3 nm inside the eastern-most side of the assigned search area flown from south to north in order to minimize sea return. The IR sensor will search an area 45 degrees either side of the nose of the UAV. A track spacing of three nm results in seven south-north legs and six east-west legs with a total of 158 nm which must be transited by the UAV in order to cover the entire area. Flown at a search speed of 60 kts, the UAV will require 2 hrs 38 min to image the entire assigned area.

Should any contacts of interest be detected, the UAV will be required to fly off track and image the contact. This results in an increased time onstation and, depending on available fuel and distance to the controlling platform, a follow-on UAV flight may be required or a second UAV tasked to be onstation simultaneously with the first. If contacts in the area should activate their surface search radars, the UAV, assumed here to be without an ESM system, will be incapable of detecting such emissions. An ESM system could greatly reduce the amount of time required for the UAV to search the area provided the target is cooperative and radiates its emitters while the UAV is in the vicinity of the search area. If the UAV were equipped with such a system and threat emitters detected, the UAV could be programmed to continue on track in an attempt to triangulate the source or turn and fly down the threat bearing searching with its onboard IR system, until the contact is identified. Normally, an appropriate distance to fly along the emitter bearing is approximately 1.5 times the predicted ESM horizon at the assigned search altitude in order to account for the possibility of any ducting of radiated energy.

b. Multi-Sensor Search

In a multi-sensor search scenario, MTI radar is the primary search sensor, even in the situation when the search asset is a manned aircraft such as MPA. The normal progression of events is a ladder search flown as described above with a track spacing normally set at 12 nm and the MTI radar pointed down wind (easterly in this scenario) in order to minimize sea return and clutter. Radar contacts

are then imaged with the onboard SAR system, taking advantage of its increased standoff capability over IR. This ensures that the air vehicle does not overfly and alert the contact of interest or come within the range of the targets onboard weapons systems. Should further investigation be warranted, a fly over may be performed and the contact imaged using the onboard IR sensor.

At the same time that radar is searching downwind, IR is programmed to search off the nose of the UAV in order to detect and identify any contacts of interest along the flight path. Additionally, these contacts will be stored in the track data base and correlated with radar contacts gained by the UAV on following tracks, reducing the time required to image contacts. The amount of time required to cover the entire area in this case is 52 min.

Once again, an ESM system would greatly reduce the amount of time required to search for and detect contacts of interest in the presence of threat emitters. The search tactics would remain the same as described in the previous section with the exception that the mission commander now has the option of radiating the UAV's onboard radar system along the threat bearing in an attempt to locate the source of emissions more quickly.

The theoretical radar horizon for an emitter searching at an altitude of 500 ft is 27.5 nm. The diagonal of the assigned search area is approximately 28.28 nm. In this scenario, the UAV would be capable of radiating over virtually the entire area from the southwest corner of the area with the onboard MTI radar. From this position, any contacts gained in the area could then be imaged with the

UAVs onboard SAR, or with the onboard IR system. Regardless, positioning the UAV in the southwest corner of the search area allows the entire area to be covered in a very short time, and contacts imaged and identified. The UAV may be used for any follow-on tasking such as identifying contacts in the general vicinity of the controlling platform.

c. Conclusions

Employment of the UAV under both cases in the above scenario provides complete coverage of the entire area. However, in the case where IR was the sole sensor, if the gunboat transiting the western portion of the assigned search area heading in any direction other than easterly when the UAV arrived onstation, it might have been outside the assigned area by the time the UAV had completed tasking. The UAV equipped with the multiple sensor payload in which the MTI radar was the primary sensor could have conducted a surface plot of all contacts from the western side of the box and imaged contacts from west to east accordingly. In both cases the entire area is covered, but the UAV equipped with a multiple sensor payload has a better chance of preventing contacts from escaping detection and identification.

Assuming a ladder search is to be performed in the scenario's 20 nm x 20 nm box, the UAV equipped with the multiple sensor payload completed coverage of the entire area in less than one-third the time required by the UAV equipped with just the IR sensor. When applied to searches of larger areas, it is readily apparent that the UAV equipped with the multiple sensor payload is more

capable of providing timely coverage and a broader extension of the host-ship's weapons and sensor systems and, ultimately, its sphere of influence.

D. SUMMARY

RSTA missions provide a SAG commander with valuable information concerning enemy surface activity within his area of responsibility. It allows him to keep abreast of changes in an enemy's force structure and bring his own forces to bear on threat sectors of immediate concern to him. Such missions may be tasked against fixed or mobile targets regardless of the availability or accuracy of cuing data.

As the military shrinks in size, so does the availability of manned RSTA assets and UAVs become an attractive alternative. Future UAVs will employ the modular mission payload concept. Only an EO sensor is to be carried onboard the baseline UAV employed in RSTA missions with later versions capable of supporting radars, ESM and IR modular payload combinations. Sensor systems will be swapped prior to each mission as dictated by the mission environment.

The most difficult task faced by a mission planner is one where inaccurate cuing data covering a broad area is the only data with which to work. Of the possible inaccuracies associated with cuing systems, the most common are those associated with timeliness of the data and target motion. Time-late data and a fast target translate to a larger AOU.

In the case of the UAV equipped with a modular mission payload where EO is the sole sensor, as the size of the AOU increases, so does the time required to provide 100 per cent area coverage. Target detection now becomes a question of target speed and location relative to the UAV and availability of follow-on assets.

Conversely, a UAV equipped with multiple sensors such as MTI, SAR, ESM and IR can cover the entire area in a fraction of the time required by the UAV equipped with a single optical sensor. This leaves more time available for target identification and classification, and frees the UAV to perform secondary missions if time and fuel permit. A UAV equipped with such a sensor suite is more capable of providing the SAG commander with timely area coverage, valuable situational awareness and a broader extension of the SAG's weapons and sensor systems and, ultimately, it's sphere of influence.

III. MULTIPLE SENSOR PAYLOADS

Military actions conducted in the past decade in Central America and the Middle East have shown the importance of having available timely intelligence to support Reconnaissance, Surveillance and Target Acquisition (RSTA) missions without risk to manned aircraft and the potential for loss of life or the possibility of prisoners of war.

The increasing capabilities of surface-to-air (SAMs) and air-to-air (AAMs) missiles and the continued unrestricted proliferation of these systems throughout the Third World could produce significant attrition of U.S. aircraft in future conflicts. When reconnaissance or attack sorties are flown near or over heavily defended target areas, they are likely to be engaged by various types of missiles and/or AAA weapons. Although intelligence information can be gathered by reconnaissance satellites and manned aircraft such as F-14 aircraft employing Tactical Aerial Reconnaissance Pods (TARPS) or S-3B aircraft equipped with Inverse Synthetic Aperture Radar (ISAR), delays in the tasking and/or data dissemination of these systems are inevitable. Such delays may be the result of command and control deficiencies or by an individual command's position on the intelligence priority and data dissemination ladder. Satellite imagery is processed by intelligence facilities ashore prior to being disseminated to the commander of the carrier battlegroup (CVBG). TARPS imagery requires postflight processing and analysis. Unless the

onstation S-3B is providing direct support to an individual ship or surface action group (SAG) as a stand-off targeting aircraft (SOTA), analysis of ISAR imagery may not be available to individual units of the CVBG until after the aircraft has returned to the carrier and mission tapes analyzed. UAVs can act as an extension of an individual ship's weapons and sensor systems providing timely intelligence to the controlling platform. They can be used to pinpoint and verify potential targets identified by both national and non-organic sensors and perform Battle Damage Assessment (BDA) as required. A UAV tactical reconnaissance system tasked by tactical commanders could be used to penetrate heavily defended enemy positions, collect imagery data, and disseminate this data to other battle force assets expeditiously.

The ability of UAVs to perform reconnaissance missions over enemy territory provides the Strike Warfare Commander (STWC), the Anti-Surface Warfare Commander (ASUWC) and the Commander, Amphibious Task Force (CATF) with the intelligence data required to take timely action against enemy forces. These same reconnaissance UAVs can provide detailed imagery of individual formations and also perform targeting functions for incoming strikes, harass enemy command, control and communications facilities, carry out jamming and other electronic warfare (EW) missions, gather and transmit signals intelligence (SIGINT) and provide communications relay capabilities and BDA.

