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Advanced Electro-optical Space-Based Systems for Missile Surveillance

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Michael Zambrana

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13. ABSTRACT (Maximum 200 words)

This report describes an analysis/simulation methodology used to assess a nominal space-based infrared surveillance architect against a Theater Missile Warning (TMW) mission for two potential theatres of operation. System performance is derived for three generic infrared scanning sensor designs (which were analyzed in parallel for sensitivity, subsystem definition, mass, and power) and parameterized .against the potential wvariations and uncertainties in scene background structure which produce clutter. The results provide insight into the cost, in terms of sensor mass, that is paid for background phenomenology uncertainty.

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1. Introduction

The ability to provide early warning against theater missile attack has become a key mission area for military planners. A space-based surveillance system can provide such warning. However, enhancing the timeliness and utility of any future space-based infrared surveillance system will depend greatly on an accurate appraisal of the phenomenology involved and its impact on sensor design and performance. System performance may be seriously compromised if non-optimum sensor designs or system architectures are deployed. The cost of optimum system performance is being carefully scrutinized by decision-makers as part of the ongoing process of DoD acquisition reform that has distinguished the procurements of the past decade. Indeed, system cost is now treated as an independent variable.

The Aerospace Corporation is often asked to provide quick-response assessments of a wide variety of space-based sensor concepts. These assessments involve the accurate determination of system performance, underpinned by reasonably detailed sensor design constructs. The latter is important for the accurate estimation of sensor and ultimately of space segment mass, power, volume, and cost estimates, along with the evaluation of the associated technology risks for sensor subsystems and their components. These assessments require the use of a variety of analysis and simulation tools. Frequently, an analytic approach is deemed adequate for sensor performance assessments. However, in cases where the interaction of the background scene structure with the sensor produces a significant component of the total system noise, highly detailed, scene-based simulations are required. In these simulations, the details of the spatial structure of the background against which target detection will be accomplished must be incorporated into the analysis. For these cases, one often finds that the approximations required to render an analytic approach are violated. For example, in the analytic approach, one usually assumes that the background scene amplitude distribution is Gaussian, leading to a simple convolution of the background clutter with the noise distribution inherent in the sensor. However, many backgrounds do not have Gaussian amplitude distributions because of commonly occurring features such as cloud edges, land/sea interfaces, etc. Under such circumstances, detailed pixel-level focal plane simulations are required if an accurate assessment of the sensor's performance is to be made. On the other hand, when the emphasis is on the system performance of a constellation of sensors, such a level of detail has generally been viewed as too time-consuming and costly to incorporate within a constellation-level simulation.

In this report we describe a methodology for accurately quantifying the impact of spatially structured backgrounds on the performance of space-based infrared sensors and, further, couple these results with sensor design constraints and other mission performance tools thereby enabling high-level systems engineering trades that provide insight into cost/performance relationships. In effect, high-fidelity sensor and phenomenology models are used to generate constraints and databases for use within constellation-level simulations, thereby enhancing their overall accuracy. This integrated simulation capability has been used to support both sensor and system trades for a number of space-based, infrared surveillance system studies, including those dealing with Theater Missile Warning (TMW). An early version of this capability was used to support the *SBIR (Space-Based Infrared) System Phenomenology Impact Study (SSPIS),*[1] conducted by The Aerospace Corporation, in collaboration with the MIT Lincoln Laboratory, during the winter and spring of 1994. When completed, this study made recommendations for a background phenomenology collection campaign that ultimately involved the Miniaturized Space Technology Initiative 3 (MSTI 3) and Midcourse Space Experiment (MSX) satellite experiments, as well as background observations from a high-altitude aircraft. This background phenomenology database was later made available to the High and Low components of the Space Based Infrared System (SBIRS). The simulation was also used during the 1994 Surveillance Summer Study as a tool for developing the system requirements ultimately levied on the SBIRS program.

These simulation tools[2,3] serve to facilitate the trade-offs required for optimizing sensor designs to meet mission requirements, and indicate the best approach for minimizing the system costs while maximizing performance. In effect, the inclusion of system costs in architecture studies represents a significant and important extension of the traditional Aerospace role in its support of the Air Force Space and Missile Systems Center (SMC).

In order to illustrate the models and analysis procedures, we evaluate a nominal space-based infrared surveillance architecture against the TMW mission for two potential theatres of operation. System performance is derived for three generic infrared (IR) scanning sensor designs (which were analyzed in parallel for sensitivity, subsystem definition, mass and power) and parameterized against the potential variations and uncertainties in the background structure. The results provide insight into the cost, in terms of sensor mass, that is paid for background phenomenology uncertainty.

2. Infrared Sensor Design

In order to connect system performance with system cost, the sensor performance must be linked to specific system architectures with well-defined sensor payloads and associated spacecraft bus, communication, ground, and launch system elements. The focus for this report is a key system element: the infrared sensor payload configured for the detection and tracking of theater missiles. The sensor is assumed to be a scanner deployed in a geostationary orbit with a field-of-regard to cover the anticipated threat areas, e.g., the Middle East and Northeast Asia, as illustrated in Figure 1 below.

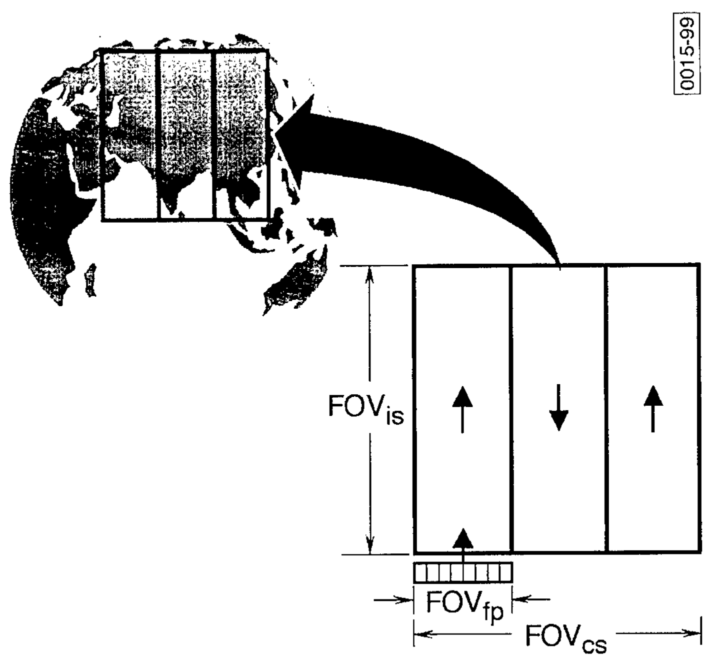


Figure 1. Scan pattern of conceptual sensor for theater missile surveillance.

