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Capturing the Essential Factors in Reconnaissance and Surveillance Force Sizing and Mix

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Project AIR FORCE

PREFACE

This documented briefing describes research in the Project AIR FORCE Reconnaissance, Surveillance, and Targeting project; it includes work relating to intelligence, surveillance, and reconnaissance (ISR) mission analysis, technology assessment, and methodology / model development. The briefing also describes RAND's Reconnaissance and Surveillance Allocation Model (RSAM) that has been developed as part of the project. The model will be used in conjunction with a weapon allocation model to determine reconnaissance and surveillance requirements for attacking ground targets through an entire campaign. By varying the campaign plan and the ISR option packages in RSAM, tradeoff studies can determine the best types and required numbers of sensors and platforms.

The project is conducted within the Force Modernization and Employment Program of Project AIR FORCE. It is sponsored by the Directorate of Operational Requirements.

PROJECT AIR FORCE'

Project AIR FORCE, a division of RAND, is the Air Force's federally funded research and development center (FFRDC) for studies and analyses. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is performed in three programs: Strategy and Doctrine, Force Modernization and Employment, and Resource Management and System Acquisition.

GLOSSARY

AI	Airborne interceptor
AOA	Angle of arrival
ATC	Automatic target cueing
ATO	Air tasking order
ATR	Automatic target recognition
AWACS	Airborne warning and control system
BDA	Bomb damage assessment
BM	Battle management
BM/C^3I	Battle management/command, control, communication, and intelligence
C^4I	Command, control, communication, computers, and intelligence
CAGIS	Cartographic and geographic information system
CFLOS	Cloud-free line-of-sight
CMT	Critical mobile targets
CONOPS	Concept of operations
CTEM	Conventional targeting effectiveness model
DTED	Digital terrain elevation data
ELINT	Electronic intelligence
EO	Electro-optical
EO/IR	Electro-optical/infrared
EW/GCI	Early warning/ground control intercept
GRD	Ground resolved distance
HARM	High-speed anti-radiation missile
IF	Intermediate frequency
IMINT	Imagery intelligence
INTS	Intelligence sources
IPB	Intelligence preparation of the battlefield
IR	Infrared
IRGC	Islamic Revolutionary Guard Corps
IRST	Infrared search and track

ISR	Intelligence reconnaissance and surveillance
LO	Low observable
LOS	Line-of-sight
LP	Linear program
MTI	Moving target indicator
MTI/SAR	Moving target indicator/signature aperture radar
NIIRS	National Imagery Interpretation Rating Scale
NLO	Near low observable
POL	Polarization
R&S	Reconnaissance and surveillance
RADINT	Radar intelligence
RCS	Radar cross section
RS&T	Reconnaissance, surveillance, and targeting
RSAM	Reconnaissance and Surveillance Allocation Model
SA	Situational awareness
SAM	Surface-to-air missile
SAR	Synthetic aperture radar
SEAD	Suppression of enemy air defenses
SIGINT	Signals intelligence
SSMTEL	Surface-to-surface missile transporter-erector-launcher
TBM	Theater ballistic missile
TDOA	Time difference of arrival
U.S.	United States
UAV	Unmanned aerial vehicles
VHF	Very high frequency
VHF RCS	Very high frequency radar cross section
VLO	Very low observable

Capturing the Essential Factors in Reconnaissance and Surveillance Force Sizing and Mix

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This briefing describes an approach to reconnaissance and surveillance force sizing that is attuned to technology advances in command, control, communications, computers, and intelligence (C^4I); platforms, sensors, and processing; and concepts of operations (CONOPS) that exploit the synergy arising from intelligence, surveillance, and reconnaissance (ISR) fusion. We describe a methodology and model that quantitatively capture the effects of ISR fusion, and platform and sensor tradeoffs in an overall campaign context. CONOPS for critical missions and appropriate platform / sensor packages are described. Notional results for ISR force sizing and mix illustrate the importance of intelligence preparation of the battlefield (IPB), cueing, fusion of moving target indicator (MTI) and synthetic aperture radar (SAR), multiplatform signals intelligence (SIGINT), defense drawdown, basing, and technological factors in the context of a campaign with phased objectives.

The Reconnaissance and Surveillance Allocation Model (RSAM) has many potential applications. Determining the best approach to practical continuous or frequent revisit surveillance using a mix of manned aircraft and unmanned aerial vehicles (UAVs) is a prime example. UAV platform and sensor design, collection and attack tactics, and system factors must all be considered in a meaningful tradeoff.

Outline

– **Introduction**

– **Methodology and Scenario**

– **Missions, CONOPS and Technology**

– **Exemplar Results**

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Background

Context

- **National SIGINT architecture studies**
- **National IMINT architecture studies**
- **Airborne reconnaissance architecture studies**

Trends for the future

- **C4I technology can support broader fusion of intelligence data**
- **Technology of sensors, platforms, and processors is advancing**
- **CONOPS can exploit synergy arising from intelligence fusion**

How to obtain the best future force mix

- **Need to capture the effects of intelligence fusion and appropriate CONOPS**
- **Need to perform appropriate sensor and platform tradeoffs**
- **Need to measure R&S force effectiveness in context of campaigns**

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To place our study in an overall context, it should be noted that there are many recent and ongoing studies on ISR and related subjects. In particular, there have been studies of national SIGINT and imagery intelligence (IMINT) architectures and airborne reconnaissance architecture. However, we know of no studies that integrate air and space/SIGINT and IMINT and are producing quantitative results.

We also note that the trend is toward broader and more rapid fusion of intelligence data from any and all air, space, and ground sources and across the intelligence sources (INTS). Moreover, C^4I technology improvements can support such fusion, and the technology of sensors, sensor platforms, data processing is advancing to supply more and better ISR data. With new CONOPS tailored to exploit these advances, the potential synergy can be realized.

To obtain the best future ISR force sizing and mix, the effects of ISR fusion and appropriate CONOPS must be part of the analysis and modeling. Sensor and sensor platform tradeoffs are essential.

Finally, ISR force effectiveness must be measured in the context of adequately realistic campaigns and the numbers and types of targets involved.

Essential Factors in Sizing R&S Force

Pre-conflict collection and exploitation capability
- Intelligence preparation of the battlefield (IPB)
- Crisis activities

Cueing
- Area limitation cueing of MTI and IMINT
- MTI and SIGINT cueing of IMINT sensors
- Low resolution cueing of high resolution sensors

Fusion
- MTI and SAR for tracking CMTs
- Multi-platform SIGINT

Campaign factors
- R&S support for targeting
- Peacetime / crisis / wartime transition
- Time-phased force deployment (TPFD) and defense drawdown
- Basing options and no-fly zones
- BDA and timeliness
- Weather and intervisibility

Technological factors
- Sensor range, resolution, search rate, weight
- Platform range, endurance, capacity, signature, altitude, speed
- Processor throughput, algorithm performance, weight

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In the above chart, we enumerate the factors that we believe are essential to capture in an ISR force sizing and mix model. Later in the briefing we will explain how our methodology, analysis, and model handle these factors.

First, we note that each of the phases of data collection—peacetime, crisis, and transition to war, has unique considerations that must be accounted for. Also, the data collected in these pre-war phases reduce the wartime ISR requirements and support situation awareness that can provide a tactical advantage.

Cueing can provide high ISR force multiplication factors and reduce data processing loads by greatly reducing the areas that must be searched or kept under surveillance. One form of cueing is area limitation from pre-war reconnaissance and other intelligence data. In extended operations, area limitation possibly can be refined in near real-time during crisis or wartime operations. Area limitation can cue imaging sensors for stationary objects and MTI radars for mobile targets. Further targeting for imaging sensors can be provided by MTI radars or SIGINT collectors. Low-resolution imaging sensors or sensing modes can be used to more quickly cover large areas and provide cues for high-resolution imaging.

Fusion from multiple sensors can improve target detection and identification or reduce false alarms. An important example is the fusion of MTI motion track information with imaging. Another is the fusion of SIGINT from several platforms to reduce the cued area by orders of magnitude.

It is also essential to capture the quantitative effects of air-to-ground campaign operations. This includes ISR support for targeting, including the effects of target type and geographic distribution, the need for bomb damage assessment (BDA) to support efficient re-attack and high assurance of kill, and consideration of timeliness factors for rapid weapon delivery or extended track of mobile targets. It also includes the time phasing of weapons platforms into the theater, which affects campaign timing, and the drawdown of enemy air defense assets—attack wave by attack wave—which in turn affects which ISR platforms are survivable and what standoff ranges are required. ISR platform basing options and no-fly zones, imposed for political or operational reasons, must also be accounted for. Finally, it is essential to account for the effects of weather (on the various sensor types) and intervisibility (as a function of platform position and altitude).

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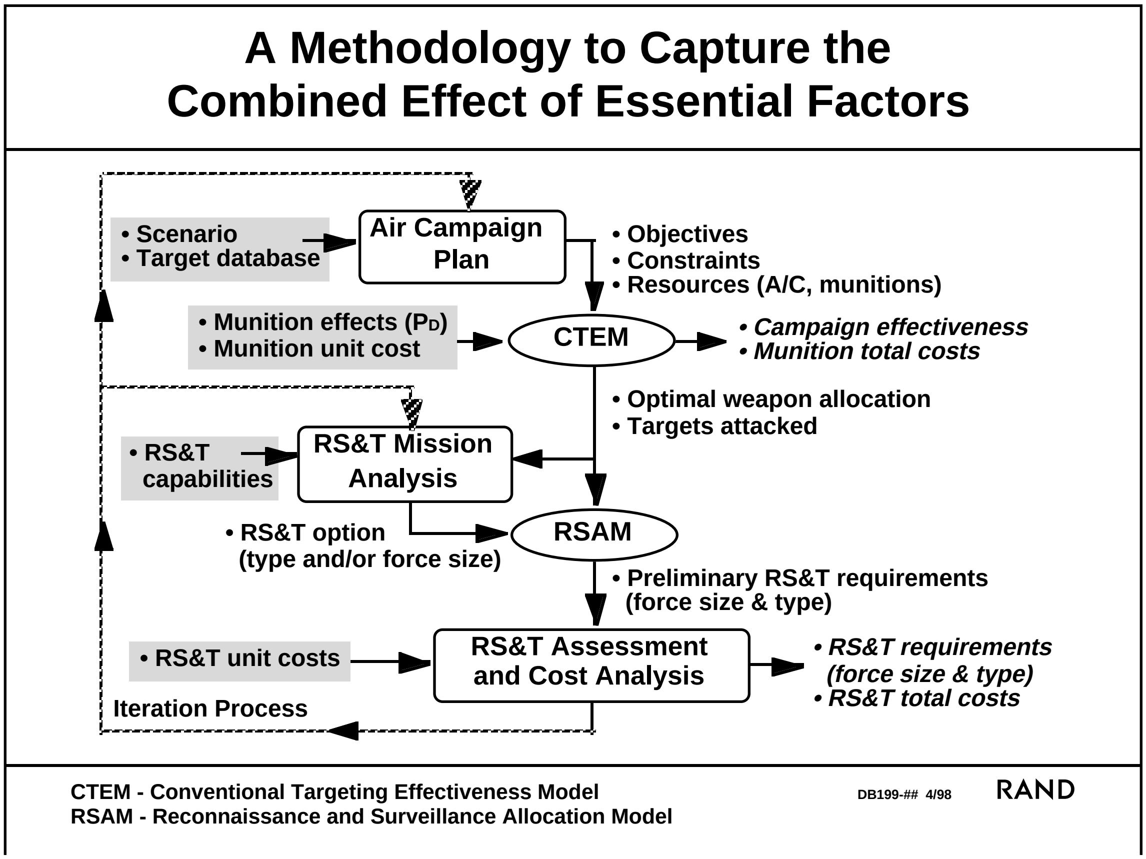

This chart illustrates our overall methodology for determining reconnaissance, surveillance, and targeting (RS&T) requirements and costs. Starting with a scenario and target database, an air campaign plan is described in terms of prioritized and sequenced objectives, constraints on force operations, and time-phased deployment of aircraft and munitions into theater operations. A linear program for weapon allocation, the Conventional Targeting Effectiveness Model (CTEM), is used to determine optimal weapon / platform / target pairing and allocation. As indicated, munition effects and munition costs are also input to CTEM. The outputs include the optimal allocation of platforms and weapons to targets for each wave of the campaign. This “ticker tape” (time-phased weapon allocation) contains the number of targets in each category attacked, broken down by platform, weapon type, and number of weapons. The campaign effectiveness in terms of the achievement of objectives as a function of time and munition costs is also produced. It should be noted that CTEM is not a true campaign model. It simply calculates the requirements to kill specified numbers of targets in various categories. Killing these targets is assumed to achieve campaign objectives such as halting the invading army.

CTEM assumes no strike limitations for the targets it attacks, i.e., it assumes the targets have been found, identified, and located, and the battle management

(BM), and command, control, communications and intelligence (C^3I) has been performed. The output of CTEM is the input to the RSAM. RSAM calculates the reconnaissance and surveillance assets required to implement the attack determined by CTEM, and described by the ticker tape.

In addition to the ticker tape, inputs to RSAM include RS&T option packages, sensor platforms, and sensor types and numbers. The option packages are chosen based on current and projected RS&T capabilities, and mission analyses to determine feasible and effective operational concepts for specific missions and target categories. Force size is specified in terms of a baseline force (e.g., a fixed U-2 force in theater), and an inexhaustible "rubber" force of a particular platform / sensor combination, which is drawn upon to determine requirements.

The output of RSAM, in the first iteration, is a preliminary RS&T requirement to serve the attack specified by the CTEM ticker tape.[1, 2] For each option package, the required number is produced. These types and numbers and their unit costs are then input to an assessment and cost analysis process, which involves tallying the total costs, assessing the output of RSAM, and potentially modifying the target database and objectives input to CTEM. This may lead to an iterative process in which one then modifies the option package input to RSAM. The goals of the iteration are to produce more efficient campaign execution and to perform tradeoffs between RS&T assets and the effectiveness in executing campaign targeting and attack.

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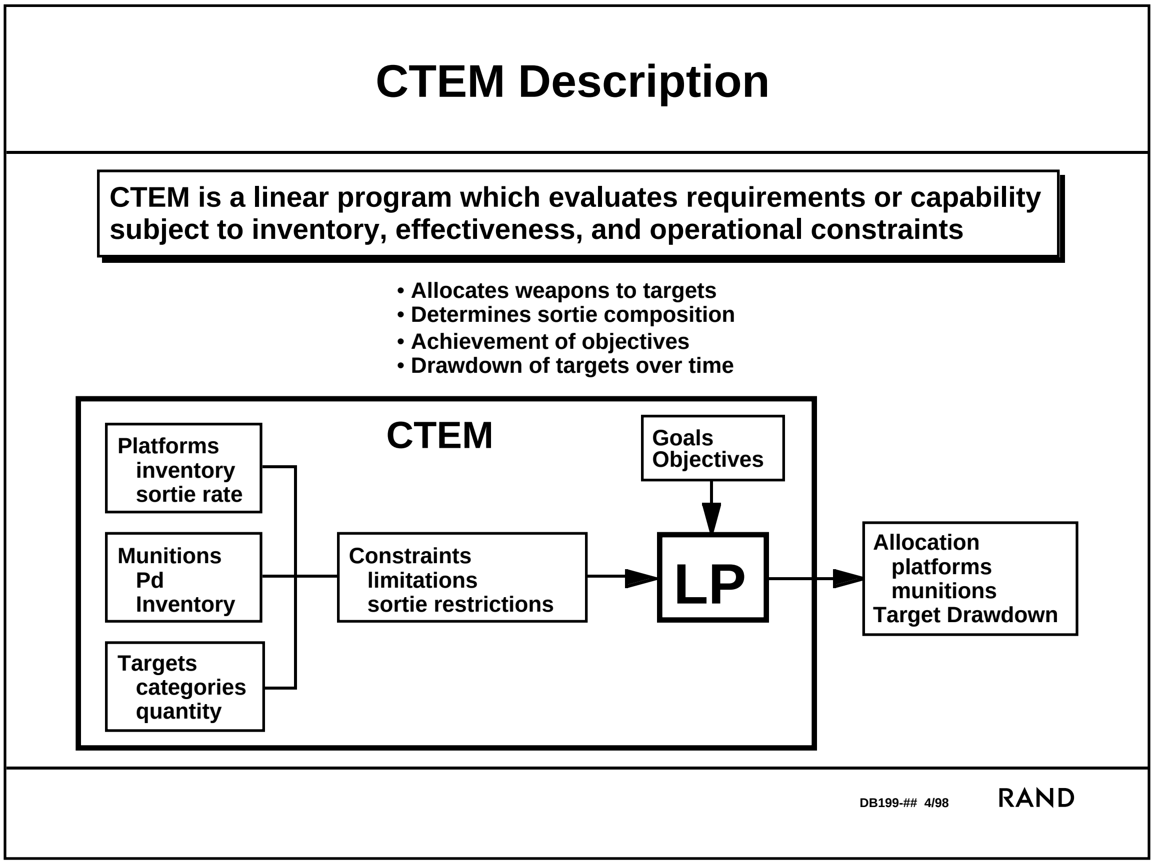
[1] In the current version of RSAM, target detection and target identification requirements are quantitatively matched to the sensor capabilities to perform these functions. In addition to identification, targeting with precise guided munitions requires high-fidelity geolocation. As a part of the Reconnaissance and Surveillance for Targeting study in which RSAM was developed, the authors studied the ability of various platform / sensor combinations to geolocate targets—and certain aspects of this capability were incorporated into RSAM. However, the matching of target location requirements and the various sensor target location capabilities has not yet been implemented in RSAM. Thus, target location errors are currently assumed to be compatible with SABSEL weapon effectiveness information.

[2] Two-way line-of-sight (and beyond line-of-sight) data links for sensor command and control (C2) data are important considerations that were treated only indirectly in RSAM. First, for very-high-data rate information such as for SAR high-resolution wide-area search, we took as a baseline that the SAR processing and automatic target recognition / cueing would take place on the sensor platform—so that modest communication link data rates would result. The performance and weight of the onboard processing were estimated and included in the sensor platform payload. Second, two-way data transfer requirements (the raw sensor data and platform command and control data) will be calculated as an ancillary output from RSAM.