A. PAYLOADS

The primary UAV serving the American military forces today is the *Pioneer* system. Equipped with an electronic data link and a Forward Looking Infrared (FLIR) camera, it is best suited for performing gunfire support missions and searching small areas where the target's position is accurately known. In its present configuration, it is ill-equipped to perform effective RSTA missions against either a moving target or a stationary target believed to be located within a large area of uncertainty (AOU). In scenarios of high merchant shipping density and environmental clutter, the *Pioneer* system in service today would be overwhelmed when tasked to search for and detect a specific individual target in a large AOU in a timely fashion.

To be effective, the next generation UAV must be capable of performing in all five stages of a RSTA mission: over-the-horizon search, detection, classification, targeting and battle damage assessment. To achieve greater imagery resolution, the UAV will be operating at lower altitudes. Therefore, it must be equipped with an electronic data link system capable of transmitting video, radar imagery and electronics intelligence (ELINT) over great distances and in mountainous regions. Infrared (IR) or radar imagery provides 24-hour coverage of the battlefield, regardless of environmental conditions. An infrared camera can identify both fixed and moving targets even at night and in the presence of limited battlefield obstructions. A Moving Target Indication (MTI) radar can search for, detect and acquire moving targets with a high degree of accuracy over a wide area. It provides

the tactical commander with the most comprehensive information about threats that are of the most immediate concern to him. An MTI radar can also cue an infrared camera, Synthetic Aperture Radar (SAR) or Inverse Synthetic Aperture Radar (ISAR), enabling them to identify targets more accurately. SAR and ISAR are particularly useful in identifying targets in the presence of heavy battlefield obscuration such as smoke or humidity, which degrades the performance of standard optical sensors. Those targets which are of the highest value will be located near command and control facilities. Electronic Support Measures (ESM) systems can detect electromagnetic emissions beyond the radar horizon, and can alert an operator to the presence and location of both search and fire-control radars before the aircraft enters the missile or gun engagement zones. A sensor package consisting of radar, ESM and IR sensors can greatly reduce the amount of time required to search a specific AOU than just IR alone. Electronic Warfare (EW) modules such as jammers or decoys could enable the UAV to react to threat emitters when operating in concert with an ESM receiver. A day-time TV system or Low-Light Level TV (LLLTV) would provide greater resolution than conventional IR systems. This capability would enable system operators to read ship names during identification fly-bys - a capability presently lacking in current IR technology.

As described above, sensor systems which could be employed in a RSTA mission are shown in Table 1 [Ref. 15:pp. 79-102].

Table 1 PAYLOAD TYPES

SENSOR		NO IDENT	PARTIAL IDENT	FULL IDENT
Radar	MTI	✓		
	SAR		✓	
	ISAR		✓	
	ELINT		✓	
	ESM		✓	
IR	FLIR			✓
	IRLS			✓
TV	TV			✓
	LLLTV			✓
Data Link		✓		

A discussion of payload types currently under consideration for employment onboard future generations of UAVs follows.

1. Electronic Data Link Systems

One of the main deficiencies of the Buffalo Hunter system that was identified after the Vietnam War was the system's lack of a data link system and its inability to process imagery near real-time [Ref. 13]. This shortcoming was corrected by the time *Skyeye* anti-guerilla reconnaissance missions were being flown in Honduras in 1984. However, the line-of-sight data link systems employed performed poorly in mountainous regions when low-altitude mission profiles were required to enhance imagery resolution.

Data links to be employed onboard future UAVs must be capable of performing in increasingly hostile electromagnetic threat environments. They must be capable of interoperability with other battlefield Command, Control, Communications and Intelligence (C³I) systems in addition to transmitting intelligence data throughout the entire spectrum of possible mission areas envisioned [Ref. 15:p. 73].

Presently, the UAV Joint Project Office is considering the AN/SRQ-4 data link system which is compatible with systems presently fielded onboard ships configured for SH-60B LAMPS helicopters. The SRQ-4 system produced by Lucas was specifically developed for use onboard manned aircraft and is therefore of considerable size and weight. Other data link systems presently available are the Low Cost Common Data Link (LCCDL) produced by Paramax, and PIXLINK produced by McDonnell Douglas. Both are much smaller in size than the SRQ-4 system. Both systems are capable of transmitting imagery and Synthetic Aperture Radar (SAR) data.

Table 2 shows the weight, volume and power consumption for all three systems [Ref. 16:p. 1038].

Table 2 DATA LINKS

MANUFACTURER	WEIGHT	VOLUME	POWER
LUCAS	79.4 lb	1.0000 ft ³	150 W
MCDONNELL DOUGLAS	27.5 lb	0.5300 ft ³	300 W
PARAMAX	18.1 lb	0.4697 ft ³	80 W

The inclusion of a data link system as a integral part of the payload suite reflects the need for positive command and control of an airborne UAV system. It has the highest priority of all payloads presently under consideration.

2. Radar Systems

a. Moving Target Indicator (MTI) Radar

A Moving Target Indication (MTI) radar system is one that is designed to reject fixed targets and pass moving targets on the basis of their doppler shifts. Most surface and airborne radar systems operate in an environment where clutter return obscures targets of interest. MTI systems comprise the most widely used class of radar processors for detecting moving targets in a background of clutter. If the target is moving relative to the clutter it is possible to filter out the undesired clutter return by exploiting the differential doppler frequency shift

produced by the relative target to clutter radial motion. MTI radars are extremely useful as the initial detection sensor and for displaying an enemy's force disposition.

b. Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar (SAR) development began in the late 1950's to meet the requirement for an all-weather, day-or-night sensor that could produce high-quality reconnaissance imagery in adverse weather and visibility conditions. Darkness, rain, smoke, fog, dust or haze have negligible effects on the imagery produced by a SAR system.

SAR gives essentially constant resolution in the along-track direction at all range intervals. The along-track resolution of a conventional radar is equal to the beamwidth of the antenna. Increasing the antenna length to a size that provides good imaging performance is not practical because such an antenna would be too large to be carried on an airborne platform. The moving antenna size "synthetically" appears to be longer than is actually the case, from whence the synthetic-aperture technique derives its name.

The transmitted pulses are referenced to a standard frequency within the radar system, and the pulse-to-pulse phase relationship of the target is stored as it passes through the radar beam, producing a phase history during the target illumination interval. Employing the same digital processing techniques used to compress the long range pulses, the target phase history can be compressed, replicating the target. The effect produces a constant size target resolution cell, independent of range. The antenna for SAR is relatively small which provides a

wide beam so that the targets may be illuminated for a longer period of time. The longer the target is illuminated (the more samples taken) the longer the synthetic aperture, and the higher the resultant resolution. Effective antenna lengths of hundreds of thousands of feet can be generated synthetically.

Though SAR systems are best utilized against stationary targets, they have performed remarkably well against ships at sea [Ref. 17:p. 207].



Figure 4 SAR imagery of a commercial cargo ship [Ref 17:p. 215].

c. *Inverse Synthetic Aperture Radar (ISAR)*

In the mid-1960's Massachusetts Institute of Technology extended the SAR concept to moving targets by using a variation of the SAR technique called Inverse Synthetic Aperture Radar (ISAR). The ISAR technique is dependent upon the target motion rather than the radar platform motion. Production of the ISAR image is achieved by analyzing two different interactions of the radar energy with the target. The intersections are in the horizontal and vertical directions of target motion.

ISAR images are similar in quality to poor video images. This poor quality is due to the oscillatory motion of the target which causes the image to stretch in crossrange (ie: vertical direction) as the target accelerates as a result of pitch, roll and yaw motions. As motion in this pitch, roll, yaw cycle slows and reverses in direction the image shrinks in crossrange and as a consequence inverts itself. Image quality can be improved through image resolution control.

ISAR has the ability to track targets in the same manner as an MTI system when operating in the Planned Position Indicator (PPI) mode. In the PPI mode, the operator views a series of blips on the radar screen which indicate target location in range and bearing from the radar antenna. When operation is shifted to the imaging mode, ISAR performs as described above. Extensive training and experience is required for an operator to become proficient at ISAR imagery interpretation.