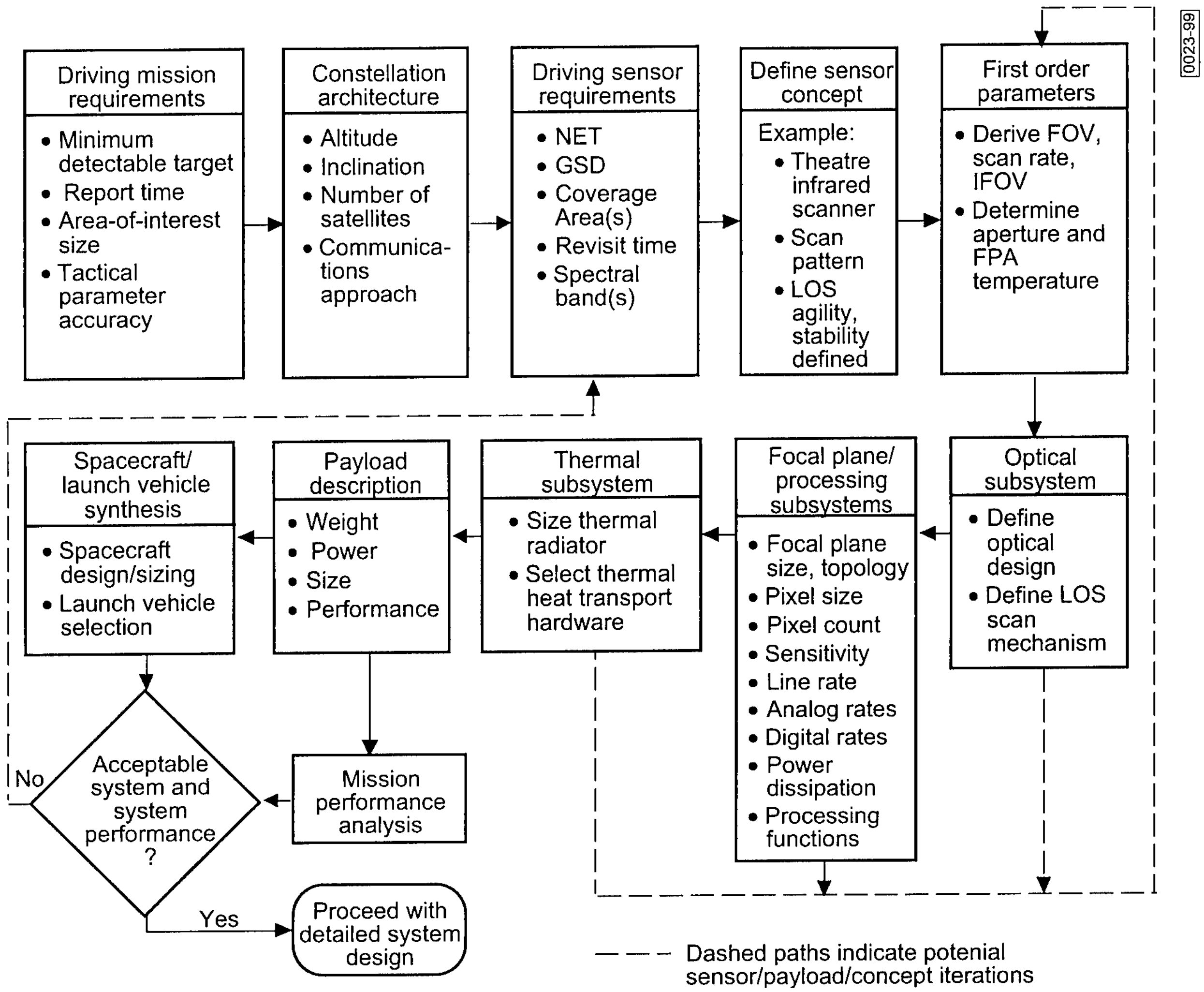


Figure 2. Flowdown of mission requirements to payload sizing and launch vehicle selection for an infrared scanner.

Typical mission requirements (Fig. 2) are the minimum detectable target, time of first report, size of the geographical area of interest, accuracy of the reported launch location, heading of the target, and accuracy of predicted impact point. These are met with a set of properly sized infrared sensors configured with an optimized constellation architecture. This constellation is located at an appropriate orbital altitude and inclination, which determines the number of satellites, data communication rates and infrastructure, and space and/or ground-based processing systems. Sensor sizing is jointly driven by the required sensor sensitivity, resolution at the target range, revisit time or target update rate, and the selection of appropriate spectral bands for discriminating targets from backgrounds.

With the input system performance parameters defined, along with the chosen constellation architecture, an infrared sensor system design is synthesized and the definition of the sensor's first-order technical design parameters is obtained. These include: sensor type (scanner or starer), system field-of-regard and scan pattern; telescope field-of-view, detector pixel instantaneous field-of-view, aperture and focal length; system scan rate; focal plane definition (single or dual color), sensitivity, topology, and frame-rate; signal processing data rates and functional definition; and overall system digital output data rates. This process is illustrated in Figure 3.

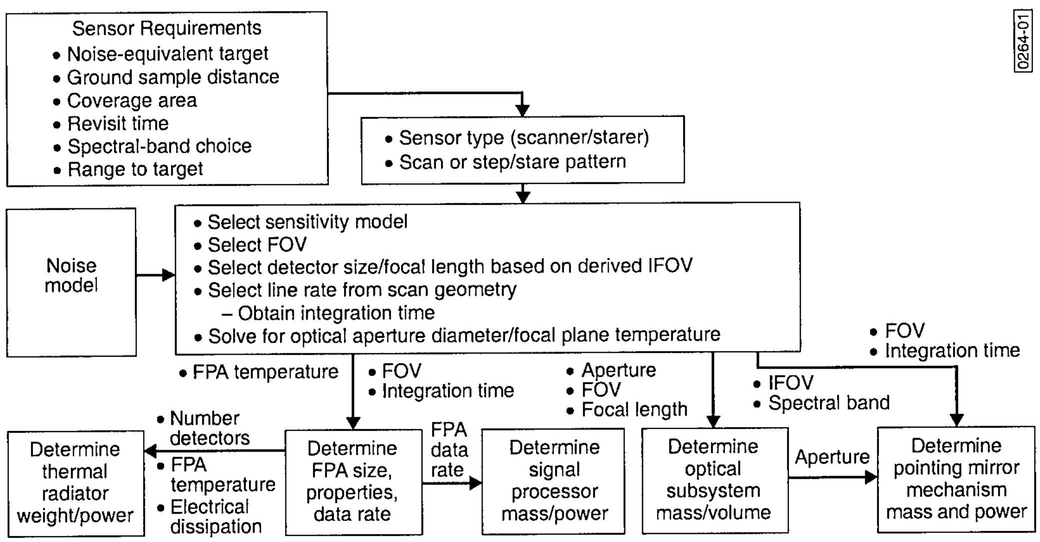


Figure 3. Driving sensor requirements for a hypothetical theater missile surveillance system.

Once these first-order design parameters are in hand, the next level of synthesis, shown at the bottom of Figure 3, "fleshes-out" the details of the infrared sensor subsystems in enough detail that reasonable estimates of the mass, power, and volume of these components can be made. At this level there is enough detail to allow meaningful technology risk assessments to be formulated as well. A variety of linked analysis tools and databases execute the payload design and sizing process, illustrated in Figures 2 and 3. For example, the process of defining the focal plane includes selection of the focal plane detector material and optical cut-off wavelength, spatial layout, detector or pixel dimensions, and line rate(s). The sensor sensitivity requirement is translated into a focal plane sensitivity constraint which then allows selection of focal plane operating temperature using a thermal noise model specifically tailored for the chosen detector material (e.g., mercury cadmium telluride). The focal plane topology (total detector count) and maximum line rate then allow the determination of the electrical power that must be dissipated. This, along with the focal plane's operating temperature, serve as inputs to a model which determines the technology, size, power, and volume of the cryogenic cooling system. For the optical system, the parameters described previously are used to select and refine a specific telescope optical design using a state-of-the art optical design and tolerancing program (e.g., CODE V). This optical program provides outputs that are used to estimate the mass and volume of the optical subsystem, and the power required to scan and point the line-of-sight mirror. Reference 3 provides an illustration of these subsystem-sizing procedures for a so-called "fiducial" design. As illustrated in Figure 2, the subsystem masses, power dissipations, and volumes are "rolled-up" into an overall payload mass, power, and configuration. This is then used to size the spacecraft bus and to select the launch system. The detailed subsystem parameters, along with the subsystem masses, power consumption levels, and configurations are then passed to an appropriate cost estimating tool(s). The spacecraft bus/ launch system sizing and costing capabilities are well developed and in use by The Aerospace Corporation's Concept Design Center.