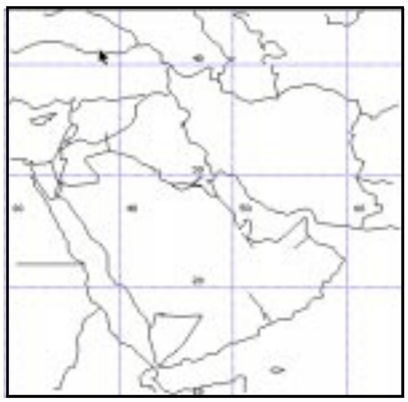
This chart illustrates the Conventional Targeting Effectiveness Model (CTEM) in some detail. CTEM is an optimal allocator that uses a linear program (LP) algorithm to evaluate requirements or capability subject to inventory, effectiveness, and operational constraints. As illustrated on the chart, inputs to CTEM are weapon platform inventory (as a function of attack wave and platform type); munitions inventory and effectiveness (probability of damage [Pd] for each weapon / target combination); and the categories, numbers, and location information on targets to be attacked. Additional constraints and limitations such as sortie restrictions to avoid air defenses also can be prescribed.

CTEM performs its optimization for a set of prioritized and sequenced goals and objectives of the air campaign given attack constraints, time-phased weapon platform deployment, munition inventory, and weapon effects and loadings. CTEM determines the optimal time-phased allocation of weapons and weapon platforms, and the resultant performance in terms of target drawdown and the consequent achievement of objectives.

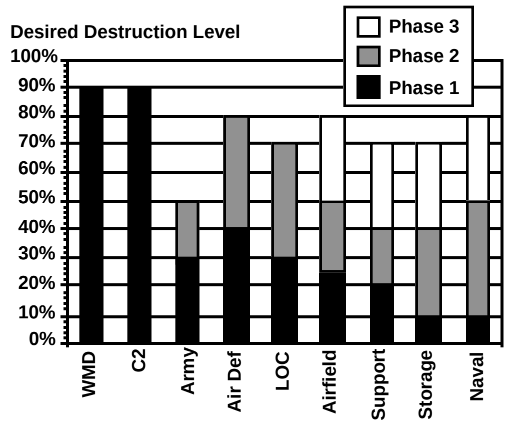
Exemplar Scenario

Iranian Scenario FY2000

- 3 Phase Air Campaign to Stop Iranian Invasion
- Iran Attempts to Grab Kuwaiti Oil Fields
- Islamic Republic of Iran Ground Forces and Islamic Revolutionary Guard Corps
- Armored Divisions Push South Toward Kuwait
- IRGC defends borders and provides internal security



- FY2000 Munition Inventory
- Air Deployment Based on Nimble Dancer



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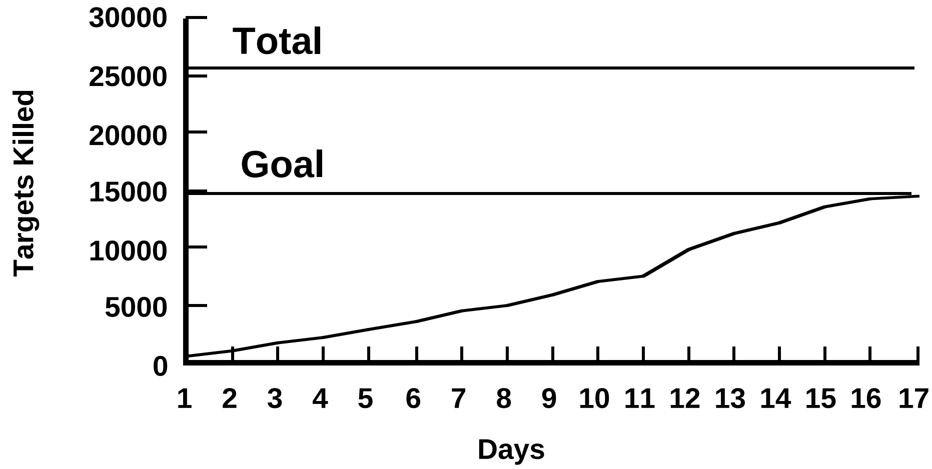
This chart illustrates, for a FY2000 Iranian scenario, a typical set of phased and prioritized objectives that would be used as inputs to CTEM. This scenario and the quantitative description of enemy targets, their distribution, and the availability of U.S. forces in theater are used in the exemplar results shown later in this briefing.

This illustrative campaign has three phases to stop an Iranian invasion of Kuwait in which Iran attempts to gain control of Kuwaiti oil fields using Islamic Republic of Iran ground forces and Islamic Revolutionary Guard Corps (IRGC). In this scenario, the armored divisions push south toward Kuwait while the IRGC defends borders and provides internal security.

For the United States, we used the prescribed percentage of the estimated FY2000 munition inventory and air deployment based on Nimble Dancer estimates.

The bar graph shows the percentage desired destruction of nine generic target classes for each of the three campaign phase objectives. Note that for some target classes a destruction level is prescribed for each phase.

Achievement of Objectives



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A notional example of CTEM output is illustrated above. The objective is simply to kill 15,000 of a total of 25,000 targets, and is achieved in 17 days. In reality, the performance with respect to prioritized objectives such as halting an invading army, defense suppression, etc., would be determined.

“Ticker Tape”

DAY	TARGET	# Attk	AC	WEP	# Used
1	SAMRADAR	160	F-15E	AGM65D	160
1	EW/GCI-RDR	118	F-18	JDAM	118
1	ACSHELTERS	22	F-117	GBU27	22
1		21	F-18	GBU24B	21
1	APC-COL	40	F-16C	CBU97	160
2	TAXIWYBRDGE	40	F-117	GBU27	40
2		9	F-18	GBU24B	9
2	TANKSCOLUMN	40	F-16C	CBU97	160
2		40	F-15E	CBU97	320
2	APCCOLUMN	35.5	F-18	JSOW	142
•	•	•	•	•	•
•	•	•	•	•	•
12	WMD PROD	10	F-16C	GBU12	10
12	POWERPROD	151	B-1B	JDAM	151
12	POWERTRANS	80	B-2	JDAM	80
12		112	B-52	JDAM	112
12		46	F-16C	GBU12	46

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This chart shows a sample of the time-phased allocation, or “ticker tape,” output from CTEM. For each wave of each day, the number of each target category attacked, and the number of weapon platforms and weapons used are specified. Only a small sample is shown here—the entire ticker tape would generally treat more than 100 target categories. The ticker tape attack is the input to RSAM that determines the ISR assets required to service the attack.

Option Packages and Scenario Assumptions

- Satellite, U-2 and Global Hawk Force
- Basing in Riyadh
- Summer Season
- IPB
- SAM Keep Out Zones
  - no overflight of known SAM zones
- Operational Keep Out Zones
  - manned platforms may overfly country only after day 7
- Assignment Priority
  - Most capable platforms assigned first
  - In-flight platforms re-tasked before new launch

- Satellite Model
  - Hi Res EO/SAR Imaging
    - x Spots/Day
  - Lo Res EO/SAR
    - swath coverage
- U2 Flight Parameters
  - Speed = x kts
  - Endurance = x hours
  - Altitude = x kft
  - Turnaround Time = 14 hours
- Global Hawk Flight Parameters
  - Speed = x kts
  - Endurance = x hours
  - Altitude = x kft
  - Turnaround Time = 17 hours

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This chart describes aspects of the ISR scenario, including reconnaissance and surveillance (R&S) option packages and key platform/sensor characteristics, for the exemplar cases that we discuss later in this briefing. The satellites are smallsats equipped with spot-imaging high-resolution optics or synthetic aperture radar. The U-2s are standard, and the Global Hawks were assumed for our analysis to have electro-optical (EO) and infrared (IR); MTI and SAR; or SIGINT payloads.[3]

The IPB varies according to the target class. Large, fixed, overt facilities such as petroleum storage tanks have a 90 percent probability of being located prior to the conflict. On the other side of the spectrum, highly mobile vehicles such as missile launchers have zero probability that their wartime location is known prior to the conflict. Targets that are not detected are assigned a default geolocation uncertainty that reflects the knowledge gained through area delimitation or all source intelligence analysis. A more detailed characterization of the IPB inputs is provided later in this briefing.

[3]According to SAF/AQIJ, Global Hawk has no current SIGINT capability and could not field a limited SIGINT capability before FY05.

Keep-out zones generated by air defenses are operative in the scenario. In addition, an in-country no-fly zone is imposed during the first seven days of the conflict as a result of the failure to achieve air superiority in that initial phase.

Assignment priorities are inputs that guide heuristics for ordering the association of sensors and platforms with targets. Parameters shown on the right-hand side of the chart are typical of those included in the RSAM input database, but are far from exhaustive. Classified parameters are denoted by "x" in the chart.

Assumed Baseline Force

Baseline Force	QTY
Satellite (EO)	2
Satellite (SAR)	2
U2 (SIGINT)	x
U2 (SIGINT)	x
U2 (SIGINT)	x
Global Hawk (EO/IR)	4
Global Hawk (SAR/MTI)	*4*
Global Hawk (SIGINT)	4

← **Initial Size of 'Rubber' Force**

Global Hawk (SAR/MTI) Force is allowed to grow to meet demand.

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This chart shows the makeup of the assumed baseline and "rubber" forces in the tradeoffs discussed later in the briefing.[4] The force is composed of two EO and two SAR smallsats, the current inventory of U-2s, and four each of the electro-optical/infrared (EO/IR), SAR/MTI, and SIGINT Global Hawks. It is likely that the Global Hawks, when deployed, will have mixed payloads, e.g., EO/IR with electronic intelligence (ELINT), but this capability was not exercised in our trade-offs for the sake of preserving clarity in our sensitivity analysis.

The "rubber" force is constituted entirely of Global Hawks with SAR/MTI payloads.

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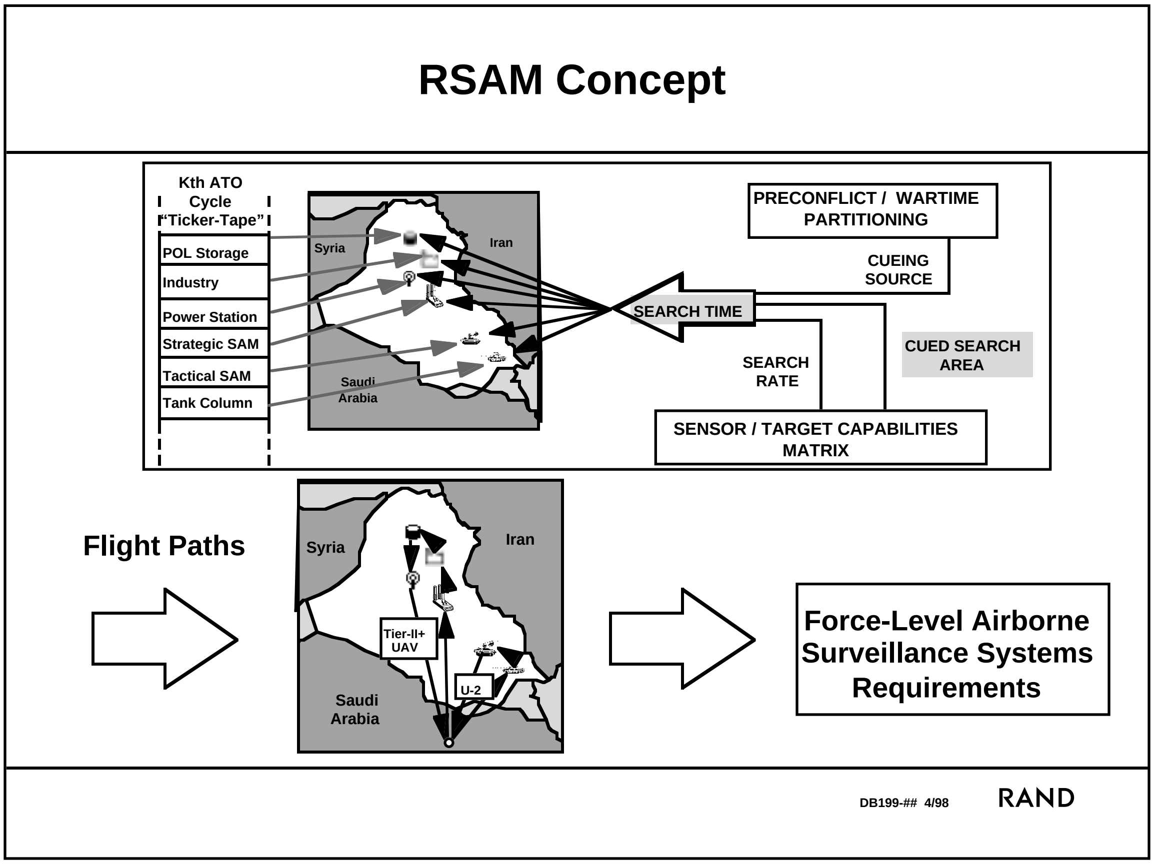
[4]The assumed baseline and "rubber" forces and assumed capabilities shown in the chart do not correspond exactly to the current and planned ISR payloads. The Assumed Baseline Force was selected to simplify analysis and traceability of effects while vetting RSAM.

According to USAF/SAF/AQIJ, the actual planned baseline force is as follows:

U-2 sensor mix:	SIGINT/EO/IR SIGINT/SAR/MTI
Global Hawk sensor mix:	EO/IR/SAR/MTI (operation is EO/IR or SAR/MTI but not both simultaneously
RC 135	SIGINT



The purpose of the RSAM module is to derive surveillance requirements from a master attack plan, the reconnaissance / surveillance partitioning, and the sensor / target category capabilities matrix. The master attack plan, generated by the CTEM, provides a listing of targets to be attacked for each air tasking order (ATO) cycle. This target listing, or ticker tape, is then used to drive RSAM's reconnaissance and surveillance allocation of assets. The above chart portrays the top-level flow of the module.

The RSAM preprocessor obtains the geographic distribution within a 100-km square grid of all the target types on the ticker tape. This distribution is then sampled for the ticker-tape targets in each ATO cycle, to randomly draw the target locations. The reconnaissance / surveillance partitioning recorded in the IPB, and later augmented by airborne surveillance cues, prescribes the cueing source and its associated location uncertainty. The sensor / target capabilities matrix provides the search rate and the resulting geolocation accuracy. The time required for surveillance of each target is equal to the area divided by the search rate. The geolocation accuracy defines the search area that would be required for any subsequent collection activity.

Finally, flight plans are determined for airborne surveillance platforms in the baseline ISR force, e.g., U-2s and Tier-II+ UAVs. The flight plans account for travel time, search time, and imaging time requirements for the targets to be visited. Routing is restricted based on the range, endurance, and keep-out zones of the platforms. Flight paths are formulated using a nearest neighbor routing algorithm, which provides efficient though not optimal paths. The resultant quantities and types of airborne surveillance systems required to service the targets establishes the force level requirement. If the baseline force can not meet R&S requirements in any ATO cycle, RSAM draws on a user-defined “rubber” force to satisfy the requirement. The user can select a choice for the “rubber” asset from any platform defined in the RSAM input set. This selection depends generally on the issue under study, e.g., UAVs if it is desired to size the UAV force.

RSAM Procedures to Capture Essential Factors

- **Step through ATO cycles**
  - Service target set from CTEM output
  - Select collection modes
  - Update air defense status
  - Update operational keep-out zones
  - Check satellite availability
- **Apply heuristic collection management rules**
- **Select candidate platforms and sensors**
  - Collect all appropriate INTs, but only those that add value
  - Sensors to exploit target observables
  - Platform range to reach target area
  - Endurance for dwell or orbit
  - Platform signature and sensor range to survive
  - Sensors appropriate to time of day and weather
  - Altitude to provide intervisibility to target
- **Assign platforms and sensors**
  - Cueing assets before imaging assets
  - Short range platforms before long range platforms
  - Enroute platforms before platforms at base
  - Multiple INT platforms before single INT platforms
  - Enroute platforms near to target before platforms far from target

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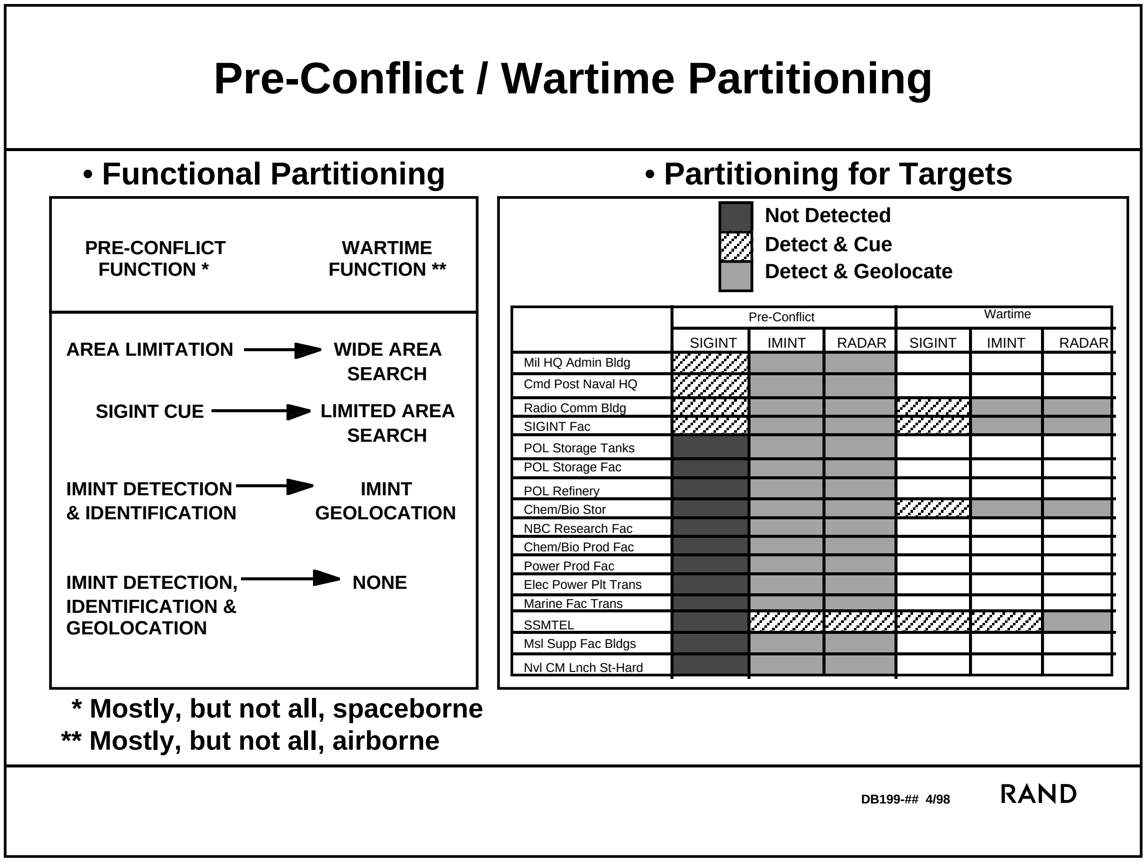
This chart lists in some detail the procedures followed in RSAM that are instrumental in capturing the essential factors enumerated previously. Stepping through the ATO cycles, one retrieves the corresponding targets from the ticker tape. The collection modes appropriate to the targets are defined; for example, a linear search is specified for road-mobile targets, and some targets are aggregated for the purposes of search if they are in close proximity and possess similar observables. Surviving air defenses are derived from the ticker tape by noting which surface-to-air missiles (SAMs) have not yet been attacked. These surviving air defense locations are used to obtain the air defense keep-out zones, which are then combined with the operational keep-out zones are that scripted day-by-day for the conflict. The availability schedule for satellite sensors is constructed either from input orbital data or from input conditional probability distributions. The distributions provide the probability of a coverage interval of some duration given a gap, and vice versa. A third means of specifying satellite coverage involves quantifying the number of spots per day of some size or the bulk area coverage rate; however, this last option obviates the scheduling process.