Table 3 shows the weight, volume, power consumption and detection capabilities of available MTI and SAR radar systems [Ref. 15:p. 89].

Table 3 RADAR SYSTEMS

NAME /MANUFACTURER	DETECTION RANGE	WEIGHT	VOLUME	POWER
MTI /HARRY DIAMOND LAB	20 km vs 10 m ² tgt	110 lbs	3.50 ft ³	1050 W
MTI /AIL	20 km vs 10 m ² tgt	80 lbs	0.95 ft ³	520 W
MTI /LOCKHEED	18 km vs 10 m ² tgt	125 lbs	2.00 ft ³	1200 W
SAR /LORAL	10 km vs 10m ² tgt	88 lbs	1.25 ft ³	470 W
MTI /LINCOLN LAB	15 km vs 10m ² tgt	55.1 lbs	1.50 ft ³	350 W
MINI SAR /LORAL	10 km vs 10m ² tgt	67.9 lbs	1.48 ft ³	360 W

The above systems reflect both SAR and MTI systems for which data was available. Most MTI systems were developed for manned aircraft use and are therefore larger in weight and volume than those designed specifically for UAV missions. Both SAR systems, however, were designed specifically for use as UAV payloads.

3. Electronic Support Measures (ESM)

As demonstrated by the Israelis in the Bekaa Valley, collection and analysis of an enemy's electromagnetic emissions can provide a wealth of information concerning tactics and capabilities. This function of electronic warfare (EW) is generally referred to as electronic support measures (ESM), and includes both communications intelligence (COMINT) and electronic intelligence (ELINT). ESM provides information in a timely fashion and in forms that are readily usable by the users it supports. An ESM system is employed primarily to passively detect and identify radar emissions with established signal parameters. In performing this function, an ESM receiver could be extremely valuable during tactical reconnaissance missions in such an environment.

On a tactical level, ESM can provide an evaluation of each electronically-controlled weapon system's capability, while on a strategic level, it can give an indication of the numbers and different types of electronically-controlled weapons systems deployed (the Electronic Order of Battle (EOB)). The Israeli Bekaa Valley Campaign clearly demonstrated the need for control of the electromagnetic spectrum and the possible payoff of electronic intelligence.

Table 4 shows the weight, volume, power consumption and the capability of available ESM systems [Ref. 15:p. 91].

Table 4 ESM SYSTEMS

NAME /MANUFACTURER	TYPE	WEIGHT	SIZE	POWER
MEDFLI /ESL	ELINT	150 lbs	5.7 ft ³	1000 W
APR-48 /IBM	RADAR /ESM	32.5 lbs	.76 ft ³	235 W
ALR-89 /E SYSTEMS	RADAR /ESM	37 lbs	.36 ft ³	210 W
APR-39XE2 /DALMO VICTOR	RADAR /ESM	36 lbs	.42ft ³	137 W

The above systems give an airborne UAV the capability of detecting radar emissions in the target area. Growth missions may include Communications Intelligence (COMINT) and Proforma. The considerable size and power consumption of the available ESM systems reflect technological advances in miniaturization. Systems of small weight and volume are specifically designed as UAV payloads.

4. Infrared Systems

The ability to see in the dark is a basic military requirement. The possibility of achieving this with a completely passive system, which does not advertise its presence has always been the ultimate objective. Two such sensor systems exist which perform this task quite well - Forward Looking Infrared (FLIR) and Infrared Line Scanners (IRLS).

a. Forward Looking Infrared (FLIR)

FLIR sensors convert infrared energy to the visual spectrum in real time. Because of the lack of shadows, they are incapable of providing three-dimensional contour information. They are, however, capable of detecting large contacts at long ranges provided there is a sufficient difference between the contact and background temperatures [Ref. 15:p. 81].

Table 5 shows the weight, volume, power consumption and fields of view of available FLIR systems [Ref. 15:p. 82]. Fields of view (FOV) are included for each system.

Table 5 FLIR SYSTEMS

NAME /MANUFACTURER	FOV (AZ x EL)	WEIGHT	VOLUME	POWER
LIGHTWEIGHT FLIR /WESTINGHOUSE	3x4 (n) 15x20 (w)	92 lbs	0.46 ft ³	675 W
MICRO FLIR /KOLLMORGEN	3x2.2 (n) 15x7.5 (w)	55 lbs	0.83 ft ³	275 W
AN/AAQ-16 /HUGHES	6.5x4.9 (n) 30x40 (w)	100 lbs	0.92 ft ³	644 W
STIS MK-11 /LORAL	3x2 (n) 30x20 (w)	75 lbs	1.78 ft ³	300 W
PRSI MINI FLIR LF CCD 2447 /LORAL	3.8x2.3 (n) 15.4x9.3 (w)	20 lbs	3.60 ft ³	60 W
IRTV-445G /INFRAMETRICS	5.2x0.60μ (n) 0.8x2.4μ (w)	71 lbs	0.50 ft ³	50 W
WF 360 /WESTINGHOUSE	3.6x2.7 (n) 14.8x11.1 (w)	205 lbs	2.56 ft ³	500 W
HP FLIR /PLIKINGTON	1.9x2.9 (n) 6x9 (w)	35 lbs	0.49 ft ³	65 W
GFS-3 /HONEYWELL	3x2 (n) 30x20 (w)	70 lbs	1.78 ft ³	300 W
STA-360 /TX INSTRUMENT	5.3X3.3 (n) 15.3X9.6 (w)	75 lbs	1.54 ft ³	300 W
FORD /FMPS	2.6x3.5 (n) 13.5x18 (w)	42 lbs	1.82 ft ³	350 W
MOSP /IAI	1.7x1.3(n) 25x19(w)	80 lbs	1.92 ft ³	240 W
MKD-400 /TADIRAN	3x2(n) 2.5x16.7(w)	55 lbs	1.35 ft ³	280 W
IR-18 /BARR & STROUD	5.3x3.54 (n) 21.2x14.2 (w)	104 lbs	3.43 ft ³	150 W

Flir systems are heavy and consume large amounts of electrical power due to their lens and camera cooling requirements. Three such systems (PRSI, IRTV-445G, HP-FLIR), however, were designed specifically as UAV sensors and therefore reflect the requirement for installation in a small payload cavity with limited available electrical power.

b. Infrared Line Scanners (IRLS)

Much like the FLIR, the IRLS provides high resolution imagery of contacts by passively converting infrared energy to the visual spectrum in real time. However, IRLS sensors do so over a much wider field of view and higher resolution than its FLIR counterpart. Because IRLS covers a wider field of view than FLIR, it is able to cover a larger area. However, in order to transmit this imagery to a controlling unit over conventional data links available today, a much wider bandwidth is required and large quantities of imagery can exceed the capabilities of current data link systems [Ref. 15:p. 84].

Table 6 IRLS SYSTEMS

NAME /MANUFACTURER	FIELD OF VIEW (FOV)	WEIGHT	VOLUME	POWER
D-5 RC /HONEYWELL	120x60 deg	244.0 lbs	5.90 ft ³	651 W
D-5 RC/SEU-A /HONEYWELL	120x60 deg	208.0 lbs	5.00 ft ³	795 W
D-500 /HONEYWELL	120x60 deg	164.0 lbs	6.90 ft ³	650 W
ATARS /LORAL	140x70 deg	76.0 lbs	1.80 ft ³	400 W
ATARS/SEU-A /LORAL	140x70 deg	144.3 lbs	3.70 ft ³	545 W
MINI IRLS /LORAL	180 deg	15.0 lbs	0.20 ft ³	65 W
RPV-800 /TX INSTRUMENTS	150 deg	30.0 lbs	0.60 cu ft	200 W
AMIDARS /CAI	60x120 deg	65.0 lbs	3.67 cu ft	600 W
BARR & STROUD	100 deg	15.0 lbs	0.39 ft ³	250 W
VINTEN 4000	180 deg	44.0 lbs	0.46 ft ³	256 W
VINTEN	180 deg	29.0 lbs	0.46 ft ³	250 W

Table 6 shows the weight, volume and power restrictions of available IRLS systems [Ref. 15:pp. 82].