The above discussion illustrates a single pass through the processes described in Figures 2 and 3. In order to develop system-level performance/cost relationships, the overall process is carried out as a function of sensor performance parameters by varying, for example, sensor noise-equivalent target, revisit time, and ground-sample distance (resolution). For such parametric analyses, scaling relationships are often used to interpolate subsystem mass, power, and volume estimates between design points. This is appropriate once a validated fiducial detailed design is developed; excursions from this fiducial design then use the appropriate scaling relationships. In the remainder of this report we discuss sensor and constellation system-level simulation tools used to calculate end-to-end performance. An example is provided wherein the sensor ground-sample distance (resolution) is systematically varied over a 2:1 range to illustrate the impact of infrared scanning sensor susceptibility to background clutter. The level of this clutter is also varied over a wide range. Variable ground sample distance is used to derive corresponding infrared sensor system designs from which payload masses are determined. To more clearly illustrate this sensitivity trade, cost is assumed to be related only to infrared sensor mass (this is a rough approximation). The specific cost/benefit relationships developed by this example are illustrated in the next section.

3. Sensor Performance Simulation Tools

The simulation of the performance of a space-based surveillance system involves the use of an ensemble of computer models and databases, starting with the generation of a set of short-wave infrared earth-cloud background scenes. For this purpose the *SBIRS Toolkit* subset of the Synthetic Scene Generation Model (SSGM), created by Photon Research Associates Inc. (PRA) for the Ballistic Missile Defense Agency of the Department of Defense, is used. The process starts with the selection of scenes from the database of weather satellite imagery. The images are pixelized and the infrared properties of the scene elements are then inserted. A key step in this process is the use of the CLDSIM model incorporated in SSGM for the solar scatter from the cloud tops at various altitudes. Scenes with only terrain, sea surfaces, and low altitude clouds are generally benign with respect to the generation of clutter from sensor line-of-sight motion, whereas solar reflections from high-altitude clouds can be responsible for a high degree of clutter, which can, in turn, stress the sensor's ability to detect targets of interest. SSGM can be used to generate a matrix of scenes with a variety of viewing geometries in the desired spectral band, selected atmospheric properties, and a specified pixel resolution.

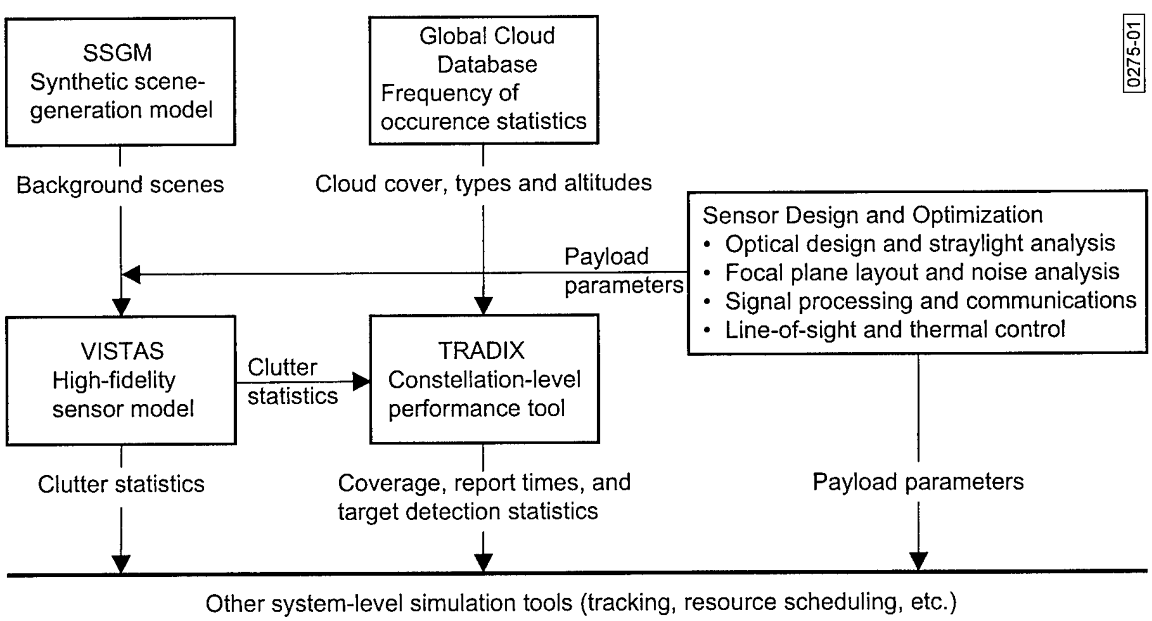


Figure 4. Flowchart of integrated electro-optical sensor design and simulation.

For the evaluation of sensor performance, the Visible and Infrared Sensor Trades, Analyses, and Simulations (VISTAS) model, formulated and coded by Aerospace, was used in the SSPIS analysis. Two scenes, one "nominal" and one "stressing" were selected. The imaging chain of an electro-optical (EO) sensor, from the background scene input to the signal processor output is modeled. The transfer function includes the effects of the optical point spread function, i.e., the blur, and for a scanner, the temporal aperture due to the scan motion during the integration time. The blurred scenes are re-sampled at the system resolution and clutter-rejection filters are applied. The output is calibrated to account for the sensor system's response to the target intensity. The output scenes are then analyzed for figures of merit such as the standard deviation of the sensor response. These products then are a statistical representation of the clutter of the background scene and sensor design under consideration.

Figure 5. "Nominal" scene: 2 – 8 km altitude clouds; 200m resolution; mid-latitude summer atmosphere.

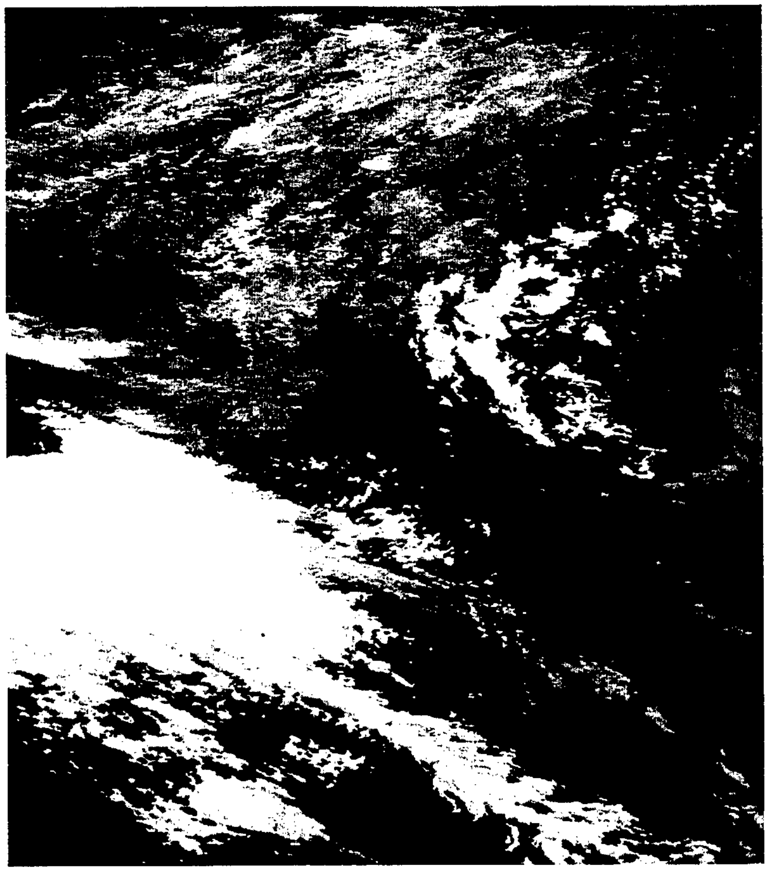


Figure 6. “Stressing” scene: 4–10 km altitude clouds; 200m resolution; mid-latitude summer atmosphere.