The selection of candidate platforms and the ordered assignment of platforms and sensors to targets obey a set of heuristic rules; the principal ones are listed in this chart. These rules are based almost entirely on standard collection management procedures recommended in Air Force, Army, and intelligence community manuals. Traditionally, collection managers have been provided with formatted check-off sheets, which call for qualitative evaluation (√ or X) of the various factors we have listed. RSAM performs the evaluation quantitatively, as we discuss later in the briefing.



The tasks of detecting, cueing, identifying, and geolocating targets are partitioned between pre-conflict and wartime intelligence operations. The bulk of the pre-conflict collection activities are non-intrusive, quasi-periodic visits that are most often performed by overhead reconnaissance assets. Although the division is not clean, wartime collection generally requires a closer and more nearly continuous presence, and must be provided by airborne surveillance systems. The following discussion should be viewed in that context, but exceptions will have to be accounted for.

The functions assigned to surveillance are determined by the information that is collected by reconnaissance. If reconnaissance provides only area limitation, surveillance must perform wide area search. At the other extreme, for some stationary targets, reconnaissance provides all that is required. Intermediate cases may arise in which reconnaissance provides a cue that limits the area to be searched, or it may provide all but the target geolocation.

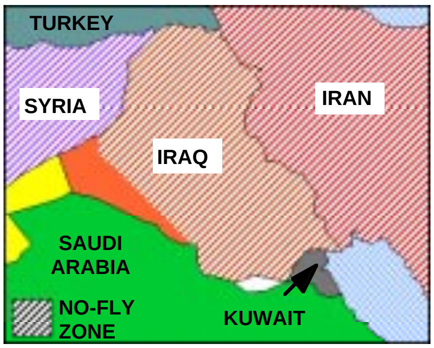
This functional partitioning between pre-conflict reconnaissance and wartime surveillance varies according to the target category, as shown on the right hand side of the chart. For the military headquarters building, everything is provided by reconnaissance; for the surface-to-surface missile transporter-erector-launcher (SSMTEL), it will at best provide a cue.

The intelligence information available pre-conflict constitutes the IPB database. A quantitative, albeit statistical, description of the IPB (in terms of the probability that each type of intelligence is collected, and distribution functions describing the resolution and the geolocation accuracy associated with each) is an input to RSAM.

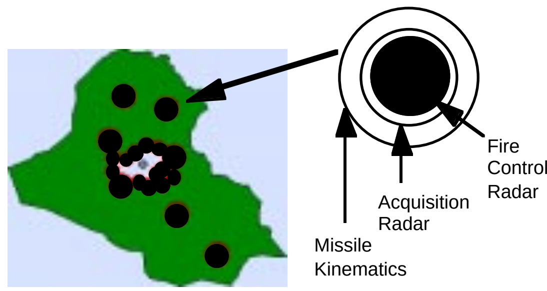
Because RSAM focuses on collection requirements associated with specific target sets, there is no requirement derived for wartime battlefield situational awareness (SA), i.e., non-target-specific surveillance. The latter activities are in many instances responsible for providing initial detections or area delimitation for targets not known or localized prior to the conflict. Formally, SA is treated in much the same manner as the IPB, using an input probability of detection; however, it is also necessary to compute (off-line) and specify the set-aside of collection assets to accomplish this function.

Keep-Out Zones

Operational



Air Defense



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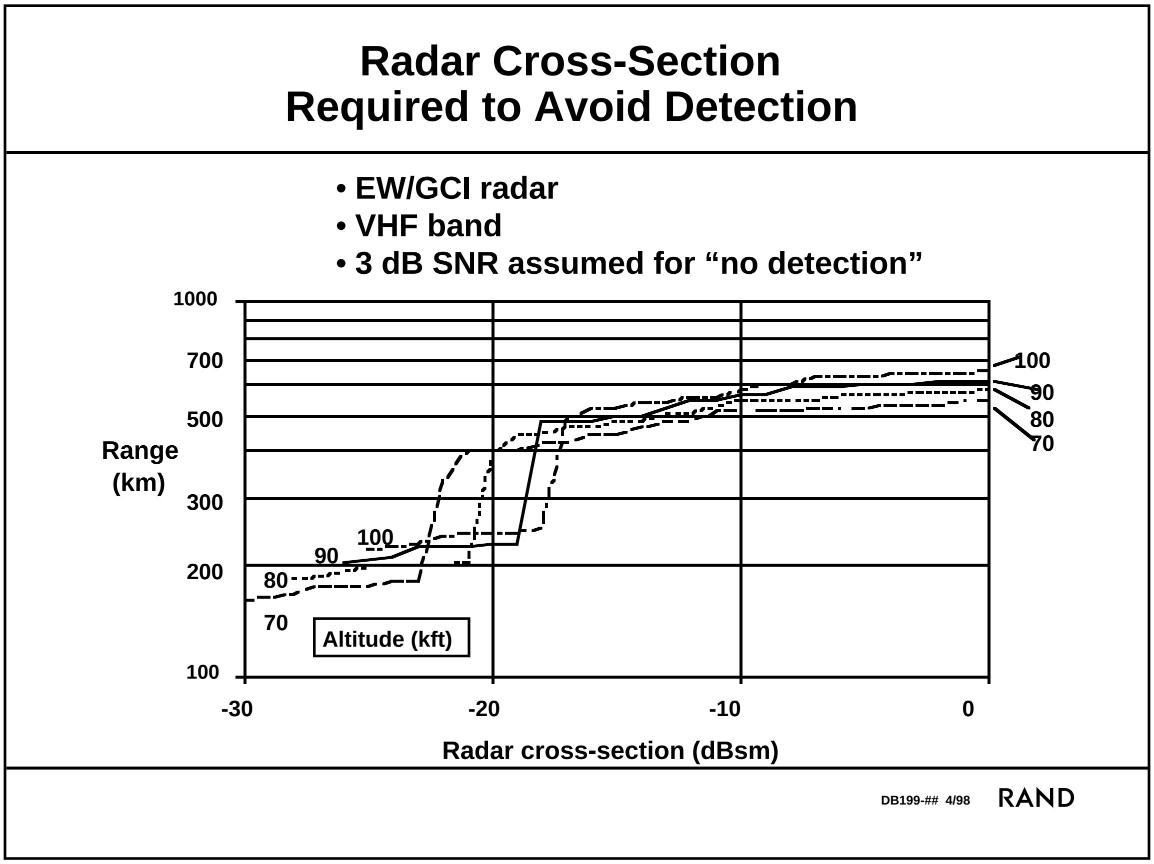
Keep-out areas are of two kinds in RSAM: those resulting from operational considerations (some of which may be governed ultimately by survivability), and those dictated by avoidance of SAM defenses. This chart addresses the operational keep-out zones; the SAM keep-out zones will be discussed later. The inaccessible areas for surveillance aircraft are determined by combining the inaccessible areas pertaining separately to operations and SAM defenses.

Operational keep-out zones are scripted inputs for each scenario. They are specified on a 100-km-square grid and are defined for each platform type and each ATO cycle. The keep-out zones serve two functions. The first is to establish no-fly zones that are imposed by the lack of air superiority or supremacy in certain areas, or where overflight is denied because of political considerations. The second is to focus the activities of certain assets into appropriate zones, e.g., to place tactical reconnaissance aircraft preferentially near engaging forces. In this latter mode, the keep-out zones supplement other heuristics in RSAM that prioritize platform assignments. This mechanism is convenient for establishing appropriate standoff orbits along national borders for platforms such as Rivet Joint. Rather than prescribing detailed orbits, one need only disallow access to the hostile region and specify the collection targets.

Depending on the collection aircraft's radar cross-section and altitude, each SAM has a maximum range for its acquisition radar, fire control radar, and missile flyout, beyond which the platform can operate in safety. The smallest of these ranges may be used to bound the SAM's effectiveness envelope, since all three functions must be executed to complete an intercept.

The envelopes for each SAM are plotted on a theater map as shown in the chart (the dark circles.) Any region completely surrounded by dark circles (e.g., the white area shown in the chart) is then treated as dark, since it is not accessible by a safe route.

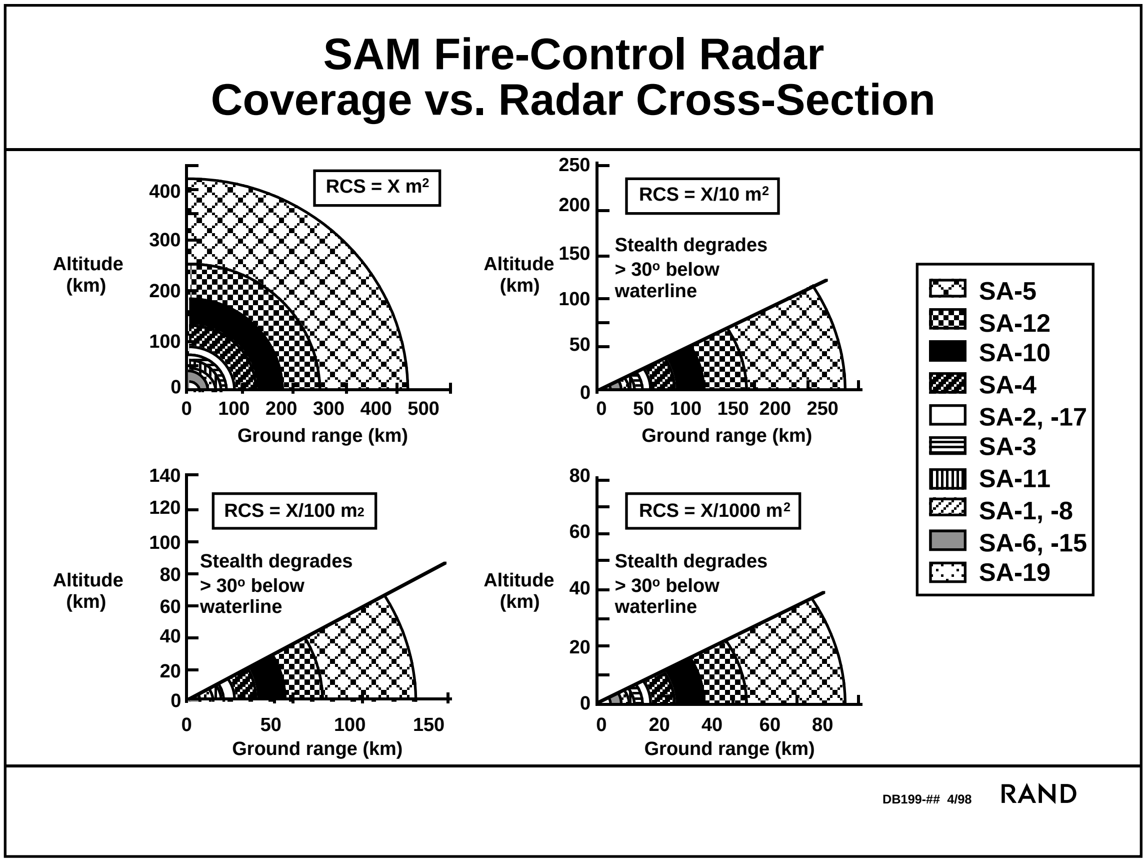
Next, we color light gray all white grid cells that are contiguous and connected by safe paths to accessible portions of the periphery. (Access might be precluded due to political or basing considerations.) This process is analogous to a computer graphics "fill" operation. When the fill is completed, all regions that are both threat-free and accessible (without crossing over dark gray) are light gray. Any region that remains white because it is surrounded by some combination of inaccessible border and dark area is now colored dark gray.



Keep-out zones imposed by the presence of SAMs are computed in RSAM based on tabulated data describing the acquisition and fire control radar ranges, and the kinematic performance of the SAMs. The range of an acquisition radar typically depends on elevation angle, which implies a dependence on the altitude of the targeted surveillance aircraft. This is a result of the complex lobe structure of the antenna gain pattern, which is induced by multipath interference. Of course, the range also scales with the radar cross-section (RCS) of the target.

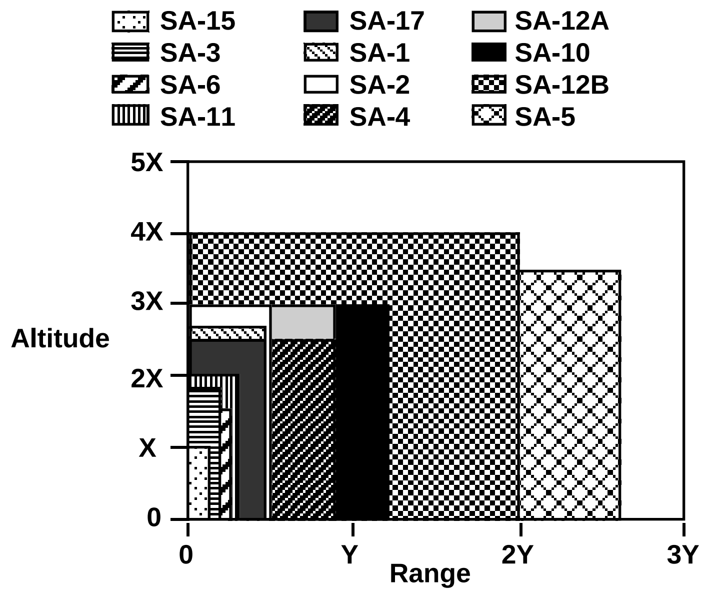
The chart shows the minimum range at which the target is *not* detected (corresponding to 3-dB signal-to-noise ratio) as a function of RCS and altitude, from which we deduce the required standoff range for a surveillance aircraft. The input file has data of this kind in digitized form for all the key SAM acquisition radars.

If one traces a particular range curve from right to left on the chart (moving from large to small RCS), one eventually reaches an RCS where the curve terminates (e.g., ≈ -40 dBsm for the 40 kft altitude case). This corresponds to the RCS at which one can overfly the radar without being detected. Most aircraft RCS undergo significant enhancement at some critical angle below the waterline, so overflying without being detected is generally feasible only for acquisition radars that focus their energy towards the horizon.



Fire control radars typically have pencil beams and operate at the higher microwave frequencies, thus mitigating multipath effects, particularly when engaging high-altitude targets. Frequently, the radars have the capability to scan their beams to near vertical elevation, which allows them to exploit enhancements of the RCS below the waterline (we assume a critical angle of 30 degrees for stealthy aircraft). This chart displays range-altitude plots of radar detection performance for RCS values at 10-dB intervals, which are coded for the different threat SAMs. The RSAM input file includes these data in digitized form.

Operational Envelopes of Surface-to-Air Missiles



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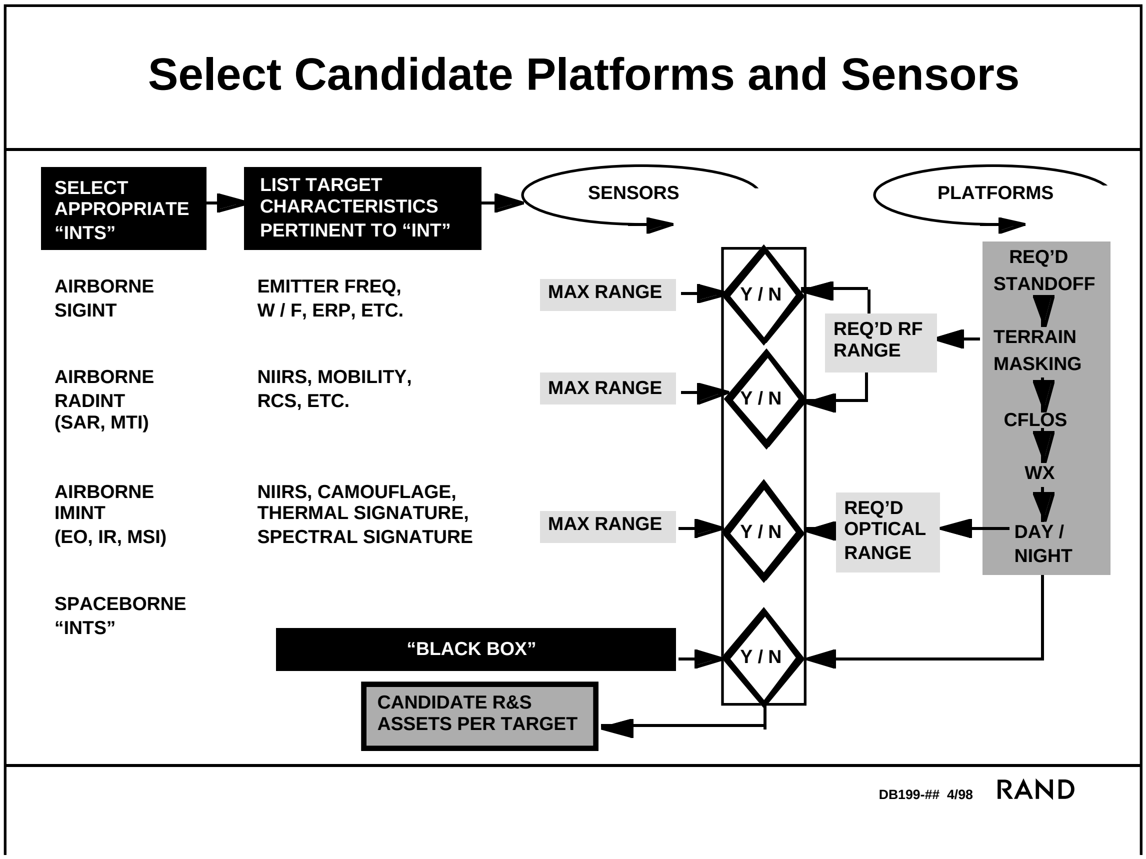
This chart shows, in somewhat simplified form, the maximum kinematic range and altitude of the threat SAMs. The maximum altitudes of the larger SAMs are dictated by the requirement to aerodynamically maneuver (usually with 2 Gs of acceleration) in the thin upper atmosphere. The maximum ranges are the limits of ballistic flight. Typically, the range-altitude envelope of kinematic performance is only approximately rectangular. Squaring off the envelope allows us to reduce the input to only two values per SAM, maximum range and maximum altitude.