Like FLIR, IRLS systems are heavy and consume large amounts of electrical power due to their lens and camera cooling requirements. One system (MINI IRLS), however, were designed specifically as UAV sensors and therefore

reflects the requirement for installation in a small payload cavity with limited available electrical power.

B. SUMMARY

Tactical warfare commanders require accurate and timely intelligence data in order to counter an enemy's movements. With the proliferation of advanced technology weapons systems throughout the world's littoral regions, Unmanned Aerial Vehicles (UAVs) have become a more attractive alternative to manned reconnaissance. Infrared sensors alone will not adequately perform RSTA missions in a high threat environment where large areas are to be expeditiously searched. Radar systems on the other hand can cover large areas but, as an active sensor, will cue enemy installations to any allied search effort. In order to respond to any possible active enemy emitters, ESM equipment must be collocated with other sensors onboard the surveillance platform. Therefore, in order to be an effective search asset on the modern battlefield, the next generation UAV must be equipped with a payload which maximizes survivability and time on station. That payload is a combination of active and passive sensors.

A high resolution imaging radar, can detect, locate, and classify tactical targets. It is particularly effective in situations where conventional imaging sensors (ie., infrared) are not, such as in adverse weather conditions and areas where targets may be obscured by dust, smoke and chemical clouds most likely to exist over a battlefield. Additionally, foliage penetration capabilities at longer wavelengths make

the imaging radar particularly desirable in areas of dense foliage. The increased ranges of these sensors over conventional systems under adverse environmental conditions permit standoff surveillance and targeting.

As shown in Chapter II, employing a radar as the initial detection sensor provides an enhanced capability to locate and identify re-deployable targets before they are alerted to move or their organic weapons systems are brought on-line. Additionally, a radar system as the primary sensor may force enemy air defense systems (ie:, air search and fire control radars) to become active which will provide additional intelligence and locational data and assist in contact identification if an ESM system is included in the UAV sensor suite. The radar can then be cued to the approximate target area, targets verified, and accurately located. Critical contacts of interest can then be handed off to onboard optical sensors. This second onboard sensor would likely require a much closer flight path and could alert the target area.

IV. UAV PAYLOAD SELECTION MODEL

A. MODEL DESCRIPTION AND FORMULATION

UAV PAYLOAD SELECTION MODEL, an optimization model capable of selecting a multiple sensor payload to fit an individual UAV payload cavity, is formulated as a mixed integer linear program. The model is an extension of the traditional knapsack problem [Ref. 18:p. 13]. A description of the knapsack problem in the current context is as follows: given a set of n items (sensors) and a *knapsack* (payload cavity) with

- u_j = the value or utility of item (sensor) j ,
- w_j = the weight of item (sensor) j ,
- c = the payload carrying capacity of the knapsack (payload cavity),

select a subset of the items so as to

$$\text{Maximize} \quad \sum_{j=1}^n u_j x_j$$

Subject to:

$$\sum_{j=1}^n w_j x_j \leq c$$

where x_j is a decision variable defined as:

- x_j = one if item j is selected and zero otherwise.

This is referred to as the 0 - 1 knapsack problem because each item must be either selected or omitted; the model will not select a fractional portion of an item or take an item more than once. Our extension of this traditional model is developed in the next section.

B. UAV PAYLOAD SELECTION MODEL

The goal of the UAV PAYLOAD SELECTION MODEL is to provide a sensor mix to be carried onboard the next generation of UAVs that will maximize the platform's on-station performance while employed in Reconnaissance, Surveillance and Target Acquisition (RSTA) missions. The mathematical formulation is presented below after the introduction of appropriate notation. Section C provides a detailed description of the model's mathematical constraints.

1. Indices

The following indices are used throughout the model. They define a specific sensor system by both its type and manufacturer.

j = specific sensor system types;

k = sensor manufacturers

Values of the indices used in runs of the model to date are:

$j \in \{\text{MTI (Moving Target Indicator), SAR (Synthetic Aperture Radar), ELINT (Electronic Intelligence), ESM (Electronic Support Measures), FLIR (Forward Looking Infrared), IRLS (Infrared Line Scanners), DL (Electronic Data Link)}\};$

$k \in \{\text{Harry Diamond Labs, AIL, Lockheed, Lincoln Labs, Loral, ESL, IBM, E Systems, Dalmo Victor, Westinghouse, Kollmorgen, Hughes, Inframetrics, Plinkington, Honeywell, Texas Instruments, Tadiran, Barr \& Stroud, CAI, Vinten, Lucas, McDonnell Douglas, Paramax, IAI, FMPS}\}.$

The index values chosen are an input to the model which can be changed in future runs.

2. Data

The following data are the required inputs to the optimum model.

- Tot-Wt = total payload capacity of UAV system measured in pounds;
- Tot-Vol = total volume of the UAV payload cavity measured in cubic feet;
- Tot-Pwr = total power generated by the UAV onboard electrical system measured in Watts;
- Tot-Cost = total budget allowed for purchase of sensor payload;
- False-Alm = a weighted value for the maximum allowable number of false contacts measured over time;
- MTI-ID = a weighted value for the minimum allowable identification value of MTI radar systems;
- U_{jk} = utility value from 0 to 1 assigned to system type j;
- W_{jk} = weight of system type j as claimed by manufacturer k, measured in pounds;
- Vol_{jk} = volume of system type j as claimed by manufacturer k, measured in cubic feet;
- Pwr_{jk} = amount of electrical power consumed by system type j as claimed by manufacturer k, measured in watts;
- ID_{jk} = a value from 0 to 1 of system j's capability of identifying or assisting in the identification of a contact of interest.

False_j = a weighted value from 0 to 1 of system j's capability to determine a target through background clutter;

Cost_j = the cost of sensor j as claimed by manufacturer k.

3. Decision Variables

The following binary variables are used throughout the model.

X_{jk} = a binary variable whose value is one if system type j produced by manufacturer k is selected for inclusion as part of the onboard payload, and zero otherwise.

4. Objective Function and Constraints

A mathematical presentation of UAV PAYLOAD SELECTION MODEL follows. A more detailed description of the constraints follows in section C.

$$\text{Maximize } \sum_j \sum_k U_{jk} \cdot X_{jk}$$

Subject to:

$$(1) \quad \sum_k X_{jk} \leq 1.0 \quad \forall j$$

$$(2) \quad \sum_j \sum_k W_{jk} \cdot X_{jk} \leq \text{Tot-Wt}$$

$$(3) \quad \sum_j \sum_k \text{Vol}_{jk} \cdot X_{jk} \leq \text{Tot-Vol}$$

$$(4) \quad \sum_j \sum_k \text{Pwr}_{jk} \cdot X_{jk} \leq \text{Tot-Pwr}$$

$$(5) \quad \sum_j \sum_k ID_{jk} \cdot X_{jk} \geq MTI-ID$$

$$(6) \quad \sum_j \sum_k False_{jk} \cdot X_{jk} \leq False-Alm$$

$$(7) \quad \sum_j \sum_k Cost_{jk} \cdot X_{jk} \leq Tot-Cost$$

The UAV PAYLOAD SELECTION MODEL was written in the General Algebraic Modeling System (GAMS) language [Ref. 19] and is included as Appendix A. Appendix B lists the sets, parameters and sensor data for the model. The data for which the model was run are those of the Short Range UAV (SR-UAV) presently under design for the Program Executive Officer for Cruise Missile Projects and Unmanned Aerial Vehicles (PEOCMPUAV). However, the model can be used for any UAV presently under development. Parameters used in the model were a gross payload weight of 200 pounds, a payload cavity measuring 15 cubic feet and an electrical system capable of generating 1000 Watts of electrical power.

The model chooses from those sensor systems describe in Chapter III:

- Radar - Moving Target Indicator (MTI)
 - Synthetic Aperture Radar (SAR),
- Electronic Surveillance - Electronic Intelligence (ELINT)
 - Electronic Support Measures (ESM),
- Infrared - Forward Looking Infrared (FLIR)
 - Infrared Line Scanners (IRLS),
- Electronic Data Link (DL).