TRADIX is a constellation-level analysis tool, which combines EO sensor models with target and background models to evaluate the system performance. It contains a hard-body target signature model, missile plume intensity and trajectory profiles, background models including stray light from non-rejected earthshine and sunshine, the clutter statistics generated by SSGM/VISTAS, and the atmospheric path radiance and transmission. These models are integrated with Aerospace’s orbit propagation library, ASTROLIB, to provide a dynamic simulation tool for studying the constellation-wide performance of EO sensors.

Critical inputs to the above tools include: focal plane pixel topology, sensor noise characteristics, details of the filters and signal processing, optical design and stray light rejection capability, platform drift and jitter, constellation orbits and phasing, and concepts of operation (CONOPS), i.e., scan modes, revisit times, etc.

Information on the frequency of occurrence of meteorological conditions is a critical issue in regard to the performance of a space-based infrared surveillance system against earth backgrounds. For that purpose Aerospace uses a global cloud statistical model based on the University of Wisconsin HIRS-2 (High-Resolution Infrared Sounder) data from the National Oceanographic and Atmospheric Administration (NOAA) polar orbiters. This database provides a statistical basis for assessing system performance against clouds of various altitudes for a given time of year at a specified geographical location. Typical displays of such data would be shown on a world projection in terms of the maximum, minimum, and mean distributions of the probability of clouds above a given altitude during a specified month.

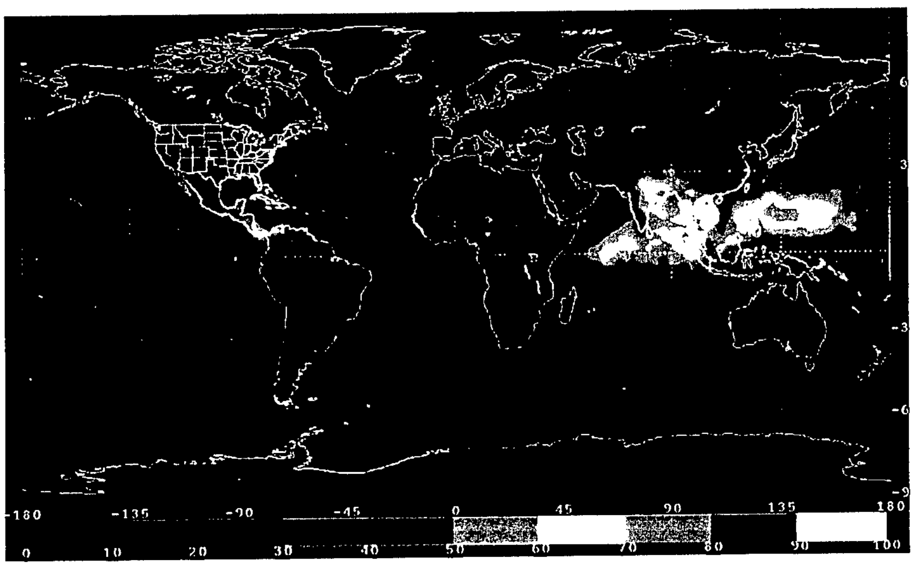


Figure 7. Mean frequency of occurrence of clouds above 10 km: U. Wisc. HIRS-2 data: Aug 1989–1994.

4. Scene-based Clutter Analysis

The performance of an earth-viewing infrared sensor, designed to operate in the SWIR atmospheric absorption band to block signals from terrestrial sources, is nevertheless dominated by the remaining structure in the radiance field. This structure is predominantly due to sunlight reflected from clouds in the scene, and depends on the sensor-cloud-sun viewing geometry, represented by the cloud "look zenith angle" (LZA) and the "solar scatter angle" (SCA). The SCA is the dominant angle, which determines the intensity of solar scatter off the cloud tops; very small values of the SCA correspond to forward scattering. The other angle, the LZA, defines the projection of the SSGM cloud scene in the sensor line of sight (LOS), and is related to the range to the cloud tops. For targets, the LZA is also directly related to the path length through the atmosphere to the target at a given altitude, and hence to the apparent target irradiance for a given time after launch. At high zenith angles, low altitude targets close to the earth limb suffer from the worst combination of range, atmospheric transmission loss, and solar-induced background clutter. Unfortunately, most of the earth's surface viewed by a sensor in space lies at the larger LZAs. However, the overlapping coverage of multiple sensors can be used to mitigate this problem.