Each target type is associated with a set of applicable INTS, e.g., SIGINT, radar intelligence (RADINT), or IMINT, for which the target has a potentially detectable signature. In the case of SIGINT, the target signature includes emitter frequency, effective radiated power, waveform type, etc., which are analyzed in light of the sensor's bandpass and sensitivity to determine whether the target is detectable, and, if so, the range. In the case of imagery, the sensor's available resolution is compared with the requirement for detection or identification, as specified in the National Imagery Interpretability Rating Scale (NIIRS), which we discuss subsequently. With synthetic aperture radar imagery, the resolution is range-independent, so the detection range is derived from the radar sensitivity and target radar cross-section. With EO or IR imagery, the resolution is linear in range, and thus the maximum standoff range depends in general on both the NIIRS requirement and the sensitivity-limited detection range for the sensor and target signature of interest. The aim is to compare the maximum standoff range as dictated by the sensor and target characteristics, with the minimum standoff required for the platform to operate in safety. The platforms and sensors that can both detect and survive are candidates for collecting against the target.

We discuss with the following charts how we compute the minimum safe standoff range for an unobstructed line-of-sight to the target. In the case of EO and IR sensors, we are also interested in having cloud-free line-of-sight (CFLOS). We discussed earlier how we obtain a CFLOS probability given the collection platform altitude and safe standoff range, geographic location, season, etc. Prior to the mission, the CFLOS probability must exceed a pre-determined threshold before the collection asset is assigned. A random draw is performed based on this probability to establish whether there is obstruction by clouds during the mission, and, if so, no imagery is obtained.

The ATO cycles in RSAM are 12 (or fewer) hours long, corresponding grossly to day and night. The EO and IR sensors are generally restricted to operation in day and night, respectively.

Weather effects are not yet included in RSAM, but our aim is to model the effect of rainfall on microwave radars. We will use the Crane model,[5] which specifies probabilities for rainfall intensities as a function of season, geographical location, etc. A random draw will be made on the probability distribution to establish the rainfall rate during the mission, and the radar sensitivity calculations will be modified accordingly.

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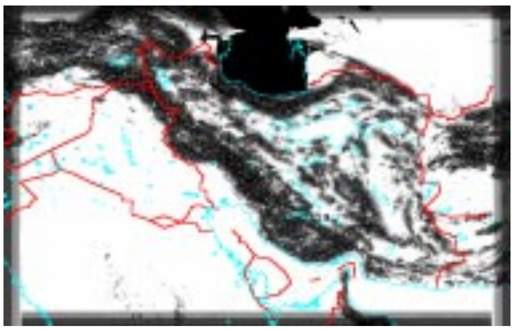
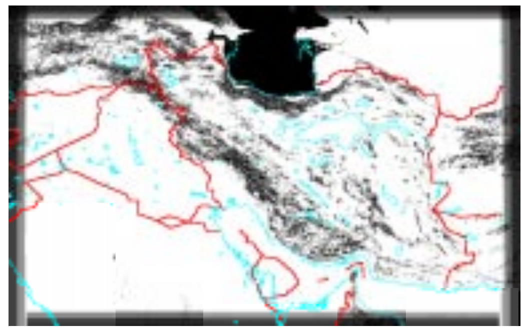
[5] R. K. Crane, "Prediction of Attenuation by Rain," *IEEE Trans. on Communications*, Vol. Com-28, No. 9, September 1980, pp. 1717–1733.

Iran / Iraq Intervisibility

2^{o} Grazing Angle



6^{o} Grazing Angle



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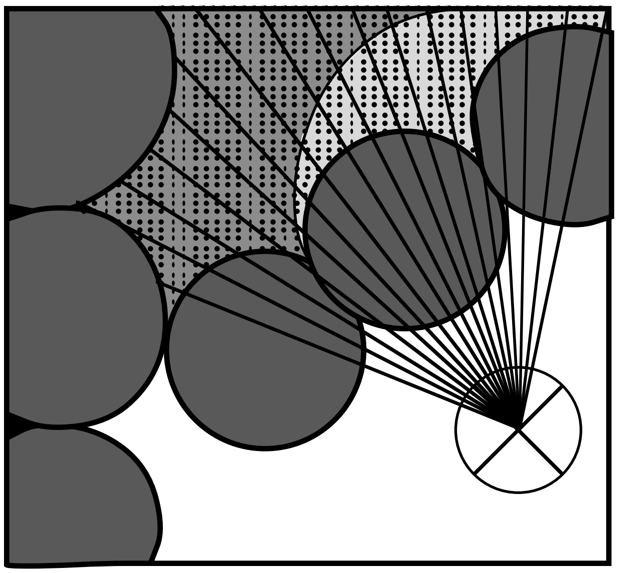
The input data used by RSAM to determine intervisibility consist of masking angles at azimuth intervals of five degrees for each target in the scenario. For a typical scenario involving 4000 targets, this consists of only (360/5) x 4000 = 288,000 numbers. The masking angle represents the smallest grazing angle at which there is a line-of-sight (LOS) unobstructed by terrain from the sensor to the target. The data for each scenario are extracted off-line from databases containing masking angles for each 1-km square cell, e.g., in Iraq, Iran, and North Korea. The theaterwide databases were developed at RAND using digital terrain elevation data (DTED) and RAND's cartographic and geographic information system (CAGIS) program, and stored on an Eagle drive. Constructing the dataset for a particular group of targets involves running a simple UNIX program that accesses the Eagle drive and formats the data for use by RSAM.

The chart demonstrates one means of displaying the intervisibility data, in this instance for a selected grazing angle of six degrees. The gray scale indicates the "probability" that unobstructed line-of-sight exists to the shaded pixel from some azimuth. Since the data include masking angles for 72 azimuths, a probability of 100 percent means that all 72 masking angles are below the selected grazing angle. The corresponding pixel is white. A probability of 0 percent means all 72 masking angles are above the selected grazing angle, which results in a black pixel. Probabilities lying between these extremes yield gray pixels.

Intervisibility Constraint



For grid point closest to target outside threat coverage

Compute elevation angle from target to aircraft

Compare elevation angle with terrain masking angle

Select grid point if target is not masked, else iterate

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This chart addresses the issue of intervisibility, which we neglected in the earlier discussion of minimum standoff range. The map is a blow-up of the preceding one, but with shading to indicate the portion of the safe zone for which the target is masked by terrain. At each grid point, the grazing angle from the platform to the target is computed, and the corresponding cell is shaded if the grazing angle is less than the masking angle obtained from the intervisibility database.

Sensor Resolution Requirements: NIIRS and Minimum Ground Resolved Distance (m)

	Detection			Recognition			Identification		
Observable	Visible	Radar	GRD	Visible	Radar	GRD	Visible	Radar	GRD
Port/Harbor	1	1	>9	2		4.5-9	4		1.2-2.5
Airfield facilities	1		>9	2		4.5-9	3		2.5-4.5
LOC		1	>9						
Arm gr forc instl	1		>9				5		0.75-1.2
Lg Ship	1	2	4.5-9	3	3	2.5-4.5	4	6	0.4-2.5
Lg A/C	2	2	4.5-9	3		2.5-4.5			
Hangar	2		4.5-9						
Gr forc instl	2		4.5-9	3		2.5-4.5	4		1.2-2.5
Lg static radar	2		4.5-9					2	4.5-9
Bridge	2		4.5-9	3		2.5-4.5	6		0.4-0.75
Lg building	2	2	4.5-9						
Lg SATCOM site							3	3	2.5-4.5
C2 HQ	3		2.5-4.5	5		0.75-1.2	7		0.2-0.4
SAM/SSM site	3		2.5-4.5	4		1.2-2.5	8		0.1-0.2
Supply dumps	3		2.5-4.5	6		0.4-0.75	8		0.1-0.2
TEL suppt vehs	3	3	2.5-4.5		5	0.75-1.2	8		0.1-0.2
Trains	3		2.5-4.5				5	6	0.4-1.2
Med A/C		3	2.5-4.5		5	0.75-1.2	4		1.2-2.5

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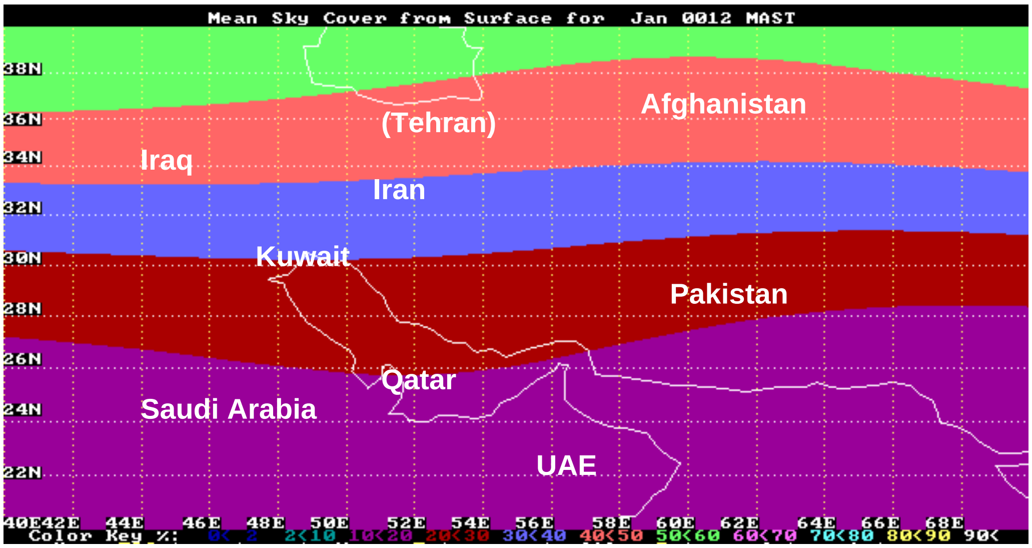
The NIIRS assigns numbers between 1 and 9 to describe semi-quantitatively the resolution required for detecting, recognizing, or identifying various targets. Originally, the scale referred only to EO sensors. In recent years, there has been a trend towards quantifying the scale more precisely in terms of ground resolved distance (GRD), and including additional phenomenologies, e.g., SAR and IR sensors. EO and SAR ratings for a subset of the targets are provided in this chart. The ratings and GRDs sometimes differ between sensors because the information content depends on the physics of the imaging process, as well as on the resolution.

The full NIIRS target list, of which the chart shows a subset, is far from exhaustive. We rely on similarities between target types to extend the ratings to unlisted targets.

Probability of Cloud Free Line of Sight

- Noon (local time) in January
- 20 km altitude, 60 degree nadir angle



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The performance of optical systems is strongly influenced by the intervening atmosphere between the sensor and the target. Capabilities can be degraded or nullified by the presence of haze, clouds, precipitation, etc., which diminish or distort the signal radiation from the target.

Because of the random nature of these effects, it is impossible to guarantee any level of system performance in all circumstances. However, existing models and programs can be used to determine probabilities of atmospheric conditions, and thus predictions of system performance, in many cases. The statistical inputs to RSAM describing CFLOS are generated using PCLOUDS, developed by Phillips Laboratory. A sample output of PCLOUDS is shown in the above chart, which gives probabilities for the Middle East in January at local noon. The look angle is specified as 60 degrees above the nadir, from an altitude of 20 km. The map is coded according to the CFLOS probability, with the upper latitudes indicating 50 to 60 percent, and the lower latitudes indicating 60 to 70 percent. The full code is displayed along the lower border of the chart.

Outline

- Introduction
- Methodology and Scenario
- Missions, CONOPS and Technology
- Exemplar Results

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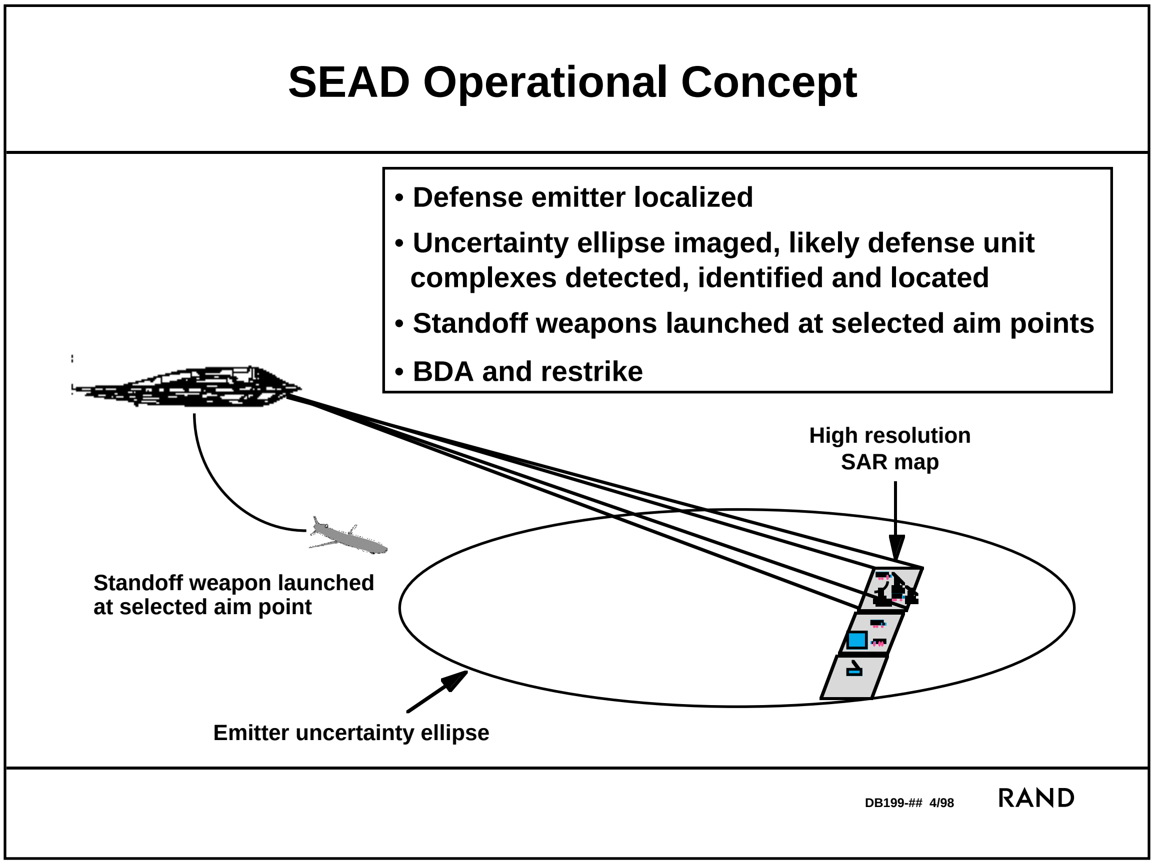

In the suppression of enemy air defenses (SEAD) operational concept illustrated here,[6] an airborne platform is cued by off- or on-board ELINT (electronic intelligence) sensors that localize the enemy defense emitter within an uncertainty ellipse.

We assume that the emitter is not continuing to radiate and that the ellipse is too large for direct targeting—therefore, neither an anti-radiation missile such as high speed anti-radiation missile (HARM) nor a direct attack weapon is applicable. Thus, the airborne platform, standing off a safe distance, uses its SAR for a high-resolution imaging search of the uncertainty ellipse and to pick out the enemy defense complex using automatic target recognition (ATR) or automatic target cueing (ATC).

To achieve the high certainty of mission success needed to ensure the safety of less-survivable aircraft or operations nearer to the danger area, standoff weapons are launched at the most likely locations of the defense complex as nominated by

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[6] David Frelinger, Joel Kvitky, Gary Liberson, Carolyn Wong, Charles Neerdaels, Jeff Hagen, Bruce Davis, and Gail Halverson, *Bomber Flexibility Study: Final Report*, RAND, MR-645-AF, August 1995 (available to authorized government requesters).

the ATR/ATC system. In the illustration, the airborne platform carrying the SAR also carries and launches the standoff weapons. More generally, the weapons could be called in from another platform and targeted to the designated aim points. The next two charts illustrate the various applicable capabilities for implementation of the concept and the solution space of potential tradeoffs.

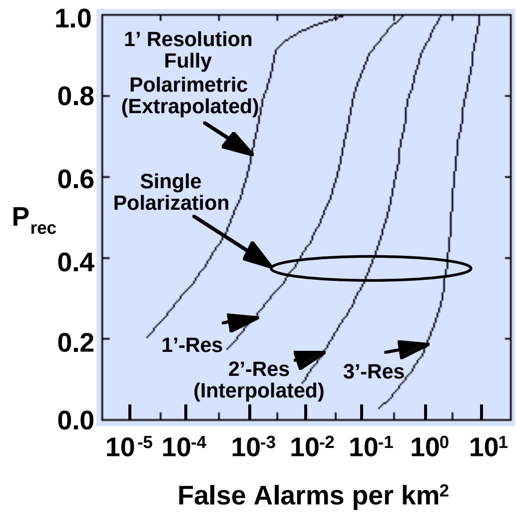
ELINT Cueing and Automatic Target Recognition Performance

- **Typical ELINT Cueing Accuracy**
  - **100 km aircraft standoff**

Description	Type	1-s Area* (sq km)
Coarse A/B DF	AOA	50 - 100
A/B DF	AOA	13 - 24
+ PRC	PRC	1.6
Fine A/B DF	AOA	1
2 UAV Concept	TDOA	4
3 UAV Concept	TDOA	0.003 - 0.01
Satellite Concept	TDOA	1 - 100**

* Aircraft are standing off 100 km
**Calculations are done for the midrange value of 16 sq km

- **Lincoln Lab 1994 ATR**
  - **Desert terrain**



Note: A/B = airborne
DF = direction finding
PRC = phase rate of change

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Two factors in the tradeoff are illustrated in the above chart.[7] The table on the left shows typical ELINT cueing areas for angle of arrival (AOA) and time difference of arrival (TDOA) systems standing off 100 km from the emitter. The numbers shown are for a one standard deviation (one-sigma) ellipse. The accuracies for the AOA systems range from 100 sq km down to 1 sq km. TDOA systems have far greater accuracy potential, particularly with a three-vehicle concept such as Guardrail Common Sensor, or three UAVs, wherein 0.01 sq km or less is technically feasible. Accuracies for satellite concepts can take on a broad range of values, depending on the sensor type (AOA or TDOA), timing accuracy, geometry, and ephemeris accuracy.