The model determines the optimum payload based on the utility or perceived value of the individual sensor in a RSTA mission scenario. Individual sensors are given a value from zero to one based upon this perceived utility. Utility values were determined by the author using the method of the analytic hierarchy process (AHP) and Expert Choice software [Ref. 20]. The method is subjective and relies heavily on the author's operational experience as both a Patrol Plane Tactical Coordinator onboard Maritime Patrol Aircraft and as mission planner on Patrol Wing and Battle Force staffs. Additionally, the model selects a sensor based upon its ability to positively identify or assist in the identification of a target, its ability to pass false contacts, and the amount of money available for the purchase of such a sensor system. Once again, the identification and false contact values range from zero to one and are subjectively determined through both operational experience and Expert

Choice software. The author chose to use Expert Choice software because it was relatively user friendly and readily available. However, weight data obtained from other methods such as the method of paired comparisons may be used with this model.

C. CONSTRAINT DESCRIPTION

Constraint (1) ensures only one of each type of sensor system is selected. This enables the model to select from several different radar systems, but only one moving target indicator or synthetic aperture radar type in order to avoid duplication of active sensor capabilities.

Constraints (2) and (3) are the physical constraints of the UAV airframe and, as such, are restricted by platform design specifications, payload weight and volume, respectively. Constraint (4) allows all selected sensor systems to be operated simultaneously without exceeding the maximum power generated by the UAV electrical system.

Constraints (5) and (6) force the selected sensor system to meet positive identification requirements. Because earlier generation UAVs carried primarily electro-optical (EO) sensors, they were capable of positively identifying a contact of interest provided mission planners received accurate target locating data. Constraint (5) ensures this capability is carried forward into the next generation of UAV. Constraint (6) attempts to keep the number of false contacts as low as the combined sensor payload will permit.

The last constraint, (7), ensures that the combined payload will remain within the purchasing budget. Unit cost data used in this thesis are estimates received from industrial sources, and are used to test the model for completeness. Total system cost reported with each test result merely demonstrates the effects of the purchasing budget constraint on the final sensor payload. These are only estimates. A summary of the data used in this model is provided as Appendix B.

D. THE ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP) was used to determine values for utility, identification and false alarm weights and is the basis for Expert Choice software. AHP assumes that the weights on any level or hierarchy can be determined independently of the other levels. These weights are in fact determined using a nine-point integer scale (1 to 9) of relative importance for evaluating pairwise comparisons. These pairwise comparisons were performed on each individual hierarchy or level. Three levels were compared based on sensor preference. The first level consisted of sensor categories (ie; Radar, Electronic Surveillance, etc.); the second level consisted of sensor types (ie; MTI, SAR, ELINT, etc); and finally, the third level separated each sensor type by manufacturer.

Table 7 shows the scale used by AHP to aid ratio judgements [Ref. 21].

Table 7 THE FUNDAMENTAL SCALE

SCALE VALUE	MEANING
1	Equal Importance
3	Moderate Importance
5	Essential or Strong
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate Values

To determine utility values for this thesis, sensor systems were initially ranked on a hierarchical principle with the first level consisting of sensor categories (i.e., Radar, Electronic Surveillance, IR, Data Link). The ranking principle was based on the author's preference for a particular sensor in a RSTA mission scenario based on that sensor's ability to cover a large area. The next step was to rank each system type (i.e., MTI, SAR, ELINT, ESM, FLIR, IRLS). The ranking principle was based on the author's preference for a particular sensor and its ability to verify a contact as a contact of interest. Last of all, individual manufacturer's sensors were ranked within a sensor type based upon their capabilities (i.e., field of view, detection range, etc). The aforementioned process was repeated for both identification value and false alarm rate, based on a sensor's perceived ability to identify or assist in the identification of a contact of interest and its ability to reject false contacts. Even

though they are required elements of the final payload package, data link systems were omitted from these last two rankings because they do not contribute to the payload's overall detection capability.

Appendix B contains sensor data previously described in Chapter III (weight, volume and power consumption). Additionally, utility, identification and false alarm values derived using Expert Choice software is included. It is imperative that future UAVs be capable of transmitting imagery data, therefore, data links are given the highest utility value. Due to their increased detection ranges over IR systems, radars were ranked second in desirability. SAR systems were given a larger utility value than MTI systems because of their capability to image contacts. Because of the higher data rates required to transmit IRLS data, FLIR systems were ranked higher than IRLS systems. Each IR system was then individually ranked within their respective category (FLIR, IRLS) based on fields of view. ESM systems were ranked lowest due to their requirement for a cooperative target.

IR systems were perceived to possess the best identification capability over all sensor systems considered and, as such, were ranked highest. Of these, FLIR systems were ranked above IRLS due primarily to their field of view capabilities. SAR systems were ranked third because of their standoff capabilities, while ESM systems were ranked fourth because of their requirement for a cooperative emitter. MTI systems, having limited identification capabilities, were ranked last.

IR systems capable of visual identification were believed to have the lowest false alarm rates and therefore were given the lowest value. SAR systems are

capable of providing target imagery, thus enabling the operator to determine if a contact warrants further investigation with optical sensors. For this reason, SAR systems were ranked second. Provided the target is employing active radar emissions, ESM systems are capable of classifying a contact based upon the parameters of the received signal, and are therefore ranked third. Of the available sensors, radar systems were believed to have the highest false alarm rates. Primarily due to background clutter, MTI radars have the highest rate, especially in high sea states.

Several complaints concerning AHP have been documented, chief among them that the procedure produces both rank reversal and arbitrary rankings [Ref. 22]. The ranking determined by the AHP may be altered by the addition or deletion of one or more alternative sensor systems. These alternatives may be completely unique or a close match when compared to the previous systems. For instance, sensor systems were originally ranked in the order Data Link, Radar, IR, and ESM in terms of desirability. With the addition of a fifth system, a Jammer, systems were ranked as Radar, IR, Data Link, ESM, and Jammer. Data Link is no longer ranked as the most desirable system, even though it is imperative that one be included in the final payload. These arbitrary rankings are produced when the principle of hierarchic composition is assumed because the scores on each alternative are normalized. The fact that these rankings may not be appropriate causes what has become known as rank reversal.

Expert Choice software was chosen to assist in the ranking of each sensor because it was both readily available and user friendly. However, because AHP provides the basis for Expert Choice software, users should be made aware of possible inconsistencies in calculated rankings. The author checked the final results of all rankings using the method of paired comparisons and ensured that they were free of all possible inconsistencies prior to implementing the UAV PAYLOAD SELECTION MODEL.

V. MODEL RESULTS

Future UAVs will employ the modular mission payload concept. Only an electro-optical (EO) sensor is to be carried onboard the baseline UAV employed in RSTA missions with later versions capable of supporting radars, electronic support measures (ESM) and infrared (IR) modular payload combinations. In general, the concept is that sensor systems will be swapped prior to each mission as dictated by the mission environment.

The UAV PAYLOAD SELECTION MODEL was run to determine the optimum payload under three conditions. The first considered a sensor purchasing budget of \$500,000 and that the AN/SRQ-4, Low Cost Common Data Link (LCCDL) and PIXLINK were all equally possible competitors for the payload data link system.

The results for the first condition are shown in Table 8.

Table 8 TEST RESULTS USING \$500,000 PURCHASING BUDGET

SENSOR /MANUFACTURER	WEIGHT	VOLUME	POWER
IRLS/TT	30.0 lbs	0.61 ft	200 W
LCDDL/PARAMAX	18.08 lbs	0.47 ft	80 W
TOTAL SYSTEM WEIGHT: 48.08 lbs			
TOTAL SYSTEM VOLUME: 1.08 ft			
TOTAL POWER CONSUMPTION: 280 W			
IDENTIFICATION VALUE: 0.011			
FALSE ALARM: 1.004			
TOTAL COST: \$370,000			

The AN/SRQ-4 (\$1,450,000) was rejected from the final sensor payload because its inclusion exceeded the \$500,000 purchasing budget. In this case, where EO is the sole sensor, as the size of the area of uncertainty (AOU) increases, so does the time required to provide 100 per cent area coverage. Target detection now becomes a question of target speed and location relative to the UAV, availability of follow-on assets and merchant shipping density in the AOU.