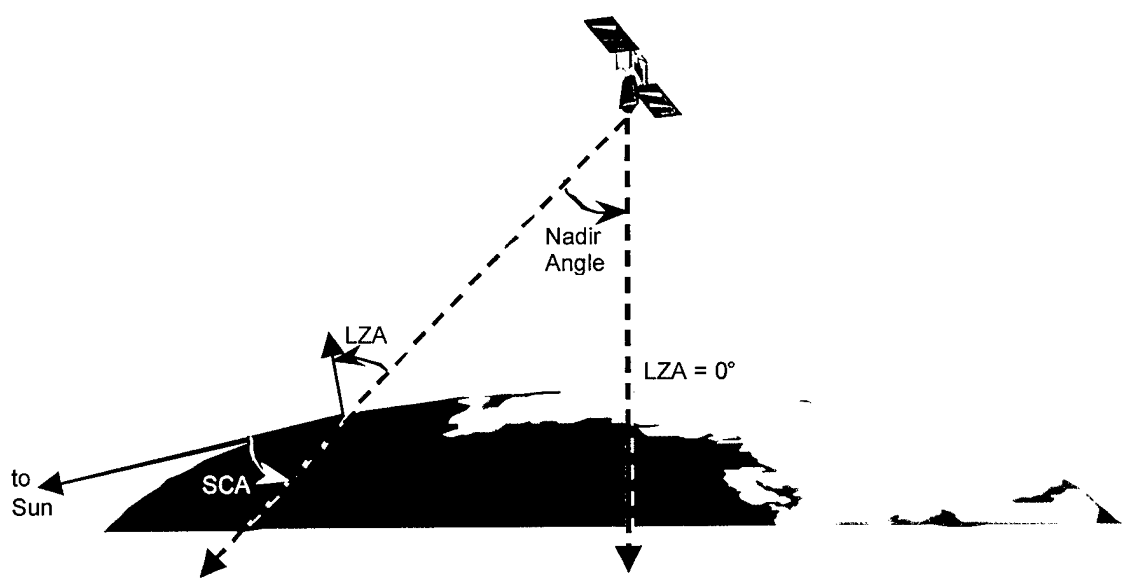
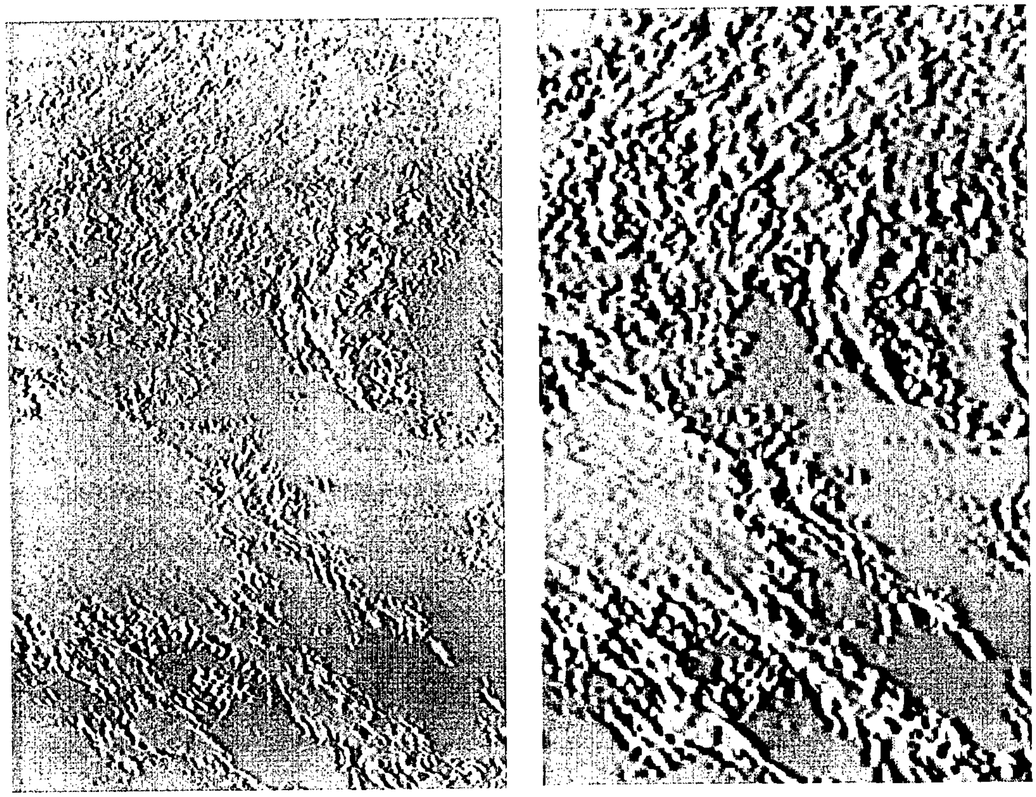


Figure 8. Solar scatter geometry: as the sensor line of sight shifts from nadir to the limb, both the range to target and the path length through the atmosphere increase while the minimum possible solar scatter angle (SCA) decreases.

The two SSGM scenes selected in this study represent a "nominal" case containing low to mid altitude clouds, and a "stressing" case with mid to high altitude clouds. The terms "nominal" and "stressing" refer to the level of the clutter generated when passed through a typical sensor simulation. Each scene covers an area of 512 × 1170 km at nadir with a 200-meter resolution, as seen through a midlatitude summer atmosphere at LZA=60° and SCA=90°; geometric projection effects at an LZA of 60° shorten the apparent size of these scenes to 510 × 570 km. The brighter clouds in these images are at higher altitudes where there is less attenuation of sunlight both before and after it scatters from the cloud tops.

The most significant caveat on this analysis is the use of the CLDSIM model contained within SSGM. A number of uncertainties are inherent in this model, one being the model for the bi-directional reflectance distribution function (BRDF) for the solar scattering from the clouds. The resultant uncertainty in the apparent cloud brightness is estimated to be less than a factor of three. The impact of the uncertainty was addressed by scaling the intensity of each scene, in the nominal case by 1/3 and 1/2 and in the stressing case by 2 and 3, thus providing a total of six cases. In this way the effect on system performance of varying the cloud types and altitudes and the additional impact of the SSGM modeling uncertainties was quantified.

In viewing such scenes, a scanning sensor typically provides an "ac-coupled" response, in effect performing a subtraction of the mean background radiance, thus providing an indication of the target intensity above the mean. The effectiveness of this subtraction of clutter from radiance differences in the scene depends strongly on the instantaneous field of view of the detectors, i.e., the pixel footprint. In this study, the footprint was varied from 1.8 to 3.6 km at a nominal range of 40,000 km (LZA ~ 75° for a geostationary sensor). The resultant output scenes then exhibited a mean background level of zero, with positive and negative values apparent at the cloud edges. These simulation outputs were used to create a probability of false exceedance (PFE) distribution vs. intensity threshold for the background clutter noise.



(a) 1.8 km Footprint (b) 3.6 km Footprint

Figure 9. Simulation of an IR scanner: AC-coupled outputs for the stressing background scene.