The graph on the right shows state-of-the art ATR performance, as reported by Lincoln Laboratory in 1994. The probability of target recognition is plotted as a function of false alarm density for 1-ft, 2-ft, and 3-ft resolution SARs with either single polarization or full polarimetric capability.

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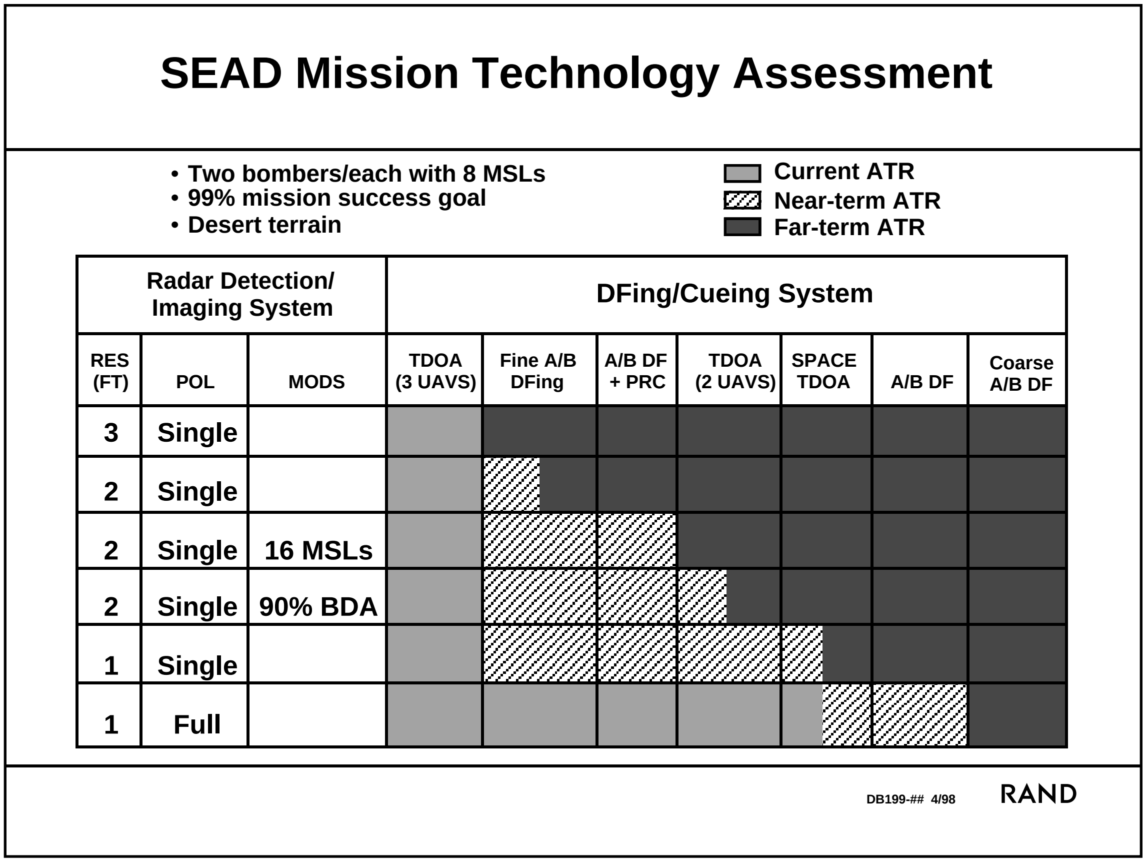
[7] Frelinger et al., 1995.

Assuming one wishes to find a target with 81 percent probability, one could operate with 90 percent probability that the target is in the searched area (corresponding to an area multiplier of 4.6) and 90 percent recognition probability. The latter probability corresponds to a false alarm density of approximately six per square kilometer with 3-ft single polarimetric imagery. If the number of false alarms is limited to six, the area to be searched is approximately one square kilometer, and the one-sigma uncertainty area is (1 $km^2 / 4.6) \approx 0.2$ square kilometers. This implies that an accurate TDOA system is required to achieve the desired performance.

On the other hand, if 1-ft polarimetric imagery is available, the false alarm density for the case we have presented is 2×10^{-3} per square kilometer, the area to be searched is 3×10^3 square kilometer, and the one-sigma uncertainty area is 6.5×10^2 square kilometer. This geolocation accuracy is possible even with the coarse airborne ELINT systems cueing the SAR.

The preceding discussion begs the question whether the area coverage rate of an airborne SAR is up to the task of searching hundreds of square kilometers at 1-ft resolution. This issue is analyzed in the final portion of RSAM in which we assign assets to targets and develop flight paths that are compatible with the endurance and reach of the collection platforms.



This chart[8] shows the overall technology assessment for a SEAD mission, with 99 percent mission success, using two bomber loads of standoff weapons. Desert terrain is assumed and results are shown for current, near-term, and far-term ATR capability. The assessment is presented in terms of the tradeoff between cueing and radar detection/imaging capabilities that afford a solution. With current ATR capability, the solution space includes the entire first (3-UAV TDOA) column with its very precise localization. It also includes a large part of the bottom row, wherein the excellent ATR capability achievable with a 1-ft full polarization (POL) radar allows the localization to be relaxed out to values achievable with 2-UAV (and some space-based) TDOA. With near-term ATR capability, the solution space is greatly expanded. Now the 1-ft single polarization radar can handle the areas that previously required full polarization and the 1-ft full polarization radar can handle all but the coarse localization airborne system.

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[8] Frelinger et al., 1995.

In the previous chart we mentioned that the accuracy of a space-based TDOA system concept can, at times, be much better or much worse than the representative value used for the space-based TDOA column here.

Overall, potential solutions exist; the selection of a particular solution depends on the desired time frame, confidence in projected ATR improvements, costs, and fungibility of capabilities between the SEAD mission and other missions.

Two CMT Operational Concepts

- **Find exposed stationary CMT**
- **Find moving CMT**

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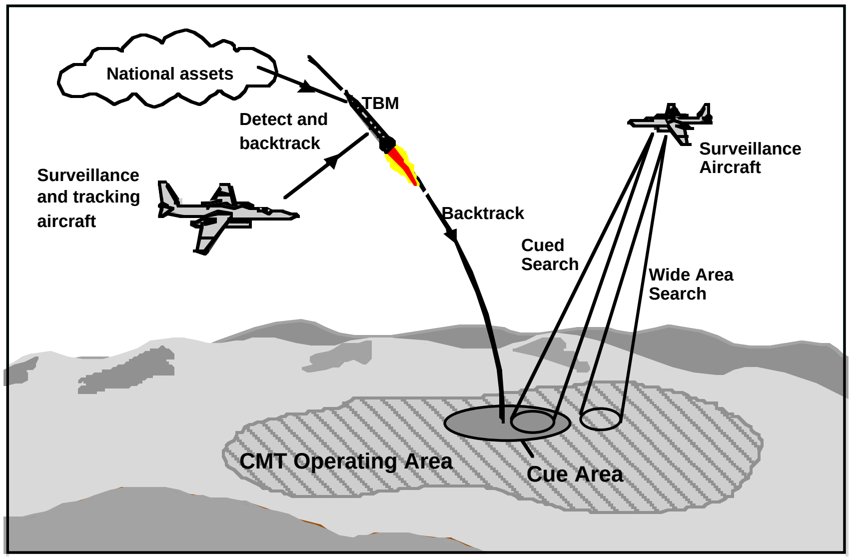
Now we turn to the more general critical mobile target (CMT) mission in which localization from SIGINT/ELINT is generally unavailable.

We will discuss two concepts. In the first concept, the idea is to find the CMT when it is exposed and stationary. In the second, the idea is to find the CMT when it is moving and can be more easily picked out from the background.

A third alternative is to find the CMT when it is in its hiding place. The advantage is that more time is generally available, but this is generally outweighed by the much greater reduction in useful observables.

Find Exposed Stationary CMT Using Cued or Wide-Area Surveillance



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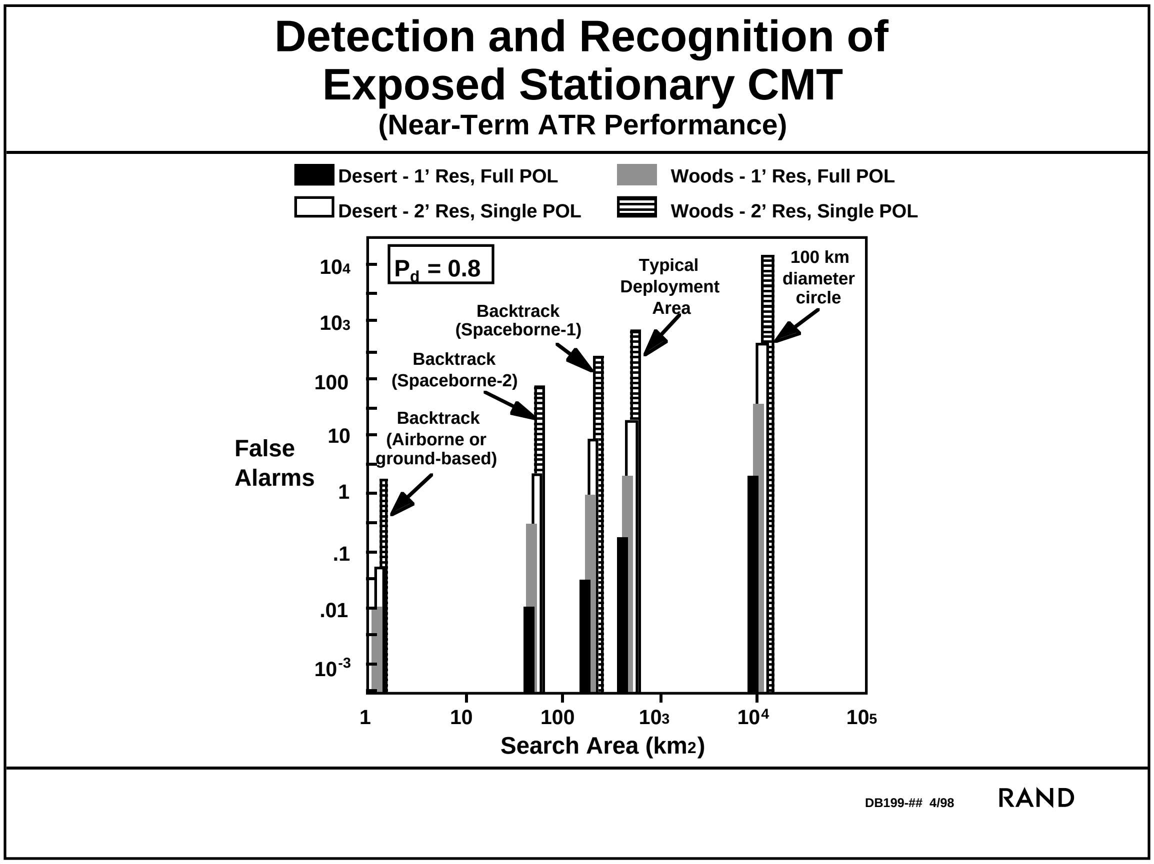
In the above chart, a surveillance aircraft attempts to find and identify the exposed stationary CMT with a high-resolution imaging system. In the absence of a cue, the search may be performed over the entire CMT operating area as estimated from area limitation studies. To have a reasonable chance of finding the CMT, the aircraft must search the entire area within the CMT exposure time. Large operating areas and short exposures require low false alarm densities because the false alarms for each search must be serviced by weapon platforms and weapon expenditures.

For the reasons above, a cue that localizes the CMT can greatly reduce the difficulty and/or improve the performance in finding the CMT. We show a theater ballistic missile (TBM) being detected and backtracked by national systems or, more accurately, by an airborne surveillance and tracking aircraft such as the airborne warning and control system (AWACS) with an infrared search and track (IRST) and laser ranger.



With the above chart, we look at the number of false alarms as a function of search area.[9] Target detection and recognition probability is fixed at 0.8. Assuming that a maximum of about 10 false alarms is acceptable, we see that in the most favorable ATR circumstances, desert background, and a 1-ft dual polarization radar, even the 100 sq km diameter circle can be handled. At the other extreme, with the best (airborne surveillance) cue, which reduces the search to 1 sq km, false alarms are acceptable even with a wooded background and a 2-ft single-polarization radar.

Overall we see that the number of false alarms varies over orders of magnitude depending on the cue area, the type of background clutter, and the radar quality. Thus, care must be taken to state the conditions involved when assessing the capability of SAR ATR systems.

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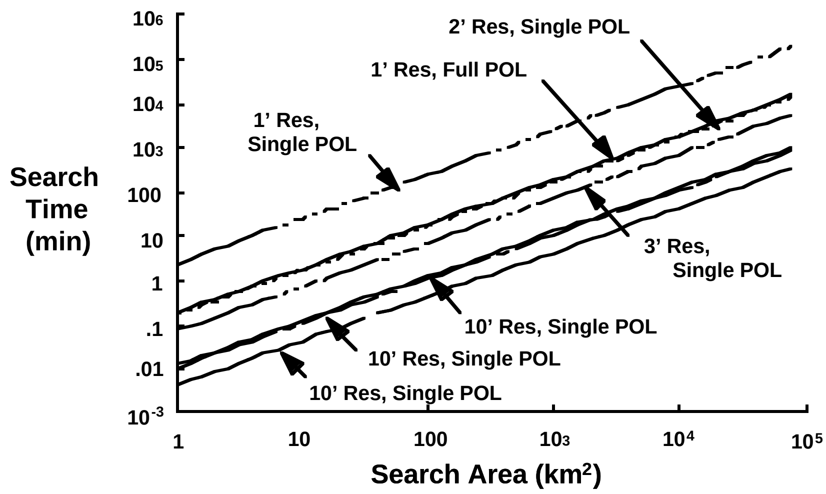
[9] Frelinger et al., 1995.

Synthetic Aperture Radar Search Capability



DB199-## 4/98 RAND

This chart shows example area coverage performance for existing SARs, for their medium and high resolution modes.[10] Although there is a clear trend toward improved coverage rate with coarser resolution, the data do not point to a consistent scaling law relating area coverage to resolution—because there is a multiplicity of factors involved.

Most of the SARs in operation today are processor-limited, i.e., in the finest resolution mode they image only a small fraction of the area illuminated on the ground. In some instances, the processor limit results only from throughput, since the number of illuminated pixels that need to be processed increases with the square of the resolution improvement.

In other instances, there is also a swath limitation imposed by the receiver’s intermediate frequency (IF) bandwidth. The latter applies to stretch processors, which in effect convert the range window to a frequency window. The frequency window cannot exceed the capacity of the receiver’s analog-to-digital converter.

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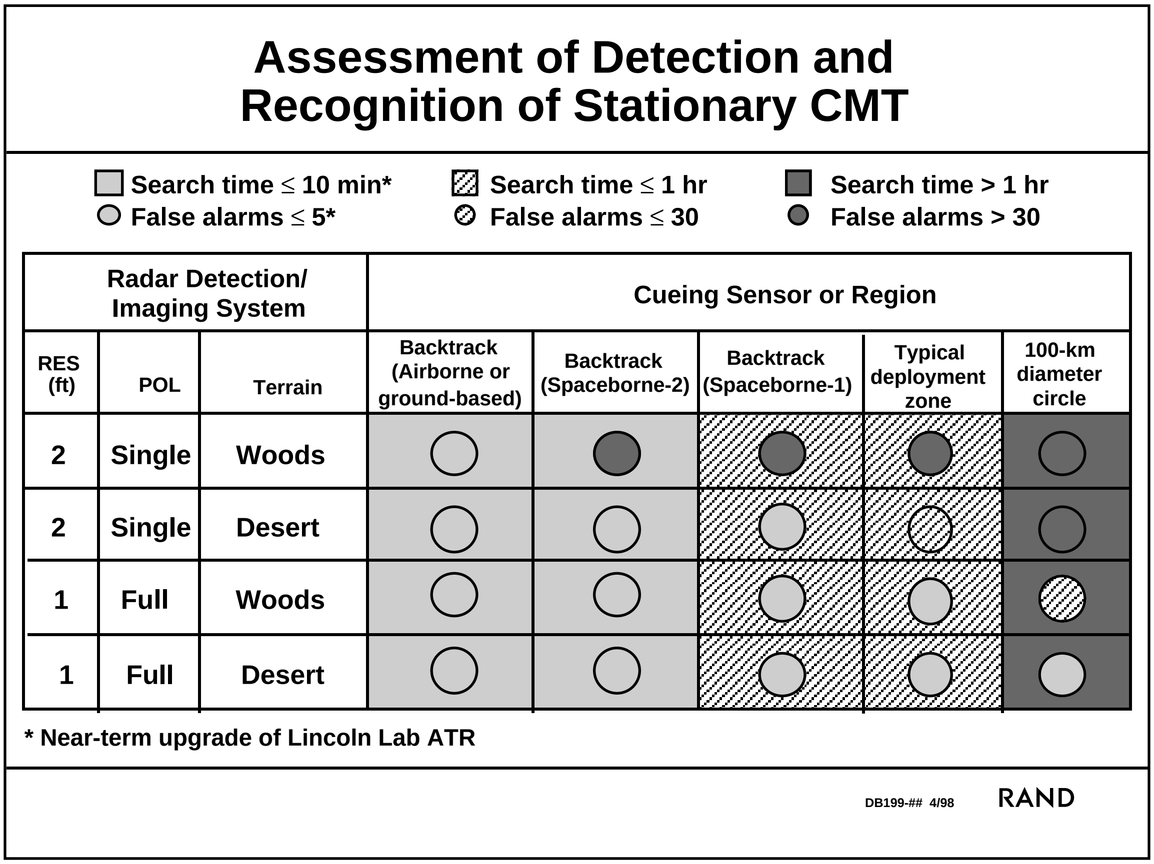
[10] Frelinger et al., 1995.

Finally, the mode of illumination is constrained by the resolution. The strip mapping mode (akin to painting a strip along track, but offset from the aircraft) is not viable if the azimuthal resolution is less than half the length of the antenna. This limitation arises because the illumination time increases linearly as resolution improves, implying the beamwidth must be wider if the boresight orientation is fixed. If the resolution is smaller than half the antenna length, one typically operates in the spotlight mode, in which the beam is squinted toward the target during the illumination period. Although the area coverage rate in the strip mapping mode (assuming no processor limits) is the product of the swath width and the aircraft speed, it can be much less in the spotlight mode.