UAVs equipped with EO sensors alone will not adequately perform RSTA missions in a high threat environment where large areas are to be expeditiously searched. Radar systems on the other hand can cover large areas but, as an active

sensor, will cue enemy installations to any allied search effort. In order to respond to any possible active enemy emitters, ESM equipment must be collocated with other sensors onboard the surveillance platform. Therefore, in order to be an effective search asset on the modern battlefield, the next generation UAV must be equipped with a payload which maximizes survivability and time on station. That payload is a combination of active and passive sensors.

To that end, conditions two and three were experiments to determine the optimum multiple sensor payload under two purchasing budget conditions:

\$2,500,000 and \$5,000,000.

Table 9 displays the results when all three data link systems (AN/SRQ-4, Low Cost Common Data Link (LCCDL) and PIXLINK) were considered as equally possible competitors and the purchasing budget set at \$2,500,000.

**Table 9 TEST RESULTS USING \$2,500,000 PURCHASING BUDGET
(ALL THREE DATA LINK SYSTEMS AVAILABLE).**

SENSOR /MANUFACTURER	WEIGHT	VOLUME	POWER
MSAR/LORAL	67.9 lbs	1.48 ft ³	360 W
MTI/LINCOLN LABS	55.1 lbs	1.50 ft ³	350 W
FLIR/LORAL	20.0 lbs	3.60 ft ³	60 W
ESM /DALMO VICTOR	36.0 lbs	0.42 ft ³	137 W
LCCDL/PARAMAX	18.08 lbs	0.47 ft ³	80 W
TOTAL SYSTEM WEIGHT: 197.08 lbs			
TOTAL SYSTEM VOLUME: 7.47 ft³			
TOTAL POWER CONSUMPTION: 987 W			
IDENTIFICATION VALUE: 0.143			
FALSE ALARM: 1.268			
TOTAL COST: \$2,270,000			

Next, only the AN/SRQ-4 system was considered available for installation.

The purchasing budget remained at \$2,500,000. The results are displayed in Table 10.

**Table 10 TEST RESULTS USING \$2,500,000 PURCHASING BUDGET
(ONLY THE AN/SRQ-4 DATA LINK SYSTEM AVAILABLE).**

SENSOR /MANUFACTURER	WEIGHT	VOLUME	POWER
MSAR/LORAL	67.9 lbs	1.48 ft ³	360 W
IRLS/TI	30.0 lbs	0.61 ft ³	200 W
AN/SRQ-4/LUCAS	79.37 lbs	1.00 ft ³	150 W
TOTAL SYSTEM WEIGHT: 177.27 lbs			
TOTAL SYSTEM VOLUME: 3.09 ft³			
TOTAL POWER CONSUMPTION: 710 W			
IDENTIFICATION VALUE: 0.083			
FALSE ALARM: 1.077			
TOTAL COST: \$2,460,000			

Table 10 illustrates the effects of the increased size, electrical power requirements and cost of the AN/SRQ-4. In this case, the model rejected the MTI radar selected in Table 9, which contributed slightly to the decrease in identification value. More significant is the change from a FLIR sensor to an IRLS sensor and the omission of an ESM system, caused mainly by the increased cost of the AN/SRQ-4 data link (\$1,450,000). These two factors dramatically effect the identification capabilities of the resulting sensor payload. The rejection of both the MTI and ESM systems contributed to the reduction in false alarm rate. This is a factor of operator

interpretation of MTI data presentation, target recognition and ESM signals recognition.

As discussed in Chapter II, the inclusion of an MTI sensor greatly reduces the time required to provide 100 per cent coverage of an assigned search area. Its large area surveillance capabilities can provide initial detection of suspected contacts of interest and reduce the size of the AOU. Based on the author's operational expertise and the benefits of both an MTI sensor and ESM system during RSTA missions, the increased identification capabilities provided by the particular payload selected in Table 9 far outweighs the increased false alarm rate.

The experiment was repeated for the third condition with a new available purchasing budget of \$5,000,000. The results are displayed in Tables 11 and 12.

**Table 11 TEST RESULTS USING \$5,000,000 PURCHASING BUDGET
(ALL THREE DATA LINK SYSTEMS AVAILABLE).**

SENSOR /MANUFACTURER	WEIGHT	VOLUME	POWER
MSAR/LORAL	67.9 lbs	1.48 ft ³	360 W
MTI/LINCOLN LABS	55.1 lbs	1.50 ft ³	350 W
FLIR/LORAL	20.0 lbs	3.60 ft ³	60 W
ESM/DALMO VICTOR	36.0 lbs	0.42 ft ³	137 W
LCDDL/PARAMAX	18.08 lbs	0.47 ft ³	80 W
TOTAL SYSTEM WEIGHT: 197.08 lbs			
TOTAL SYSTEM VOLUME: 7.47 ft³			
TOTAL POWER CONSUMPTION: 987 W			
IDENTIFICATION VALUE: 0.143			
FALSE ALARM: 1.268			
TOTAL COST: \$2,270,000			

Table 11 displays the results when all three data link systems (AN/SRQ-4, Low Cost Common Data Link (LCCDL) and PIXLINK) were considered as equally possible competitors and the purchasing budget set at \$5,000,000. The results are identical to those displayed in Table 9.

Next, only the AN/SRQ-4 system was considered available for installation. The purchasing budget remained at \$5,000,000. The results are displayed in Table 12.

**Table 12 TEST RESULTS USING \$5,000,000 PURCHASING BUDGET
(ONLY THE AN/SRQ-4 DATA LINK SYSTEM AVAILABLE).**

SENSOR /MANUFACTURER	WEIGHT	VOLUME	POWER
MSAR/LORAL	67.9 lbs	1.48 cu ft	360 W
FLIR/LORAL	20.0 LBS	3.60 cu ft	60 W
ESM/IBM	32.5 LBS	0.76 cu ft	235 W
AN/SRQ-4	79.37 lbs	1.00 cu ft	150 W
TOTAL SYSTEM WEIGHT: 199.77 lbs			
TOTAL SYSTEM VOLUME: 6.84 cu ft			
TOTAL POWER CONSUMPTION: 805 W			
IDENTIFICATION VALUE: 0.137			
FALSE ALARM: 1.101			
TOTAL COST: \$3,260,000			

The increased identification value in Table 11 is due to the inclusion of an MTI sensor in the final payload. This same sensor however, causes an increased false alarm rate in the same case. In conclusion, a UAV equipped with multiple sensors such as moving target indicator (MTI) radar, synthetic aperture radar (SAR), ESM and IR can cover the entire area in a fraction of the time required by the UAV equipped with a single optical sensor. This leaves more time available for target identification and classification, and frees the UAV to perform secondary missions if time and fuel permit. A UAV equipped with such a sensor suite is more capable of

providing the SAG commander with timely area coverage, valuable situational awareness and a broader extension of the SAG's weapons and sensor systems and, ultimately, it's sphere of influence. Given the physical constraints of the airframe, the results of all three cases indicate that multiple sensor systems may be installed onboard the next generation UAV. The entire payload system may be on-line and operating simultaneously, thereby increasing the platform's on-station detection capabilities.

VI. CONCLUSIONS

While performing Reconnaissance, Surveillance and Target Acquisition (RSTA) missions in a hostile maritime environment, expeditious coverage of assigned areas of uncertainty (AOUs) is crucial to the success of Surface Action Group (SAG) operations. In littoral regions especially, small, fast and maneuverable gunboats are most likely to be encountered in areas of dense merchant shipping. With the recent reduction in the number of MPA squadrons and overseas deployment sites, non-organic RSTA assets may not be available to the SAG commander during future conflicts.