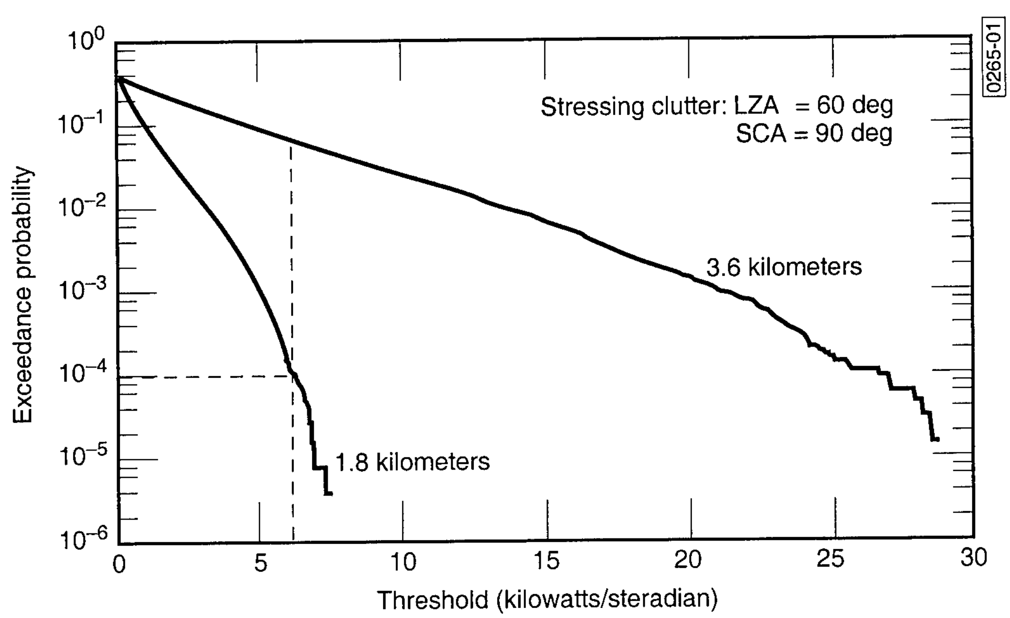
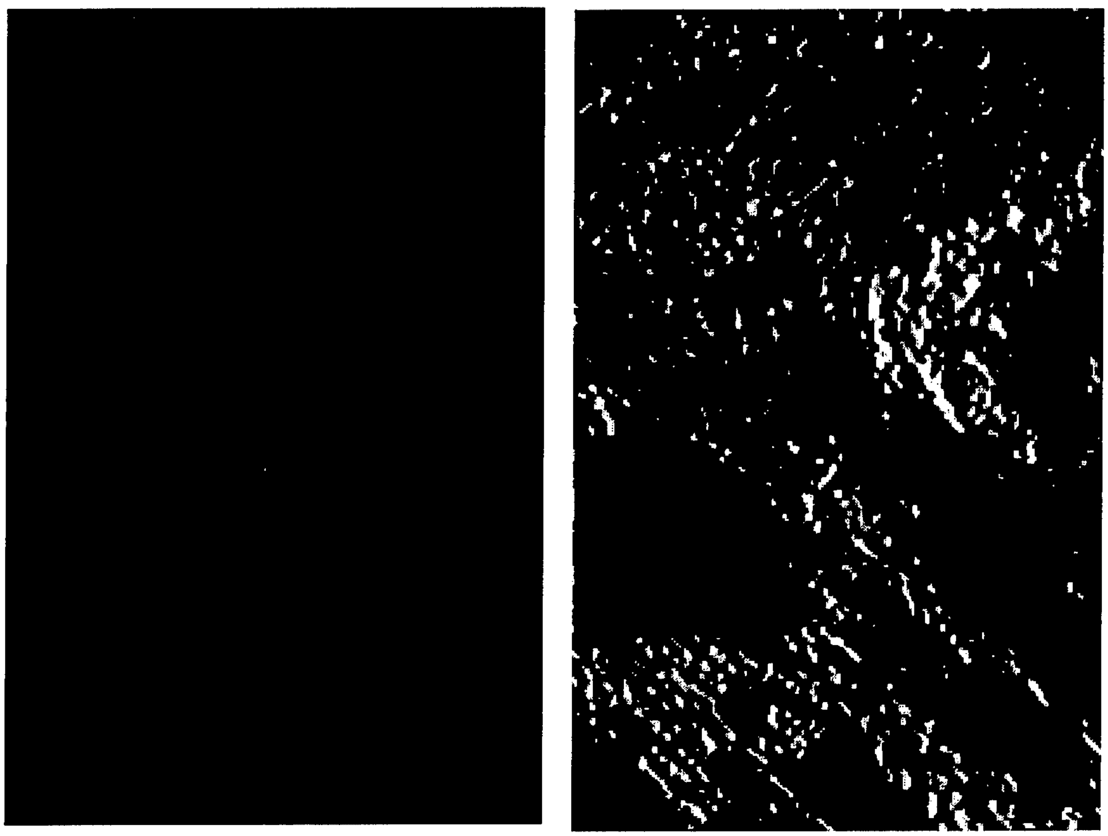


Figure 10. Probability of False Exceedance vs. threshold intensity for IR scanners viewing the stressing background scene.

In order to set a threshold, an acceptable false exceedance rate for each sensor design must be determined. For architectures where the mission data is processed on the ground, this involves several factors: the number of detectors in the focal plane, the sampling rate, the number of data bytes per sample, and the capacity of the downlink, as well as some knowledge of the target detection algorithm. For example, a scanner design with a 1.8 km footprint could indicate a threshold of 6 kW/sr for a PFE of 0.0001 whereas a design for a 3.6 km footprint viewing the same scene would indicate a PFE of 0.1 for the same threshold intensity. Of course the smaller footprint design would require many more detectors and a larger telescope, hence a heavier payload. The ground footprint of an IR scanner is a key parameter in determining sensor performance against structured backgrounds.



(a) 1.8 km Footprint (b) 3.6 km Footprint

Figure 11. Simulation of an IR scanner: outputs thresholded at 6 kW/sr for the stressing background scene.

In a more complete analysis, one must account for the sensor noise arising from the natural fluctuations in the scene and from the electronics, usually expressed as a "noise equivalent target" (NET) intensity. This accounting is expressed in a threshold vs. exceedance distribution. If the "clutter noise" from the background is random in character, it can be expressed as a clutter equivalent target intensity (CET); then a "system equivalent target" intensity (SET) can be determined simply as the square root of the sum of the squares. However, clutter from clouds in natural background scenes is usually far from random, so that more complex methods are required for combining the sensor noise with the background clutter distribution.

5. Target Response

Target response is a scale factor that describes the attenuation of a target through the sensor system. The response of a scanning sensor to an unresolved target, i.e., a "point source," depends on several factors. These are the blurring due to the optics, the temporal aperture due to the scan motion during the integration time, the sampling of the blurred target by the focal plane, the target phasing (i.e., the location of the target relative to the center of a pixel), and the electronic filtering.

For a fast scanning sensor system, the response does not depend on the temporal characteristics of the target so the calculation is fairly straightforward. The target response can be evaluated by constructing a grid in which many point sources (usually 1 kW/sr) are spaced far enough apart to avoid interference, each offset randomly by a small amount to make the grid nonuniform, thus to insure many different target phasings. This target grid is then passed through the same simulation process as the background scenes, namely blurring, downsampling, and filtering. The peak response from each target is determined, and the average is taken as the mean target response. All simulated clutter scenes are divided by this target response so they can be referenced to apparent intensities at the sensor aperture.

6. Constellation Performance

To evaluate the performance of a space-based infrared surveillance architecture against a variety of target and background conditions, the sensor response to both must be combined in a constellation-level simulation. This is done by first choosing one of the cloud databases contained within the SSGM, then generating scenes spanning the entire range of viewing geometries and sun angles for the selected sensor constellation. The scenes are then processed through the detailed sensor simulation tool, VISTAS, to produce a set of PFE-threshold clutter distributions. These are combined with the sensor NET in TRADIX, and the threshold and MDT are calculated as functions of the LZA and SCA, for the required probability of detection (POD) and PFE.

Within TRADIX, the targets and satellites are propagated in Earth Central Inertial (ECI) coordinates with an appropriate sampling interval, typically 5 to 15 minutes. This is carried out over a period of a day at various times during the year to explore the effects of seasonal variations in the sun's latitude. For a constellation in geostationary orbits and target launch sites in the northern hemisphere, the most stressing solar scattering angles are close to the summer solstice and the resultant background clutter is the dominant effect in the system performance. On the other hand, the effect of solar stray light can be more stressing close to the solar equinoxes.

Each sensor-target LOS at each time results in an LZA/SCA pair, which, with the clutter data, sets an MDT threshold for that sensor, and a time of first detection. For example, three out of four detections produces a "3of4" report from that sensor, and two such reports by separate sensors results in a stereo report for the constellation. Target detection and report time statistics are thus generated for each sensor design against each structured background for the mission of interest. This procedure has been applied to missions of global missile warning and theater missile warning (TMW).

For a typical global analysis, target launch sites are uniformly distributed over the surface of the earth from -90° to +90° latitude. We use a target spatial pattern with a resolution of 3° x 3° (earth central angle), resulting in 4586 distinct target launch locations. Each target thus represents an equal area on the surface of the earth. Missiles are usually launched in 12 to 36 azimuthal directions in order to allow for aspect angle effects on the apparent booster signature. The point of such an analysis is to obtain a measure of system performance that is not scenario driven. As many as 50 million target launches may be run in order to determine global performance for a particular space surveillance constellation.