This chart shows the overall assessment of target detection and recognition for stationary CMTs for the cued areas applicable to TBMs for the several backtrack and area limitation areas discussed earlier.[11] Here, both false alarms and search rate are shown. Good capability, light gray, corresponds to search in no more than 10 minutes and no more than 5 false alarms per search. Marginal capability, cross-hatch, corresponds to search in no more than one hour and no more than 30 false alarms. Poor capability, dark gray, corresponds to search time of greater than one hour and more than 30 false alarms per search.

For the best cue, both the false alarms and search time are good. For the stereo backtrack cue area, false alarms are starting to be a problem for wooded backgrounds with a 2-ft resolution system. For the largest search area considered in the chart (still only a few percent of the total area of Iraq), search time is deficient in all cases. Somewhat surprisingly, false alarms are acceptable for desert background with the 1-ft resolution SAR.

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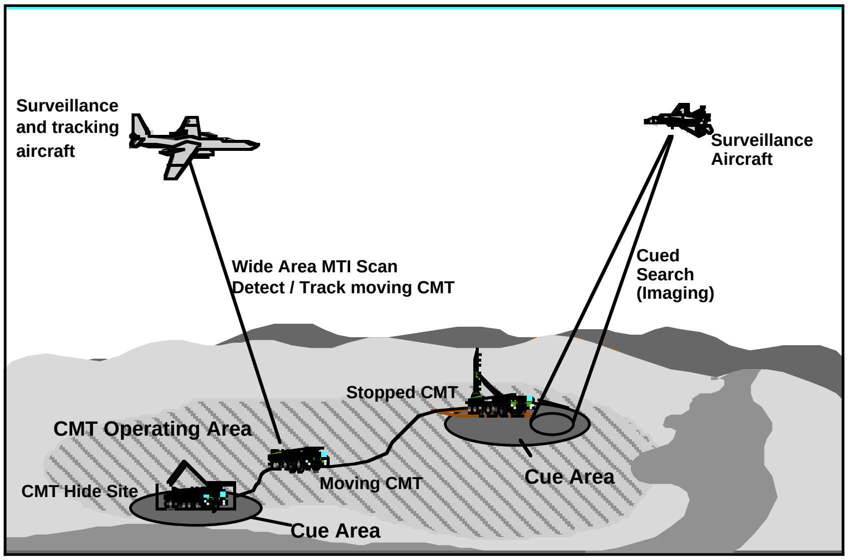
[11] Frelinger et al., 1995.

Find Moving CMT Using MTI / SAR



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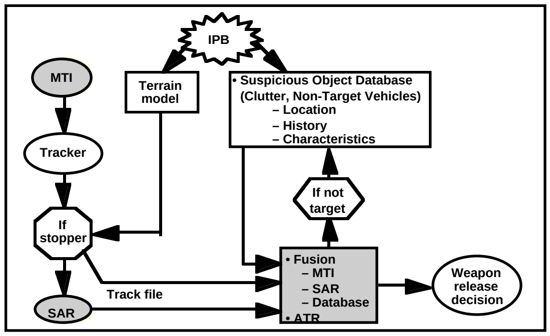
This chart illustrates the second CMT mission operational concept in which the key to initial detection is motion of the CMT and the key to identification is the appearance of a new stationary object in the operating area. An MTI radar is used to pick moving objects from the stationary clutter. Then the objects are tracked until they stop and the small area in which an object is estimated to have stopped is used as a cue for high-resolution imaging. The idea is to reduce false alarms and search rate requirements.

Also, when a CMT is found, the track can be played backward to estimate the area where the CMT originated. These cues for CMT hide sites could be searched and watched for additional CMTs or supporting equipment.

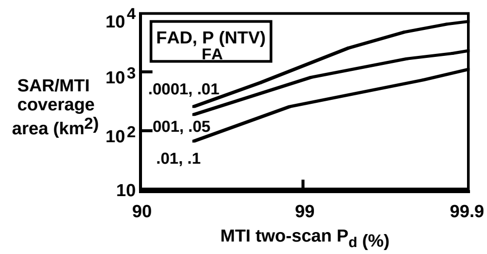
MTI-Aided Detection, and Recognition of Moving CMT



Vehicular traffic
- **20 km of road per 100 sq km**
- **1 vehicle per km of road**
- **5 hr vehicle mean time to stop**

Constraints
- **100 false alarms per day**
- **3 min maximum time to find stoppers**

Coverage area with MTI cueing



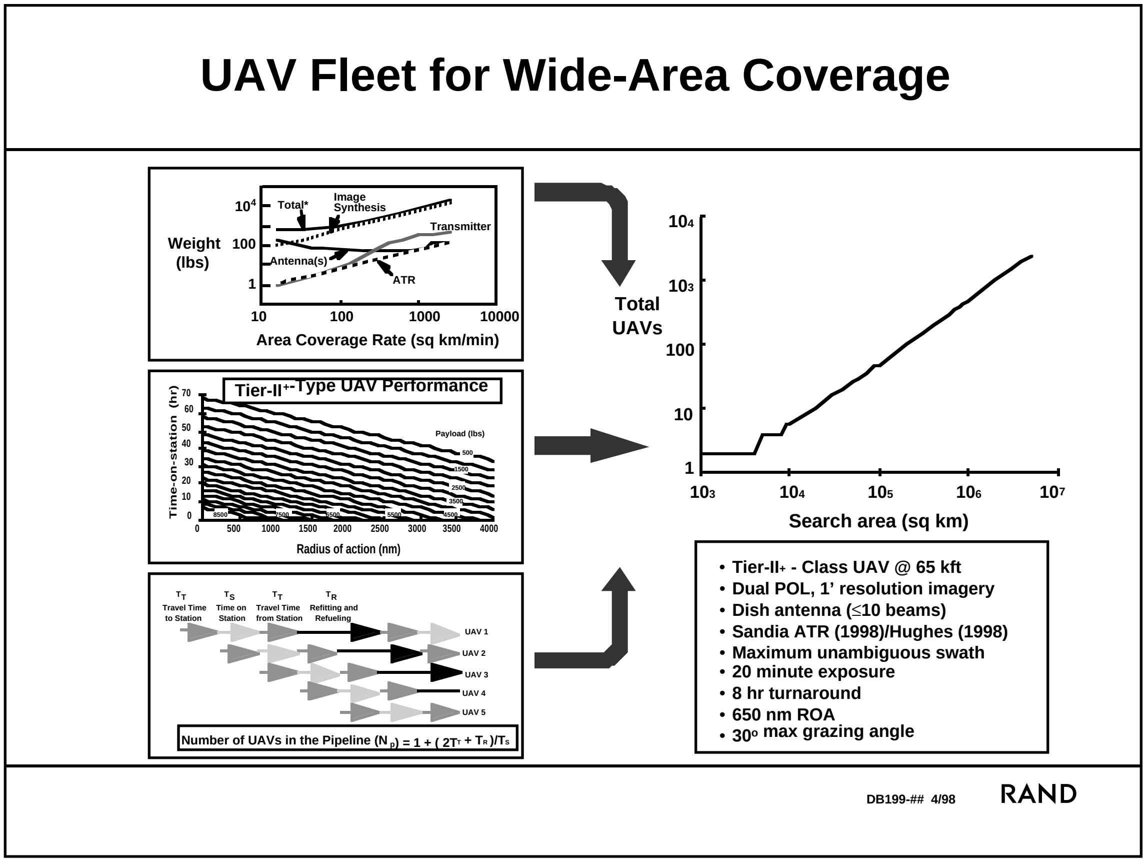
DB199-## 4/98 RAND

This chart illustrates the fusion of MTI/SAR and IPB to aid detection and recognition of CMTs. The process begins with the MTI, which tracks all moving objects. When the MTI/tracker declares an object has stopped, it is imaged by the SAR (a terrain database is used to model temporary obscuration).

In addition, IPB is used pre-war and during the war to construct and update a suspicious object database on clutter and non-target vehicles that might be mistaken for a CMT. The database would include not only location but the history of activity and the signature as detected by various sensors from various aspects.

Now, ATR is based on fusion of the motion information from MTI, the SAR image, and information from the IPB database. We know of no database for the false alarm rate for ATR with this kind of data fusion; however, we believe that reductions of an order of magnitude or more may be possible.

We have made a parametric analysis of the coverage area that might be achieved with fusion. We assumed fairly low vehicular traffic such as in the Western SCUD Box in Desert Storm and constrained the solution to limit false alarms and find the stoppers quickly, as shown on the chart. The MTI uses a slow ground mover and the SAR performs 1-ft resolution spot imaging over the entire footprint of its beam. The results are shown in the lower right quadrant of the chart, where the area that can be searched is shown as a function of the MTI radar's two-scan probability of detection. The latter is important because false stopper declarations can negate the efficiency of the basic concept. The results are paramaterized over a range of false alarm densities and non-target vehicle false alarm probabilities that may be feasible with fusion of the type proposed. The overall result is that the MTI two-scan detection probability must be on the order of 99 percent or more and the false alarm density must be quite high. Under these conditions, which may be obtainable with the fused ATR, several thousand sq km may be covered within the false alarm and time constraints. Such areas are on the order of the 100 nm diameter circle that cannot be searched rapidly enough with current high-resolution SARs.



This chart shows the results of our analysis of the capability of a fleet of Tier II+ type UAVs to perform wide-area search with an advanced dual polarization (POL) 1-ft resolution SAR.[12] This is motivated by the mission level CMT analysis shown earlier.

The final result, shown in the upper right graph, is that it is feasible to search about 100,000 sq km once every 20 minutes with a fleet of 50 UAVs—slightly fewer than planned for Tier II+. Assumptions, constraints, and supporting data are summarized in the lower right box. The overall result is derived from the three subanalyses summarized on the left. Payload weight is chosen to minimize the total number of UAVs when the interaction of all factors is considered.

The top box summarizes the total weight and the breakdown among radar antenna, radar transmitter, ATR processor, and image synthesis processor. The processor weights are 1998 projections for Sandia National Laboratory's ATR and Hughes Aircraft Corporation's SAR image processor. Somewhat to our surprise,

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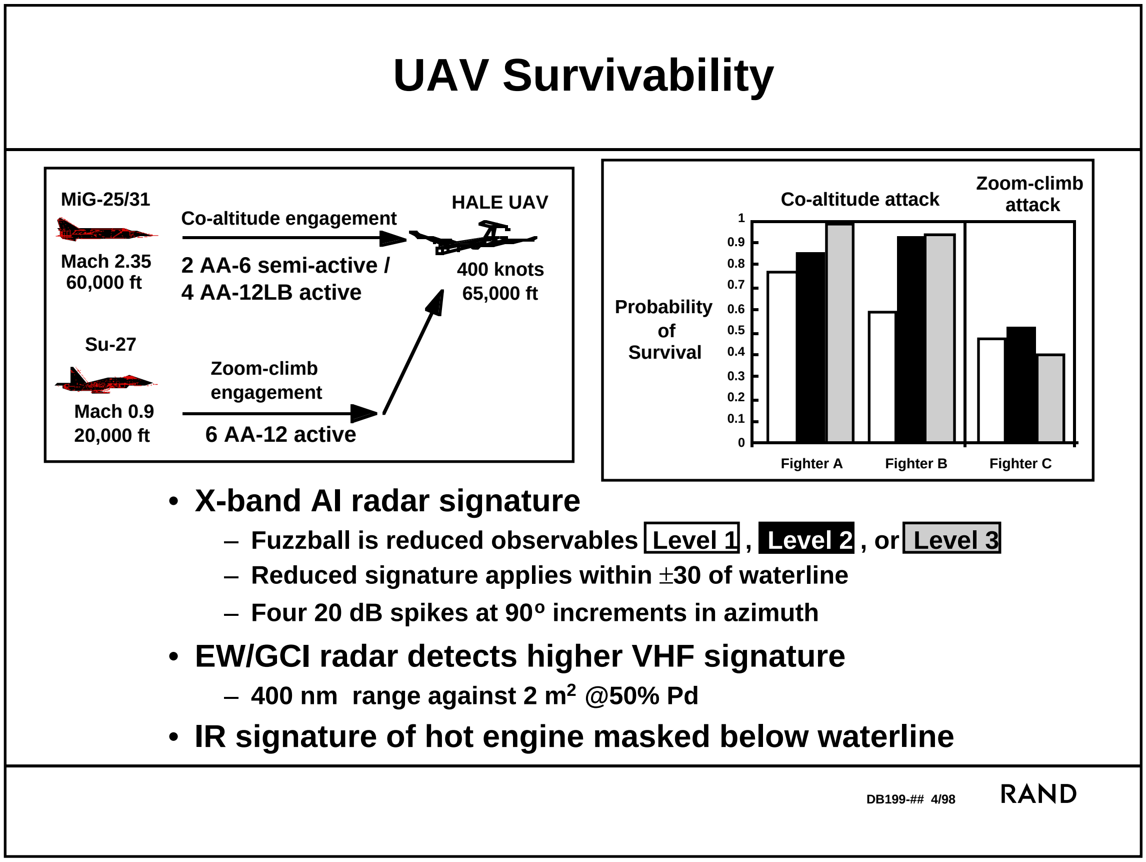
[12]According to USAF/SAF/AQIJ, there is no major development activity for multipolarization SAR. Availability on any U-2 or Global Hawk in the FY00–05 time frame is highly unlikely.

in the domain of one to a few thousand pounds, the total weight of the SAR system is dominated by the SAR image processor weight. We had anticipated that the on-board ATR processor might be a limiting factor, but Sandia's special-purpose ATR processor has dramatically reduced the weight required for the very high rate of processing involved.

The middle box summarizes our estimate of a Tier II+ type UAV performance. For each payload weight, the time on station is shown as a function of the UAV radius of action (ROA). These results were derived by scaling from CONDOR and engineering judgments. Payloads of several thousand pounds can be carried before the time-on-station and radius of action are drawn down significantly.

The final box illustrates how the travel time, time-on-station, and refitting and refueling time are combined to determine the total number of platforms required to maintain one platform on station. This effect can be seen in the overall result in which two UAVs are required no matter how small the search area.



This chart summarizes the results of TAC BRAWLER simulations for UAV survivability.[13] Two fighter aircraft tactics are considered. The results suggest that survivability against one of the tactics is questionable.

For either tactic, we assume that the UAV's X-band airborne intercept (AI) radar "fuzzball" signature has slightly reduced observables (Level 1), moderately reduced observables (Level 2), or highly reduced observables (Level 3). The fuzzball cross sections are assumed to apply within 30 degrees of the waterline. There are also four large (20 dB) spikes—separated by 90 degrees in azimuth.

We also assume that the very high frequency (VHF) early warning / ground control intercept (EW / GCI) can detect the UAV's much higher VHF radar cross section (RCS) at long range. Detection by the VHF radar gives a gross localization that is used by fighter aircraft to search in the vicinity of the UAV.

Finally, we assume that the IR signature of the UAV's hot engine is masked below the waterline. Thus, the fighters use active or semi-active radar homing

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[13] Frelinger et al., 1995.

air-to-air missiles for the final engagement if they can acquire a fire-control solution with their X-band AI radars.

In the co-altitude engagement tactic, the supersonic fighters (designated A or B) flying at 60,000 ft attempt to find the HALE UAV that is assumed to be flying at 400 knots at an altitude of 65,000 ft.

In the zoom-climb engagement, the subsonic fighter (designated C) repeatedly attempts to zoom from 20,000 ft flight to detect the large RCS of the UAV from below the waterline from as short a range as possible.

Probability of survival results of a limited number of random trials are shown in the bar graph at the right. For the co-altitude tactic, results are somewhat RCS sensitive, as evidenced by the low survivability for a Level 1 UAV against fighter B. However, for Level 2 or 3 UAVs, the survivability is around 90 percent. However, for the zoom-climb tactic, the survivability is only 50 percent and relatively insensitive to the UAV fuzzball RCS—as would be expected since the tactic relies on the large X-band RCS below the waterline.

These survivability results are for an entire sortie of the attacking interceptor aircraft, which makes as many attempts as possible before it must return to its base. Even so, the low survivability against the zoom-climb tactic is cause for concern.

Outline

- Introduction
- Methodology and Scenario
- Missions, CONOPS and Technology
- **Exemplar Results**

DB199-## 4/98 RAND

Description of Trade Analysis

Determine fleet size requirement for SAR/MTI-capable Global Hawk force in context of available U2s and other (non-SAR carrying) Global Hawks.

Evaluate Sensitivities to:

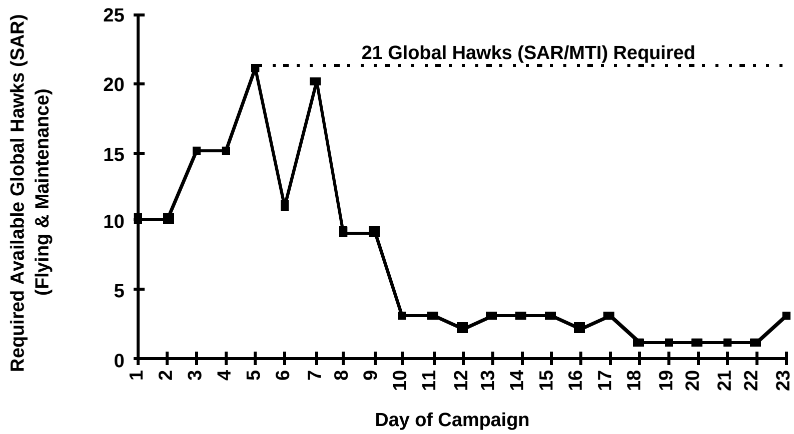
- **Intelligence Preparation of Battlefield (IPB)**
- **Availability of SIGINT Capability**
- **Cloud-Free Line-of-Sight (CFLOS) Conditions**
- **Basing Availability**
- **Radar Capability**
  - **Availability of MTI Capability**
  - **Improved SAR**
- **Threat Environment**
  - **Reduced Defenses**
  - **RCS Improvements**

DB199-## 4/98 RAND

This chart describes the tradeoffs we have performed. In each case, we determine the required size of the SAR/MTI Global Hawk "rubber" force in the context of the currently available U-2s, two each of the EO and SAR smallsats, and four each of the EO/IR and SIGINT Global Hawks. Other key outputs of the analysis are the number of successful and unsuccessful collections, and the relative contribution of each payload and platform type.