Unmanned Aerial Vehicles (UAVs) become an attractive alternative and will allow ships without organic air assets, such as the Arleigh Burke class DDG-51 which will be the main component of future surface forces, to perform long range RSTA missions independently of other units. This could include long duration barrier operations in littoral regions. Even those ships with an organic helicopter onboard will be able to generate accurate situation and targeting data against multiple threats simultaneously using both the UAV and its LAMPS helicopter, thereby increasing the size of its radius of influence. The UAV could also act as a targeting platform for armed LAMPS helicopter strikes against small gunboats and combatants or for longer range missiles such as Harpoon. The SAG commander needs an organic RSTA asset to be aware of activities in his battle space.

UAVs equipped solely with electro-optical (EO) sensors will prove incapable of providing timely, accurate location and targeting data while searching large AOU's in bounded littoral seas. This stems from the fact that the limited detection ranges of IR systems require smaller track spacings in order to provide complete coverage of the assigned area. As a result, SAG commanders will not receive the target track data necessary to recognize potential threat axes on which to concentrate organic weapons systems.

Outfitting UAVs with multiple sensor systems capable of simultaneous operation can provide a SAG commander with timely area coverage, valuable situational awareness and a broader extension of the SAG's weapons and sensor systems and, ultimately, its sphere of influence. Such a payload mix should include radar, electronic support measures (ESM) and infrared (IR) systems capable of searching for, detecting, classifying and tracking potential targets in large AOU's where locating data may be time-late and inaccurate. Additionally, an electronic data link capable of transmitting wideband imagery, IR, EO, or Synthetic Aperture Radar (SAR) data should be included.

UAVs presently under development are capable of carrying multiple mission payloads such as those described above and, in doing so, providing 100 per cent coverage of an assigned area in a fraction of the time normally required by a UAV equipped solely with IR or optical sensors. This leaves more time available for target identification and classification, and frees the UAV to perform secondary missions if time and fuel permit.

The UAV PAYLOAD SELECTION MODEL is an optimization model capable of selecting a multiple sensor payload to fit an individual UAV payload cavity. The model determines the optimum payload based on the utility or perceived value of the individual sensor in a RSTA mission scenario based on the user's operational expertise, the volume of the UAV's payload cavity, the amount of electrical power supplied by onboard electrical systems, and the weight of the payload in pounds which the UAV is capable of carrying. Additionally, mathematical constraints are included in the model which consider unit cost, target identification capability, and false alarm rate when determining the optimum payload.

The model was run for two cases under several budget scenarios. The first case considered all available data link systems to be equal competitors, while the second considered the AN/SRQ-4 to be the only data link system available for installation. Given the physical constraints of the airframe, the results of both tests indicate that multiple sensor systems may be installed onboard the next generation UAV. The entire payload system may be on-line and operating simultaneously, thereby increasing the platform's onstation detection capabilities. However, there are some trade-offs between both cases. The overall size and power requirements of the AN/SRQ-4 force the model to reject the MTI sensor and its wide area search capabilities. This in turn reduces the overall identification capabilities of the sensor payload because the platform is now forced to spend more time in a search pattern rather than identifying contacts detected by the MTI system. Consideration should

be given to selecting data link systems such as LCCDL and PIXLINK which were designed specifically for UAV applications. Their component miniaturization, reduced cost and low power consumption allow for greater onstation performance capabilities while maintaining the required connectivity between the UAV and its controlling platform.

It is a fact that future military conflicts will involve power projection in littoral regions. It is also a fact that tactical commanders require an organic RSTA asset capable of providing timely, multiple sensor, over-the-horizon reconnaissance. Through this thesis, we have demonstrated that, in their present configuration, UAVs are incapable of meeting these needs. Sensor technology is presently available, however, which can provide UAVs with multiple sensor systems and, at the same time, meet the requirements of the tactical commander. If we are to continue to require our military forces to "show the flag" in areas of the world which are hostile to the policies of the United States government, then we must ensure that they do so with the best equipment technology has to offer. With regard to UAVs, that technology is available today - on the open market.

APPENDIX A: UAV PAYLOAD SELECTION MODEL FORMULATION

```
$OFFUPPER ONSYMKREF
$INLINECOM { }
$TITLE UAV PAYLOAD SELECTION MODEL
*
```

```
$ONTEXT
```

The UAV PAYLOAD SELECTION MODEL is designed to determine a sensor payload to be carried onboard the next generation UAV presently under consideration by the UAV JOINT PROJECT OFFICE. The selected payload must be capable of performing Reconnaissance, Surveillance and Target Acquisition (RSTA) missions under wartime conditions.

The selected payload will be capable of matching the identification requirements set for the PIONEER UAV which performed during both Operations Desert Shield and Desert Storm. Additionally, because the payload selected by the UAV PAYLOAD SELECTION MODEL will include both RADAR and ESM systems, the next generation UAV will be capable of searching larger areas of interest than were previously possible with the PIONEER system.

The constraints used in the model are designed to conform to the design specifications for the Maritime UAV presently under consideration by the UAV Joint Program Office, however, with minor modifications of the PARAMETERS file, they will conform to any version of UAV presently under consideration for development.

The data in the DATA file is a product of the JPO UAV Master Plan and various articles found in the writing of this thesis. COST data, however, was made available through industrial sources and are estimates.

Author: LCDR John Francis Keane, USN 018-52-6688/1320

```
*-----
$OFFTEXT
```

```
*----- GAMS model options -----
```

```
OPTIONS
LIMROW      = 20
LIMCOL      = 20
SOLPRINT    = Off
LP          = xa
MIP         = xa
RMIP        = xa
OPTCR       = 0.0
OPTCA       = 0
ITERLIM     = 100000
RESLIM      = 10000
INTEGER1    = 1
;
```

```
$Include UAVSETS.SET
```

Parameters

Tot_Wt	total payload carrying capacity for the UAV sensor system measured in pounds
Tot_Vol	total volume of the UAV's onboard payload cavity
Tot_Pwr	total power available through UAV's onboard electrical system
Tot_Cost	total budget available for purchase of UAV sensor payload

```

MTI_ID      weighted value for identification value of MTI radar system

False_Alm   mission planner's desired false alarm rate

U(j,k)      utility value given to system j
W(j,k)      weight of system j measured in pounds
VOL(j,k)    volume of system j measured in cubic feet
PWR(j,k)    power requirements for system j measured in watts
ID(j,k)     identification requirements of system j
FALSE(j,k)  false alarm factor for system j
COST(j,k)   cost in dollars of system as quoted by manufacturer k
;

$INCLUDE UAVPARa.PAR
$INCLUDE UAVDAT3a.DAT

* Only systems with a valid utility value will be considered for employment
onboard the UAV *system.

JK(j,k)      = YES $ SENSOR(j,k,"VALUE");
U(JK)        = SENSOR(JK, "VALUE");
W(JK)        = SENSOR(JK, "WEIGHT");
VOL(JK)      = SENSOR(JK, "VOLUME");
PWR(JK)      = SENSOR(JK, "POWER");
ID(JK)       = SENSOR(JK, "ID");
FALSE(JK)    = SENSOR(JK, "FALSE");
COST(JK)     = SENSOR(JK, "COST");

FREE VARIABLE
Z            objective function value
;

BINARY VARIABLE
X(j,k)      variable set to 1 if system selected for use
;

EQUATIONS

OBJ         objective function

ONE(j)      only one of each type system will be selected by the model

* WEIGHT    the total weight of the combined selected payload will not exceed
the payload carrying capacity of the UAV

* VOLUME    the total volume of the combined selected payload will not exceed
toat of the UAV's payload cavity.

* POWER     the total amount of electrical power required to operate the
selected payload will not exceed the total power supplied by the
UAV's onboard electrical system.

* IDENT     the selected payload will be able to positively identify or
assist in the identification of contacts of interest. The
selected payload system must be able to at least meet the
identification standards set by the PIONEER
UAV system.

FALSEa      the number of false alarms will be minimized.

* COSTa     the total cost of the selected payload system will be kept within
the amount of money available for purchase.

;

OBJ..
SUM(JK, U(JK)*X(JK) )=E=Z
;