For the TMW mission, a representative short-range missile was assumed with an infrared intensity profile increasing as the missile rose through the atmosphere to a maximum, then decreasing as the "afterburning" of the exhaust diminished, as viewed from a broadside aspect at the two extreme LZA of 0° and 90°, corresponding to the nadir and the limb. The analysis was limited to the worst case for clutter-limited detection and was focused on two theaters of operation, one in the Middle East, the other in Northeast Asia. A "pinched" constellation of five satellites was selected to provide excellent overlapping coverage of both areas simultaneously.

An SWIR line scanner was selected as the sensor design option. Although not the most effective choice for clutter suppression, a scanner reduces the program risks associated with extreme LOS stability and focal plane producibility associated with IR starer designs. On the other hand, for acceptable performance against highly structured backgrounds, a scanner must have a relatively small footprint. In this study, three designs with footprints of 1.8, 2.6, and 3.6 km were considered.

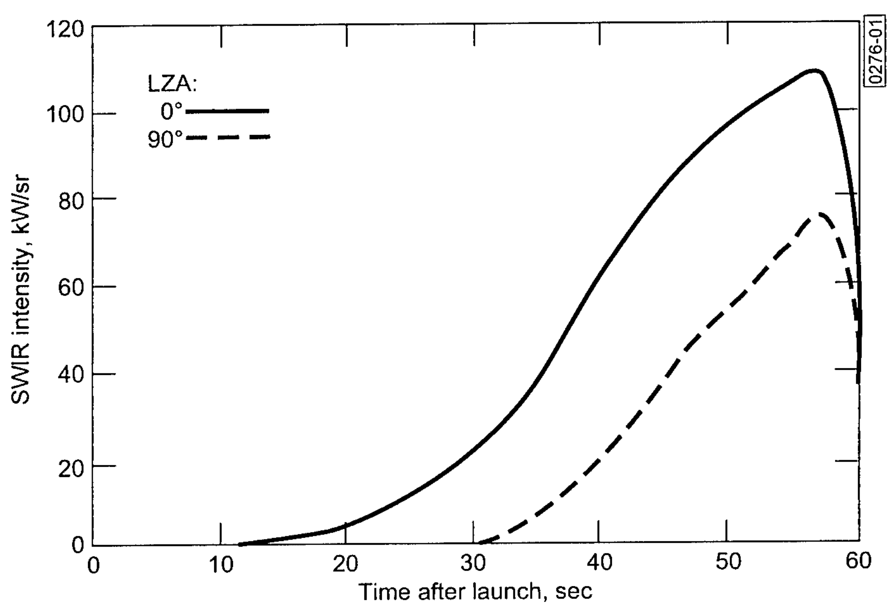


Figure 12. Theater missile SWIR intensity vs. time after launch when viewed at nadir and the limb; includes attenuation by the atmosphere.

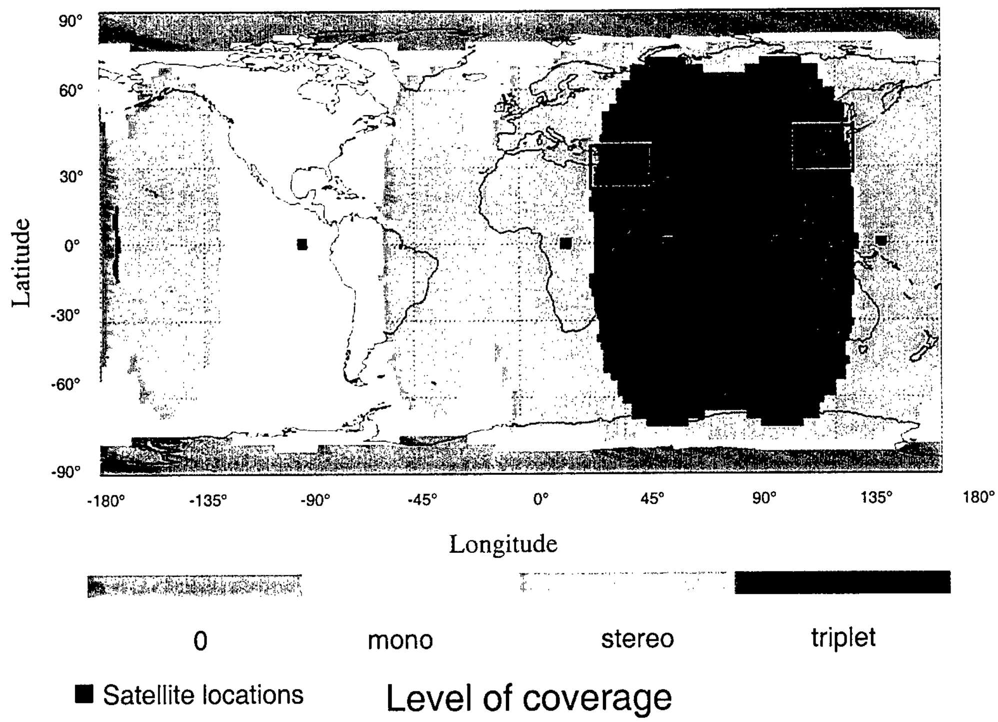


Figure 13. Line-of-sight coverage of two theaters by five "pinched" geostationary satellites.

The IR scanner optics consisted of a triplet refractor and a 2-axis entry flat for scanning. To achieve a low NET, sensor aperture was traded against time delay and integration (TDI) capability on the focal plane. The result was a 27-cm aperture with 12 stages of TDI. A 2-second revisit time taken as a mission requirement necessitated a scan rate of 4°/sec and resulted in an NET of about 1 kW/sr at 40,000 km. A single-hit POD of 95% was chosen; this led to a cumulative POD of 99% for the 3of4-hits algorithm. The resultant POD and PFE combination led to an MDT as a function of viewing geometry for each sensor design, background scene, and clutter scale factor. The TRADIX constellation analysis tool was then used to evaluate the performance of the three sensor designs against the nominal and stressing backgrounds.

The costs associated with the deployment of a surveillance satellite are closely related to the payload weight, both in regard to the payload itself and that of the launch vehicle required to lift it and its satellite platform into a geostationary orbit. Accordingly, rather than attempting to carry out a detailed cost analysis, this study was focused on estimations of payload weights, which included the telescope, sensor housing, and scan mirror, the focal plane assemblies and signal processors, power supplies, and other subsystem weights. As might be expected, the highest performing sensor with the smallest footprint and best clutter suppression ends up also being the heaviest and most expensive. Of course, the overall system costs would have to be weighed against the value of the mission in regard to the national interest; such considerations were beyond the scope of this investigation.

The study described here illustrated the application of analytical tools and databases developed and assembled at Aerospace to support the development of advanced space-based surveillance systems. The example shown represents a hypothetical system for the specific purpose of missile warning that covers two widely separated geographical areas of concern. Comparable analyses are being applied currently in the Aerospace support to SMC and BMDO for the development of both the SBIRS High and SBIRS Low systems with their additional missions.