Each tradeoff is focused on the sensitivity of the results to an important element of the scenario, including the extent of IPB, the availability of SIGINT, MTI, or improved SAR payloads, the obscuration from clouds, the availability of near-theater basing, the status of enemy air defenses, and the extent of signature reduction of collection platforms.

Baseline Results: Required SAR-Capable Global Hawks



- **Platform requirements include aircraft in flight and in ‘maintenance’**
- **Attrition may be added to availability requirement off-line**

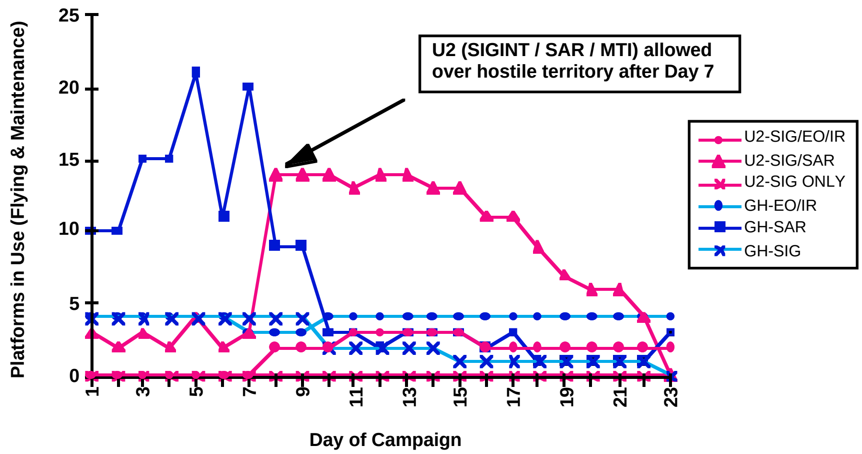
DB199-## 4/98 RAND

This chart shows the quantity of available SAR/MTI-equipped Global Hawk platforms required (not docked for attrition) on each day of the conflict. The platform requirements include aircraft in flight and in “maintenance” at the base. The largest number of Global Hawks needed is 21, which occurs during the initial seven-day period prior to the attainment of air superiority, when manned platforms are not permitted in-country.

One observes a significant fluctuation in the Global Hawk requirement on day six. This is due to the maintenance cycle. An appreciable number of the Global Hawks in use on day four, and being refurbished on day five, are again flight-ready on day six, but are not needed. Aircraft that are flight-ready, but remain at the base, are not included in the tally of required available platforms.

The effect of attrition would be to increase the required number of platforms by some factor corresponding to the percentage daily attrition rate. If one subscribes to the threat avoidance policy implicit in RSAM, the attrition would result entirely from pop-up SAMs that are not localized, or from airborne interceptors destroying UAVs in the initial phase of the conflict.

Baseline Results: Summary of All Platforms In Use

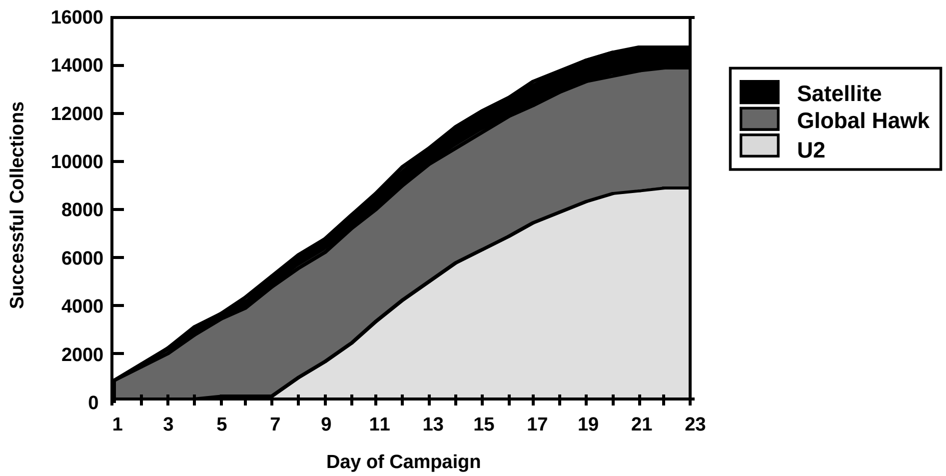


DB199-## 4/98 RAND

This chart shows the utilization of all the airborne platforms for each day of the conflict. One observes an abrupt increase in utilization of U-2s with SAR/MTI, and an equally steep decrease of similarly equipped Global Hawks on day seven of the conflict. Prior to day seven, when air superiority is achieved, the U-2s are restricted to standing off and peering into hostile territory. After day seven, these U-2s are preferred over the Global Hawks under RSAM's heuristic rules because of their multi-phenomenology payloads. We note that, when deployed, Global Hawks are likely to have ELINT capability as well.

The SIGINT-equipped U-2s are not utilized at all, because the four SIGINT Global Hawks are capable of fulfilling all the SIGINT collection requirements.

Baseline Results: Successful Collections



DB199-## 4/98 RAND

This chart shows the *cumulative* number of successful collections by smallsats, Global Hawks, and U-2s during the course of the conflict. The smallsat collections are a small fraction of the total, but increase steadily with each day of the campaign. The Global Hawks dominate during the first seven days, but then are displaced by the U-2s after air superiority is achieved. Collections by all platforms diminish toward the end of the conflict as operations wind down.

Trade Analysis

- Intelligence Preparation of Battlefield (IPB)
  - No IPB Available
- Availability of SIGINT Capability
- Cloud-Free Line-of-Sight (CFLOS) Conditions
- Basing Availability
- Radar Capability
- Threat Environment

DB199-## 4/98 RAND

The first tradeoff analysis we discuss is the effect of having no IPB.

IPB Characterization

- 84 target types used in Iran scenario
- 9 target classes for categorizing accuracy and level of target ID
- Default geolocation accuracy based on area limitation
- If IPB available, target geolocation and level of ID improves
- Multiple levels of IPB available

Target Class	Default	IPB
HQ Building	25%	75%
Comm Building	50%	50%
POL Storage	10%	90%
Chem/Bio Storage	95%	5%
TEL/Mobile Army	100%	0%
EW/GCI	25%	75%
Mobile SAM	100%	0%
Pontoon Bridge	100%	0%
Ship	100%	0%

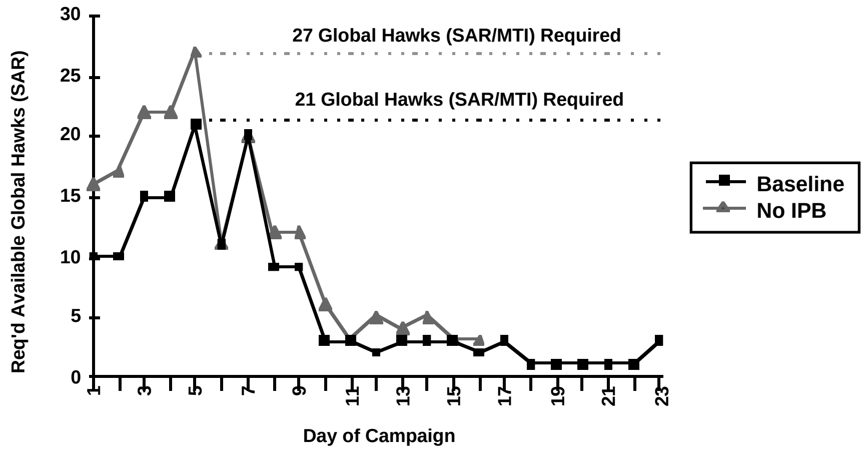
DB199-## 4/98 RAND

This chart shows the baseline IPB assumptions. The 84 target types in the scenario are each assigned to one of nine target classes based on gross characteristics such as size, overtness, transportability, and electromagnetic emanations. The target classes are labeled by representative members of the class, such as military headquarters buildings or mobile SAMs.

Each target class is assigned probabilities that area delimitation only is available ("default"), or that either IMINT or SIGINT is available ("IPB"). The input database includes statistical distributions for geolocation accuracy associated with area delimitation, IMINT, or SIGINT. After the preprocessor assigns a target to the default or IPB status based on the probabilities in the table, a random draw is made upon the appropriate geolocation distribution to obtain the location uncertainty at the start of the conflict.

As noted earlier, the baseline IPB assigns high probabilities for IPB to large fixed targets, and low probabilities to mobile targets. The spread of geolocation accuracies associated with SIGINT are larger than those for IMINT.

Lack of IPB Increases Global Hawk (SAR) Fleet Size Requirement by Nearly 30%



DB199-## 4/98 RAND

This chart shows that the number of available SAR/MTI Global Hawks required when there is no IPB is 30 percent more than with the baseline IPB. One might anticipate a more dramatic impact, but it should be noted that the baseline IPB calls for several classes of targets to have a low probability of pre-conflict IMINT or SIGINT collection.

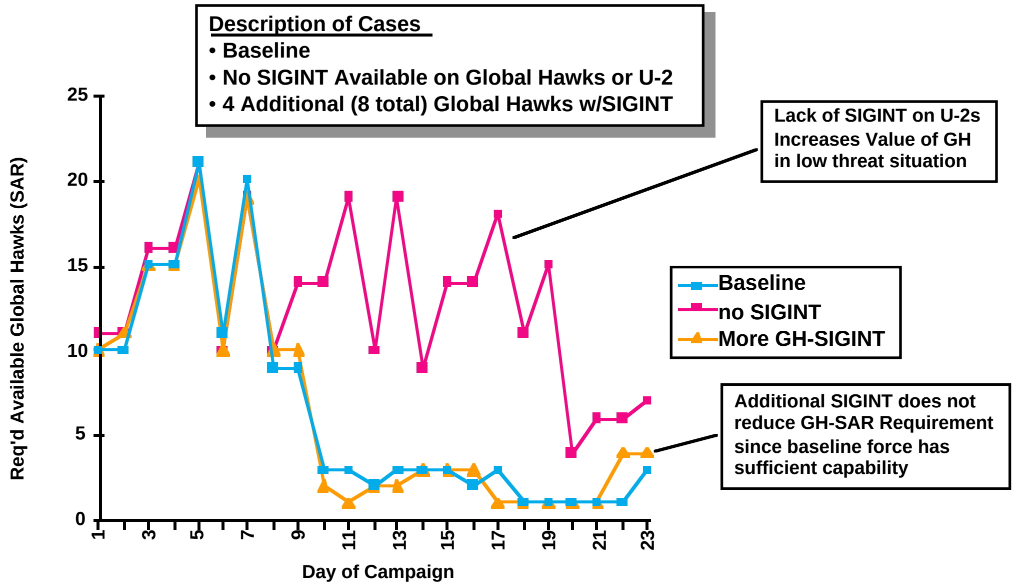
Trade Analysis

- Intelligence Preparation of Battlefield (IPB)
- Availability of SIGINT Capability
  - No SIGINT Available
  - Additional (+4) SIGINT Global Hawks Available
- Cloud-Free Line-of-Sight (CFLOS) Conditions
- Basing Availability
- Radar Capability
- Threat Environment

DB199-## 4/98 RAND

The second tradeoff examines the effect of varying the availability of SIGINT platforms. Two extreme cases are considered: eliminating SIGINT-capable aircraft entirely and doubling the SIGINT Global Hawk force.

Absence of SIGINT Capability on U-2 Makes Global Hawk (SAR) More Attractive Option



DB199-## 4/98 RAND

The effect of excluding SIGINT payloads is twofold. First, the peak requirement for SAR/MTI Global Hawks is slightly increased. This results from the loss of SIGINT cues, which increases the demand for low-resolution wide-area SAR coverage. Second, the removal of ELINT from U-2s downgrades the assignment priority of U-2s in RSAM's heuristic collection management framework. With the U-2s deprived of their multi-phenomenology edge over Global Hawks, the Global Hawks draw upon their greater endurance to dominate the collection of SAR imagery, which persists even after air superiority is achieved on day seven.

The effect on the requirement for SAR/MTI Global Hawks of doubling the SIGINT-capable Global Hawk force is negligible, because of the sufficiency of SIGINT-capable Global Hawks in the baseline force.

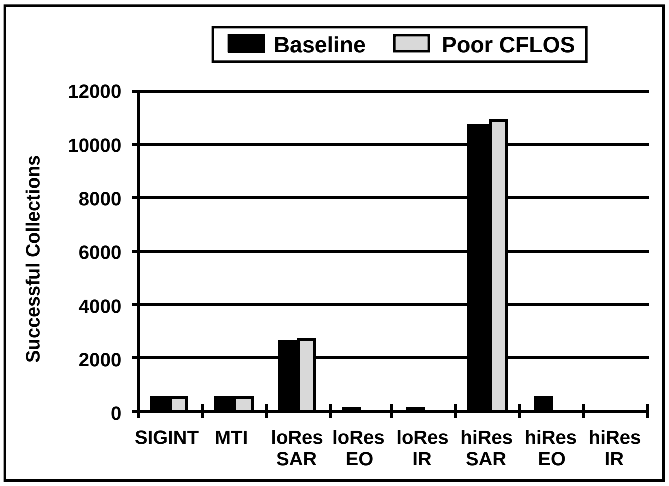
Trade Analysis

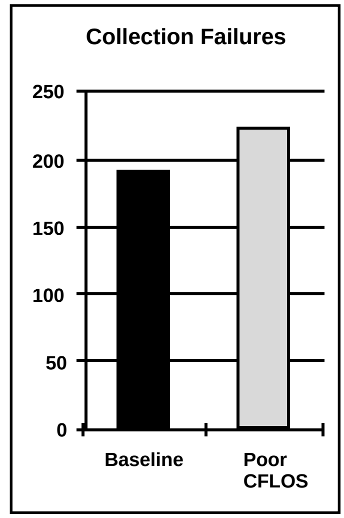
- Intelligence Preparation of Battlefield (IPB)
- Availability of SIGINT Capability
- Cloud-Free Line-of-Sight (CFLOS) Conditions
  - Poor CFLOS - No EO/IR Capability
- Basing Availability
- Radar Capability
- Threat Environment

DB199-## 4/98 RAND

The third tradeoff examines the impact of poor optical visibility. An extreme case is considered: the complete loss of cloud-free line-of-sight.

Due to Heavy Reliance on SAR, Poor CFLOS Conditions Have Minimal Effect





- Non-expert mapping of targets to NIIRS requirements
- Relatively few targets require NIIRS capability provided by EO/IR

DB199-## 4/98 RAND

The left-hand chart shows that in the baseline case (which employs typical cloud-free line-of-sight statistics for southwest Asia), the collection of imagery by SARs far outweighs the collection by optical sensors. This is because of the combination of their poor nighttime performance (IR has poorer resolution), their shorter range, and the blockage by clouds. Since the role of EO/IR is minimal to begin with, the complete loss of optical imagery resulting from poor visibility does not increase SAR collections by a significant fraction.

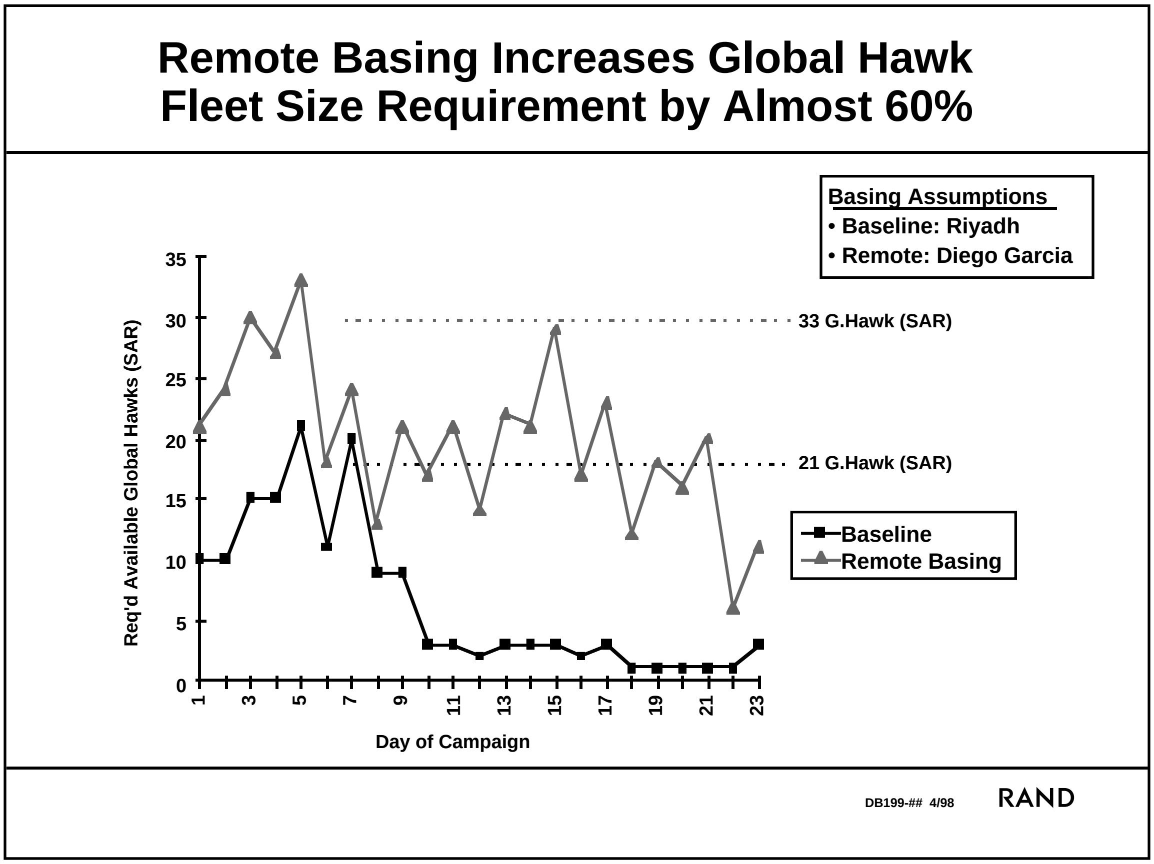
The 15 percent increase in collection failures with the loss of optical imagery, as shown in the right-hand chart, may be more important. A small set of targets requires NIIRS 7 or NIIRS 8 imagery for identification, and the current-generation SARs do not provide this. Targets in this category include radar equipment, command and control headquarters, nuclear weapons components, land minefields, POL and ordnance supply dumps, rockets and artillery, aircraft, missile sites, and vehicles. The number of such targets in our scenario is evidently small, but this may not always be the case.