```

```

ONE(j) ..
    SUM(k$JK(j,k), X(j,k) )=1=1
;

WEIGHT..
    SUM(JK, W(JK) * X(JK) ) =1= Tot_Wt
;

VOLUME..
    SUM(JK, VOL(JK) * X(JK) ) =1= Tot_Vol
;

POWER..
    SUM(JK, PWR(JK) * X(JK) ) =1= Tot_Pwr
;

IDENT..
    SUM(JK, ID(JK) * X(JK) ) =g= MTI_ID
;

FALSEa..
    SUM(JK, FALSE(JK) * X(JK) ) =1= False_Alm
;

COSTa..
    SUM(JK, COST(JK) * X(JK) ) =1= Tot_Cost
;

MODEL UAV / ALL /;
SOLVE UAV USING mip MAXIMIZING Z;
display U;
display W;
display VOL;
display PWR;
display ID;
display FALSE;
option X:5:0:1;
display X.L;
display One.L;
display WEIGHT.L;
display VOLUME.L;
display POWER.L;
display IDENT.L;
display FALSEa.L;
display COSTa.L;

```

APPENDIX B: UAV PAYLOAD SELECTION MODEL DATA

A. INDICES

*-----

\$ONTEXT

The following is a listing of the specific systems under consideration for employment onboard the next generation of Unmanned Aerial Vehicle (UAV). In addition to the specific sensor type (index j), the set includes a list of sensor system manufacturers (index k). For ease of selection, sensor systems are identified by their respective manufacturer.

*-----

\$OFFTEXT

SETS

- j set of specific sensor systems
- / MTI Moving Target Indicator Radar
- SAR Synthetic Aperture Radar
- MSAR Miniature Synthetic Aperture Radar
- ELINT Electronic Intelligence
- ESM Electronic Support Measures
- FLIR Forward Looking Infrared
- IRLS Infrared Line Scanner
- DL Electronic Data Link
- /

*-----

k set of sensor system manufacturers
 / AIL AIL
 HDL Harry Diamond Labs
 LHD Lockheed
 LNC Lincoln Labs
 LOR Loral
 LOR1 Loral
 LOR2 Loral
 ESL ESL
 IBM IBM
 ESYS E Systems
 DAL Dalmo Victor
 WHS Westinghouse
 WHS1 Westinghouse
 KOL Kollmorgen
 HUG Hughes
 IRM Inframetrics
 PLK Plinkington
 HON Honeywell
 HON1 Honeywell
 HON2 Honeywell
 TI Texas Instruments
 FMS FMPS
 LAI Israeli Aircraft Industries
 TAD Tadiran
 BS Barr & Stroud
 CAI CAI
 VIN Vinten
 VIN1 Vinten
 LUC Lucas
 MAC McDonnell Douglas
 PAR Paramax
 NAC Naval Avionics Center
 FAI Fairchild_Weston
 FAI1 Fairchild_Weston
 MOT Motorola
 MOT1 Motorola
 /

\$ONTEXT

Note: (1) In the case where a manufacturer produces several types of sensor system j, the manufacturer's abbreviated name has been numerically appended. For example: Loral produces two models of FLIR and therefore has been designated LOR and LOR1 in order to distinguish between the two systems.

\$OFFTEXT

JK(j,k) compatible system - manufacturer pairs;

*-----

\$ONTEXT

A compound set which ensures that only those system - manufacturer pairs with a valid utility value are considered for inclusion as part of the selected sensor payload.

*-----

\$OFFTEXT

B. PARAMETERS

*-----

\$ONTEXT

The following is a listing of the design specifications limiting the capabilities of the UAV system. They include:

- payload capacity
- volume of the payload cavity
- power available through onboard electrical systems
- budget available with which to purchase sensor systems

*-----

\$OFFTEXT

Tot_Wt	=	200
;		
Tot_Vol	=	15.0
;		
Tot_Pwr	=	1000.0
;		
MTI_ID	=	0.006
False_Alm	=	2
;		
Tot_Cost	=	2500000

C. DATA

*-----

\$ONTEXT

Sensors presently under consideration for inclusion in the UAV sensor package include:

- Moving Target Indicator Radars
- Synthetic Aperture Radars
- Mini - Synthetic Aperture Radars
- Electronic Intelligence
- Electronic Support Measures
- Forward Looking Infrared
- Infrared Line Scanners
- Electronic Data Link

They are listed below as functions of utility, weight, volume, power, identification capability, perceived false alarm factor and unit cost. Unit cost values are estimated unit costs.

*-----

\$OFFTEXT

Table SENSOR(J,K, *)

	VALUE	WEIGHT	VOLUME	POWER	ID	FALSE	COST
* The following is a listing of RADAR systems under consideration for inclusion in the UAV sensor payload.							
MTI.AIL	0.0130	80.0	0.95	520	0.006	0.167	700000
MTI.LHD	0.0130	125.0	2.00	1200	0.006	0.167	350000
MTI.LNC	0.0130	55.1	1.5	350	0.006	0.167	700000
MTI.HDL	0.0130	110.0	3.50	1050	0.006	0.167	700000
SAR.LOR	0.0400	88.0	1.25	470	0.072	0.073	730000
SAR.LOR1	0.0400	67.9	1.48	360	0.072	0.073	730000

* The following is a listing of ESM systems under consideration for inclusion in the UAV sensor payload.

ELINT.ESL	0.0160	150.0	5.70	1000	0.033	0.040	600000
ESM.IBM	0.0100	32.5	0.76	235	0.020	0.025	730000
ESM.ESYS	0.0100	37.0	0.36	210	0.020	0.025	550000
ESM.DAL	0.0100	36.0	0.42	137	0.020	0.025	400000

* The following is a listing of FLIR systems under consideration for inclusion in the UAV sensor payload.

FLIR.WHS	0.0010	92.0	0.46	675	0.045	0.003	600000
FLIR.KOL	0.0007	55.0	0.83	275	0.045	0.003	400000
FLIR.HUG	0.0010	100.0	0.92	644	0.045	0.003	700000
FLIR.LOR	0.0016	75.0	1.78	300	0.045	0.003	350000
FLIR.LOR1	0.0040	20.0	3.60	60	0.045	0.003	350000
FLIR.IRM	0.0005	71.0	0.497	50	0.045	0.003	900000
FLIR.WHS1	0.0002	205.0	2.56	500	0.045	0.003	600000
FLIR.PLK	0.0007	35.0	0.49	65	0.045	0.003	900000
FLIR.HON	0.0017	70.0	1.78	300	0.045	0.003	500000
FLIR.TI	0.0005	75.0	1.54	300	0.045	0.003	280000
FLIR.FMS	0.0001	42.0	1.82	350	0.045	0.003	400000
FLIR.IAI	0.0009	80.0	1.92	240	0.045	0.003	360000
FLIR.TAD	0.0002	55.0	1.35	280	0.045	0.003	900000
FLIR.BS	0.0003	104.0	3.43	150	0.045	0.003	700000

* The following is a listing of IRLS systems under consideration for inclusion in the UAV sensor payload.

IRLS.HON	0.0003	244.0	5.90	651	0.009	0.003	500000
IRLS.HON1	0.0003	208.0	5.00	795	0.009	0.003	500000
IRLS.HON2	0.0003	164.0	6.90	650	0.009	0.003	500000
IRLS.LOR	0.0006	76.0	1.80	400	0.009	0.003	400000
IRLS.LOR1	0.0005	144.3	3.70	545	0.009	0.003	400000
IRLS.LOR2	0.0003	15.0	0.20	65	0.009	0.003	600000
IRLS.TI	0.0030	30.0	0.61	200	0.011	0.004	280000
IRLS.CAI	0.0004	65.0	3.67	600	0.011	0.004	400000
IRLS.BS	0.0001	15.0	0.39	250	0.011	0.004	700000
IRLS.VIN	0.0003	44.0	0.46	256	0.011	0.004	500000
IRLS.VIN1	0.0030	29.0	0.46	250	0.011	0.004	500000

* The following is a listing of DATA LINK systems under consideration for inclusion in the UAV sensor payload.

DL.LUC	0.2450	79.37	1.00	150	0	1.0	1450000
DL.PAR	0.2450	18.08	0.47	80	0	1.0	90000
DL.MAC	0.2450	27.50	0.53	300	0	1.0	20000

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