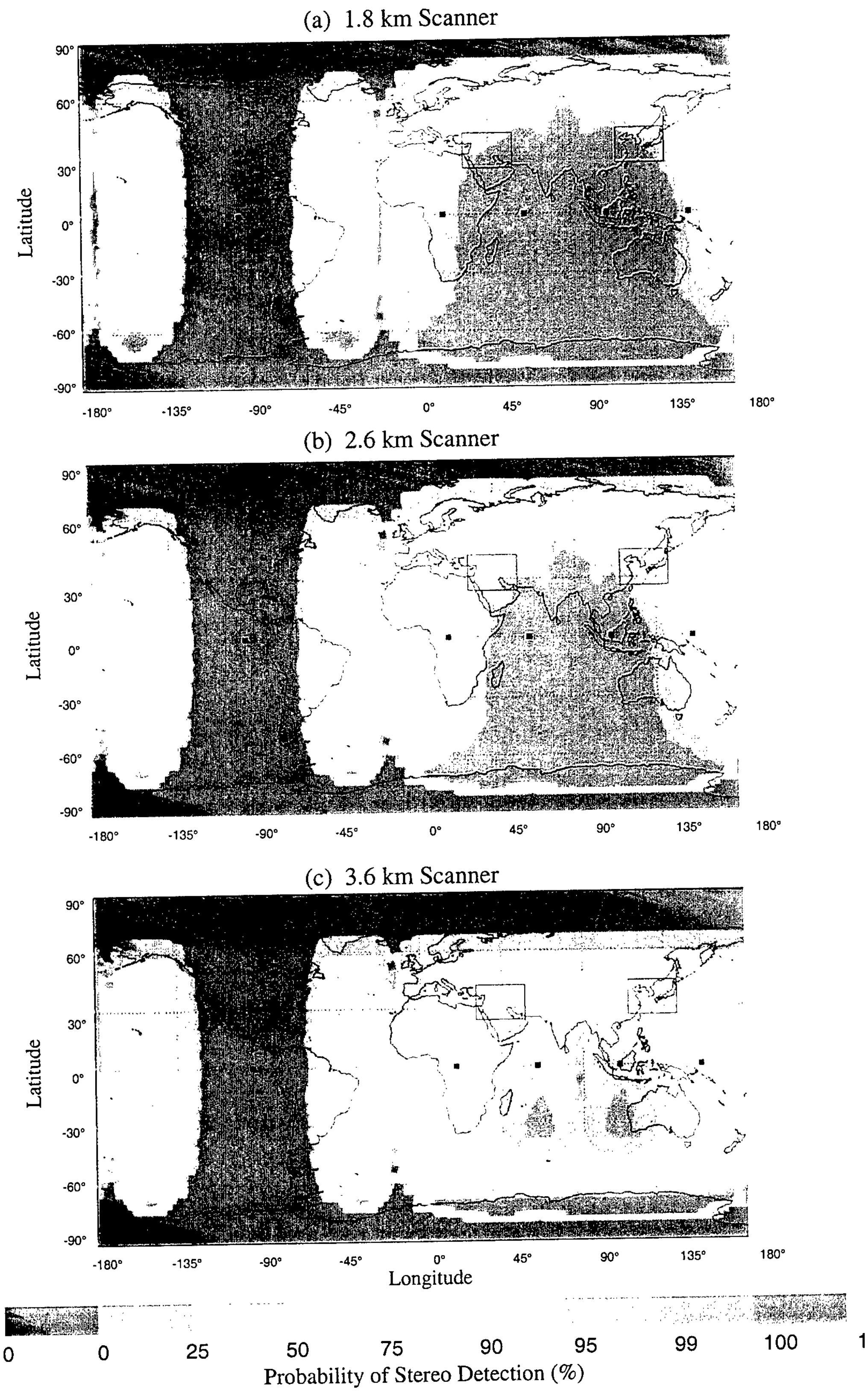


Figure 14. TMW stereo performance of five pinched satellites with stressing clutter.

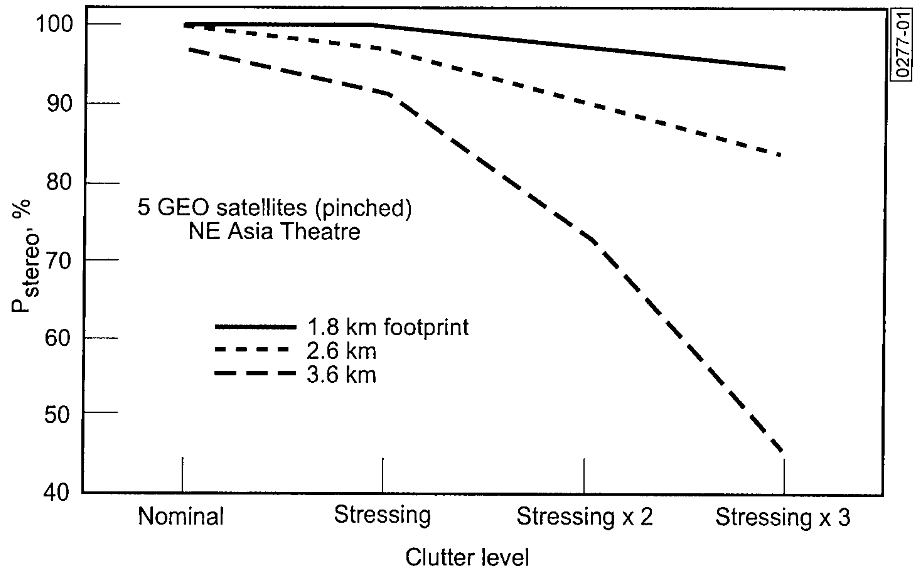


Figure 15. TMW stereo performance sensitivity to sensor footprint and clutter.

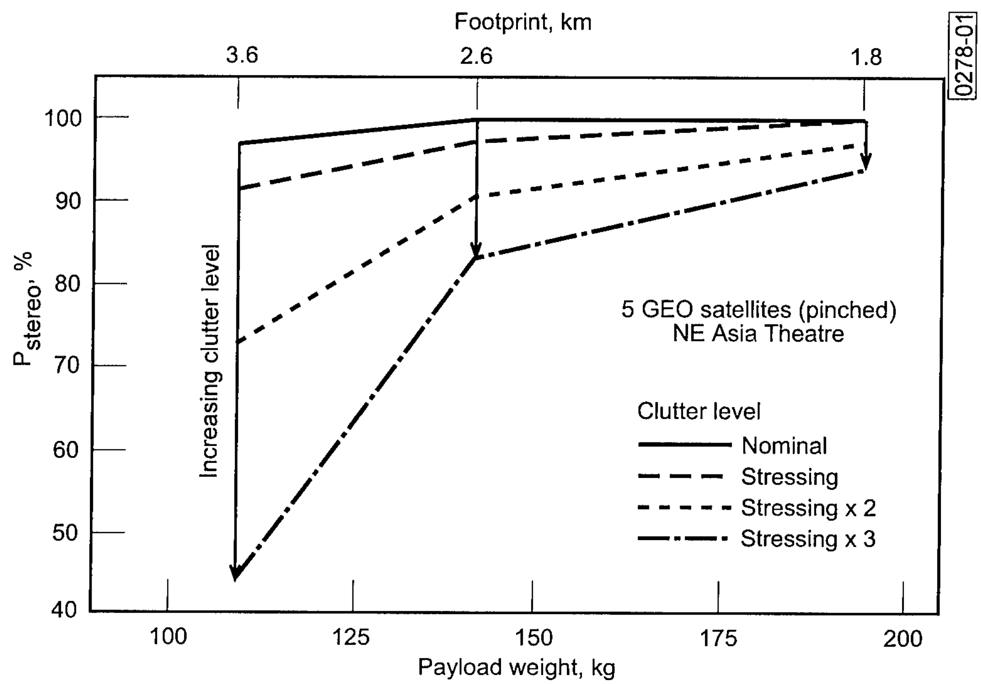


Figure 16. Weight and performance sensitivity to sensor footprint and clutter.

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