Trade Analysis

- **Intelligence Preparation of Battlefield (IPB)**
- **Availability of SIGINT Capability**
- **Cloud-Free Line-of-Sight (CFLOS) Conditions**
- **Basing Availability**
  - **Remote Basing Only - Diego Garcia**
- **Radar Capability**
- **Threat Environment**

DB199-## 4/98 RAND

The fourth tradeoff examines the effect of losing in-theater basing. The alternative we have focused on is basing out of Diego Garcia. Remote basing out of Europe or from the CONUS might be other practical possibilities.



Basing out of Diego Garcia instead of Riyadh increased the required SAR/MTI Global Hawk force by approximately 50 percent. This is simply a reflection of the reduced time-on-station for the Global Hawks. The utilization of Global Hawks after day seven, which in the baseline case is diminished in favor of U-2s, persists with remote basing because the U-2s have sufficient range to service only the southernmost corner of Iran.

Trade Analysis

- Intelligence Preparation of Battlefield (IPB)
- Availability of SIGINT Capability
- Cloud-Free Line-of-Sight (CFLOS) Conditions
- Basing Availability
- Radar Capability
  - No MTI
  - Improved SAR
    - better antenna
    - faster processor
- Threat Environment

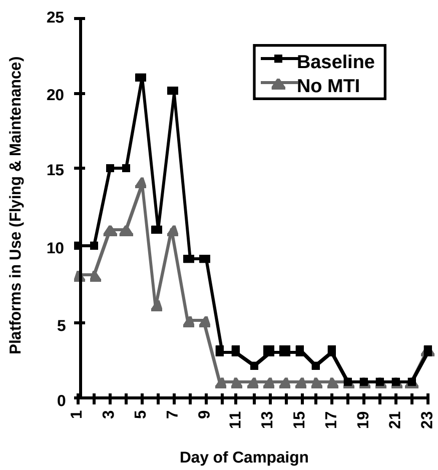
DB199-## 4/98 RAND

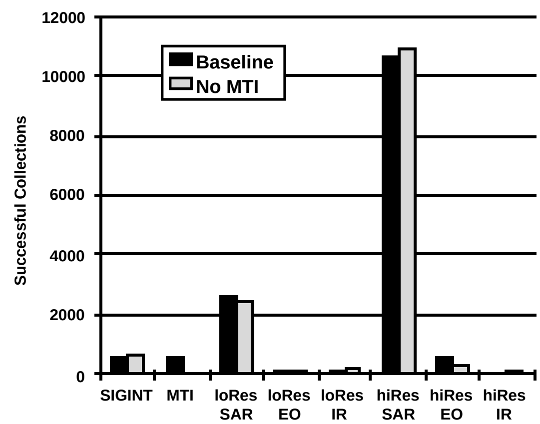
The fifth tradeoff analysis examines the effect of eliminating MTI payloads, and separately, the effect of increasing the area coverage rate of the SAR.

The current SAR swath widths are mostly processor-limited, so that they do not include the full antenna footprint on the ground. This constraint will be eliminated in the near future as faster processors become available. Our baseline SAR sensor already incorporates these near-term improvements.

Coverage rate advances beyond our baseline will require a more fundamental redesign of the radar to deal with range-Doppler ambiguities that arise when the swath is extended. A recent RAND analysis indicates that a multiple elevation beam design (requiring a new antenna) can provide a fivefold increase in coverage rate over an ambiguity-limited single-beam design. A corresponding increase in processor speed is also required. The improved SAR assumed in this tradeoff analysis incorporates the multiple-beam design.

Other ‘Ints’ May Compensate for Lack of MTI Capability

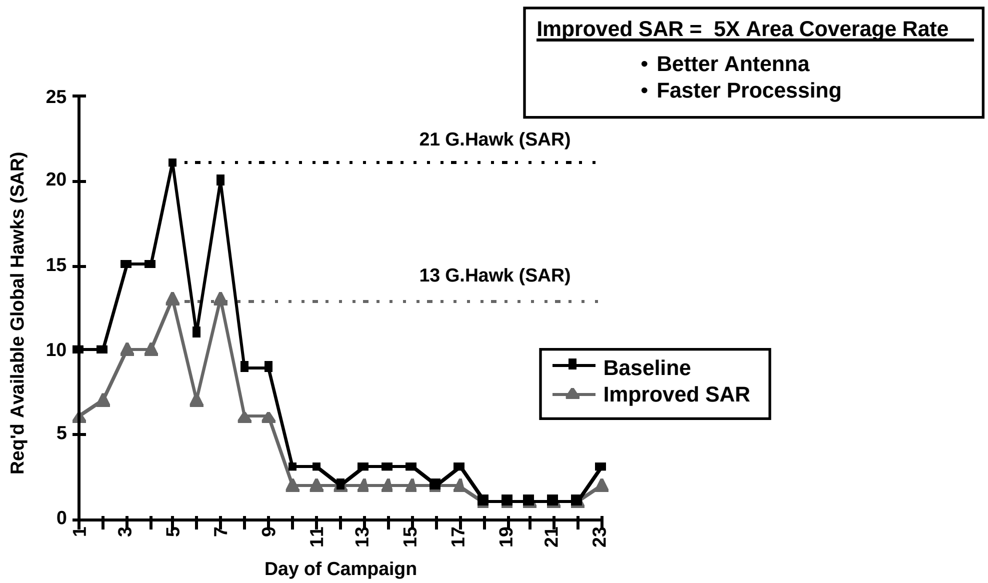




DB199-## 4/98 RAND

There are two kinds of effects resulting from the elimination of MTI payloads. The first is to reduce the utilization of SAR/MTI Global Hawks by approximately 40 percent. The second is to increase the number of collections by SIGINT, low-resolution EO/IR sensors, and high-resolution SAR. Apparently, other sensor payloads are compensating for the lack of MTI cueing capability. The overall impact appears to be minimal, but this should be seen more as a reflection of the small number of mobile targets in our scenario rather than as a fundamental consideration.

Improved SAR Reduces Global Hawk (SAR) Fleet Size Requirements by Almost 40%



DB199-## 4/98 RAND

The improved SAR, with a fivefold increase in coverage rate relative to our baseline, reduces the required SAR/MTI Global Hawk force by 40 percent. This effect is fairly striking, but a cost analysis would be in order before recommending this approach.

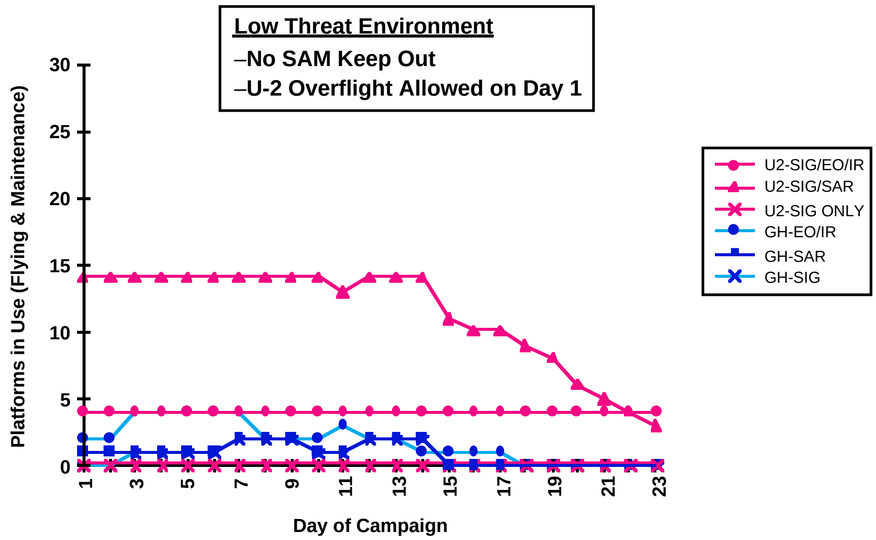
Trade Analysis

- Intelligence Preparation of Battlefield (IPB)
- Availability of SIGINT Capability
- Cloud-Free Line-of-Sight (CFLOS) Conditions
- Basing Availability
- Radar Capability
- Threat Environment
  - Low Threat
    - No SAM Keep Out
    - U-2 Overflight Allowed on Day 1
  - Reduced RCS on Global Hawks

DB199-## 4/98 RAND

The sixth tradeoff analysis has two parts involving the nature of, and the response to, the air defense threat. First, we turn off all the SAM defenses and assume air superiority is achieved at the start of the conflict. This means there are no keep-out zones, and manned aircraft can operate in-country on day one. In the second tradeoff, we assume a reduced RCS for the Global Hawks.

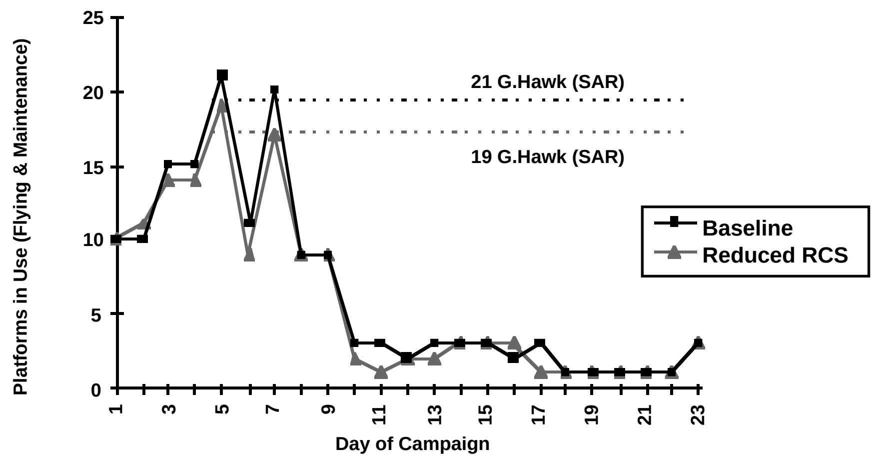
Low Threat Environment, U-2s Preferred Over Global Hawks Due to Additional Capabilities (SIGINT/SAR/MTI)



DB199-## 4/98 RAND

This chart shows the platform utilization under the low threat environment. The requirement for Global Hawks is much reduced, because the U-2s are no longer relegated to a standoff role during the first seven days of the conflict. The U-2s with their multi-phenomenology payloads are assigned preferentially over Global Hawks during the whole course of the campaign.

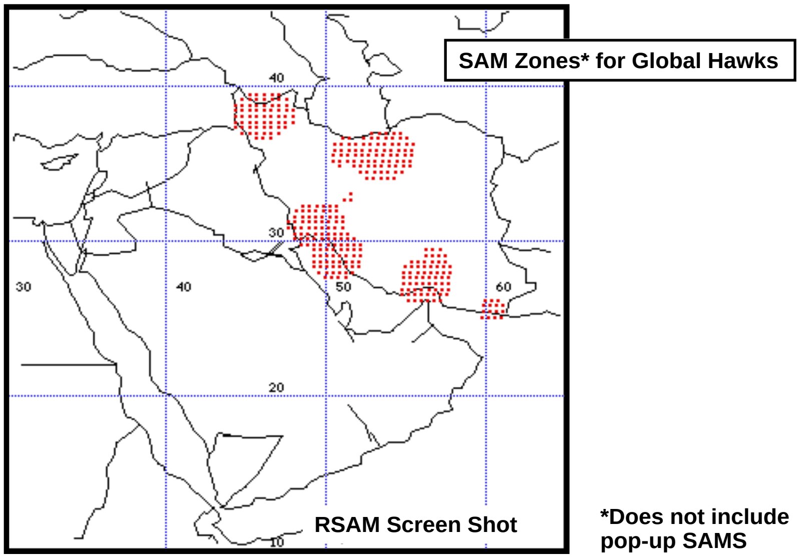
In This Scenario, Reduced RCS Provides Small Reduction in Global Hawk (SAR) Force Size Requirements



DB199-## 4/98 RAND

In this tradeoff analysis, the effect of reducing the Global Hawk's radar cross-section is shown to decrease the requirement for SAR/MTI Global Hawks by 10 percent. The difference arises from the fact that EO/IR Global Hawks, which have a shorter reach, are now able to penetrate to a useful range and thereby displace some of the SAR/MTI Global Hawks. One might anticipate a greater impact for reduced observables—for example, an *increased* utilization from the ability to reach targets to which access is otherwise denied by the defenses. To gain insight into this matter, it is necessary to consider the relationship between the size of the defended regions and the reach of the sensors. This is addressed in the next two charts.

High Altitude of Global Hawk Plus Standoff Provided By SAR Minimizes SAM Threat in Baseline Iran Scenario



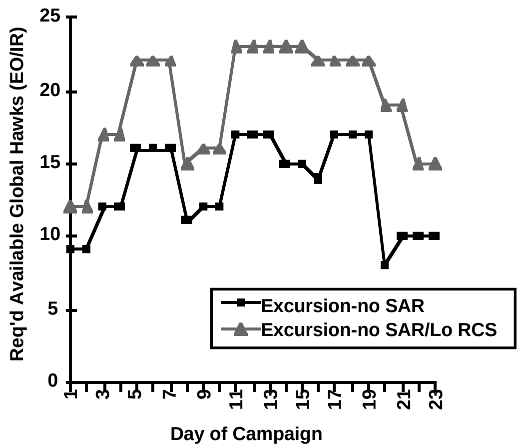
*Does not include pop-up SAMS

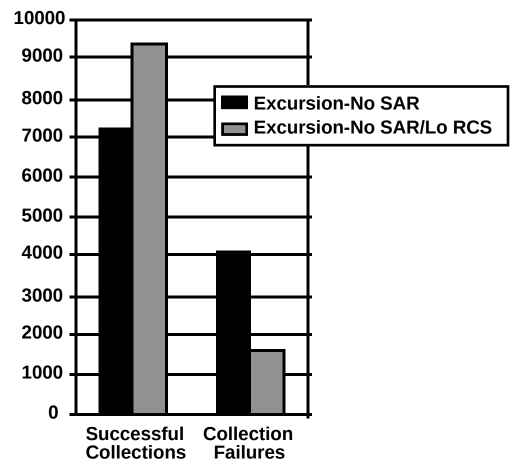
DB199-## 4/98 RAND

This chart shows the extent of the SAM keep-out zones in Iran. The effects of pop-up SAMs and fighter area defenses are not included. In most instances, the radii of the keep-out zones are less than 200 km. Consequently, the Global Hawk's SAR is generally capable of peering into these defended areas from a safe standoff position. This implies that *for the scenario in question*, in which the defenses are relatively sparse, reduced observables do not contribute much to increasing overall target access. However, there is some increased capability for EO/IR Global Hawks to access the targets, as shown in the next chart.

Excursion: No SAR Capability / EO/IR Global Hawk Rubber Force

- EO/IR Collection Requires Closer Ranges for Collection
- Global Hawks with EO/IR Benefit More from Smaller RCS





DB199-## 4/98 RAND

This chart shows the result of a tradeoff analysis in which the SAR payloads are excluded and the “rubber” force is made up entirely of EO / IR Global Hawks. The impact of reduced observables on target access for EO / IR payloads is therefore highlighted. The required EO / IR Global Hawk force is increased by 35 percent, as shown in the left-hand chart, when platform observables are reduced. This may appear counterintuitive, but the point is that without signature reduction, the defenses deny access to a large fraction of the targets because of the limited range of EO / IR sensors. With reduction in the Global Hawk signature, many more targets become accessible, and more platforms are then required to service them. This is confirmed in the right-hand chart, which shows that the number of collection successes is increased by nearly 30 percent and the number of collection failures in reduced by more than 60 percent when platform signatures are reduced.

Summary of Trade Analysis

Preliminary Analysis on Iranian Scenario Shows:

- **Lack of IPB Increases G. Hawk (SAR/MTI) Fleet Size Requirement by Nearly 30%**
- **Availability of Multiple Ints on Platform Increases Utility**
  - **In Low Threat, U-2's Utilization Increases**
  - **In Absence of SIGINT, G. Hawk Utilization Increases**
- **Poor CFLOS Does Not Impact Fleet Size Requirements When SAR Provides Required NIIRS**
- **Remote Basing Increases G. Hawk (SAR/MTI) Fleet Size Requirement by Almost 60%**
- **Improved SAR Decreases G. Hawk (SAR/MTI) Fleet Size Requirement by Almost 40%**
- **Reduced G. Hawk RCS Does Not Add Significant Value When Defenses are Sparse and SAR Provides Adequate Standoff**
  - **EO/IR Utilization Increases Significantly with Reduced RCS**

DB199-## 4/98 RAND

This chart summarizes the results of the tradeoff analyses. We stress that the quantitative outcomes, and in some instances the trends, are highly scenario dependent, and that these analyses were performed with a partial database of R&S platforms and sensors.

Prospective RSAM Tradeoffs

- Determine the relation between campaign performance and ISR options
- What is appropriate ISR force level and balance between space-based and airborne (manned and unmanned)?
- What is the most effective space architecture (Large Sats, Small Sats, Commercial Sats?)
- What is the effect of performance of ISR assets?
  - Flight altitude, endurance, speed
  - Stealth
  - Payloads (sensors, communications, processors)
- What is the effect of various basing options (In-theater vs. CONUS basing)?
- What is the impact of changes in ISR objectives?
- What is the minimum cost set of resources to accomplish a set of ISR objectives?
- What is the impact of modernizing the weapons inventory (with their associated ISR requirements)?
- What are the communications bandwidth requirements to support the ISR data flow?

DB199-## 4/98 RAND

The RSAM is an analytical tool designed to operate in concert with CTEM (or other planning tools that produce an attack plan) to perform campaign-level assessments of ISR options, force levels, and characteristics. It is database driven and heuristic in nature, written in FutureBasic II, and hosted on a Macintosh PC.

Studies that could be supported using RSAM include determining the appropriate architecture, force level, and balance between space-based (large, small, and commercial satellites) and airborne (manned and unmanned) assets; cost-benefit evaluation of future payloads (sensors, communications, processors) and platforms (including performance and survivability tradeoffs involving increased endurance, reduced observability, electronic countermeasures, and increased altitude); and the effect of various basing options on the optimal mix of airborne assets. At a higher level of consideration, one can examine the consequences of changes or evolution in ISR objectives, such as those resulting from different scenarios.

RSAM addresses the primary factors affecting these issues, including intelligence preparation of the battlefield, basing, operational restrictions, intervisibility, cloud obscuration, collection tactics, threat avoidance, sensor performance, and airborne platform speed and endurance.

In the future, as we insert cost data into RSAM, master the interplay between CTEM and RSAM, and include estimates of data flow from sensors and processors, it will be possible to optimize cost in relation to a set of ISR objectives, to assess the impact of modernization of the weapons inventory, and to evaluate communications bandwidth requirements to support ISR data flow. In the interim, cost tradeoffs can be performed off-line.