Global Space-Based Ground Surveillance: Mission Utility and Performance of Discoverer II[1,2]

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Abstract— The Discoverer II (DII) program will demonstrate an affordable space-based radar (SBR) with High Range Resolution Ground Moving Target Indication (HRR-GMTI), Synthetic Aperture Radar (SAR) imaging, and Digital Terrain Elevation Data (DTED) collection that is expected to revolutionize reconnaissance, surveillance and precision targeting support to the tactical warfighter. This paper presents a utility analysis of DII, including mobile missile launcher surveillance, strategic facilities monitoring, maritime surveillance, and detection of underground facility construction. A subbanding approach to the signal processing that allows parallel implementation is presented. A 30Gflop chip set capable of wideband channelization and delivering 128 point FFTs every 200nsec, with 25 to 50 GOPS per Watt power efficiency is described. Performance analyses of space time adaptive processing (STAP), GMTI tracker operation, STAP clutter suppression and GMTI tracking results from airborne collections are presented. Approaches for collecting precision DTED, and airborne testbed results near the DTED 5 level are presented.

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1. INTRODUCTION

Discoverer II is a technology demonstration that seeks to demonstrate the technological feasibility and affordability of *global precision surveillance* support to the tactical warfighter. Global precision surveillance requires a space-based capability, for access anywhere without regard to restrictions or deployment, as well as radar sensing, for virtual immunity to cloud cover or night sensing. Precision is achieved by incorporation of radar features that support high resolution over tactically significant areas with targeting-quality geopositioning accuracy. Surveillance requires near-continuous viewing of selected target areas, which drives the configuration of the objective Discoverer II satellite constellation.

The Discoverer II (DII) program is an Air Force, Defense Advanced Research Projects Agency (DARPA), and National Reconnaissance Office (NRO) joint initiative. It will develop and demonstrate an affordable space-based radar (SBR) with High Range Resolution Ground Moving Target Indication (HRR-GMTI), Synthetic Aperture Radar (SAR) imaging capabilities and Digitized Terrain Elevation Data (DTED). This system will support the capability of U.S. military forces to directly task space-based collection activities and receive the requested data at theater ground stations in near real time. The Discoverer II program is currently funded to develop, build, launch, and operate two satellites to demonstrate the feasibility of an objective Discoverer II constellation, which could be acquired as early as 2010, following a decision to proceed with acquisition after completion of the demonstration.

2. DII SCENARIO ANALYSIS

Discoverer II provides significant and unique advantages in theater surveillance. Current airborne capabilities suffer from two limitations – they must be deployed, along with extensive support equipment, to air bases near the theater of operations; and once they are deployed, their visibility of enemy missile launchers in a standoff flight profile is limited in areas with significant terrain relief, due to masking. Figure 1 compares the amount of terrain masking that would have been experienced in a recent military operation by a typical airborne GMTI platform at 35,000 feet with the terrain masking during a typical Discoverer II satellite pass. The wide diversity of look angles, in azimuth and elevation, generated by a Discoverer II constellation offers an additional advantage compared to the small range of azimuth look angles from which an aircraft in a standoff profile will be able to see targets, especially in the presence of terrain relief.

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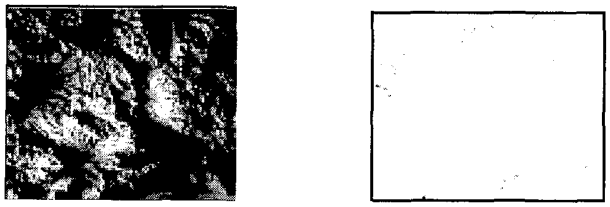
[1]

[2] Updated December 15, 1999



Airborne Platform **Discoverer II**

Figure 1 Probability of clear line of sight (Black =0, White = 1)

Ground moving target indication is a valuable surveillance mode in military operations. The capability to detect moving objects limits an adversary's mobility. It also allows friendly forces to quickly discern the scope and direction of large-scale movements of forces, providing warning and the information needed to counter the threat. Although the two-dimensional resolution of moving objects is coarser with GMTI than with imaging radar, GMTI is more efficient to collect and to exploit. The radar dwell time required for effective GMTI operation is much shorter than for SAR, so wider areas can be covered. A second benefit is realized in exploitation. In SAR imagery, discrimination of military objects from background objects is a difficult and time consuming task for human operators to perform, and limited success has been realized with automated approaches. With GMTI, the motion of the object provides discrimination from background objects, resulting in highly efficient exploitation.

Mobile Missile Surveillance

During a period of heightened tensions, the objective system would be used to monitor all types of military activity, particularly movement of mobile Theater Ballistic Missiles (TBMs) and Surface to Air Missiles (SAMs). An attempt would be made to detect and track as many TBMs and SAMs as possible so that they could be attacked early if hostilities begin. It may also be possible to detect storage locations or garrisons for these systems, making it feasible to subsequently destroy multiple weapons with one strike. The objective system could conduct surveillance during heightened tensions without provoking a potential adversary.

In the event that hostilities begin with little warning, the objective system would provide surveillance data while other assets are brought to the theater. For an example projected conflict, analysis indicates that the objective system, by itself, could fulfill approximately 55% of the required surveillance requirements in the early stages of the conflict.

A number of analyses have been conducted to determine the contribution that the objective system can make to the destruction of SAMs during a conflict. The Simulation of the Location and Attack of Mobile Enemy Missiles (SLAMEM) tool developed by Toyon Research Corporation has been used in most of the detailed analyses of SAM scenarios. One scenario is based on a conflict between the US and an adversary whose capital is approximately 1000 km from the closest border accessible to US forces. The capital is protected by four mobile SAM units each of which periodically moves to a new location. The objective system is used to try to locate and destroy the units in order to minimize the risk to attacking aircraft. An attempt is made to track each SAM unit by using high range resolution mode to measure the range profile of targets and, therefore, increase the probability of correctly associating each target with a track. When a target is no longer detected, a high resolution SAR image is obtained in the area of the last detection and, if the target is stopped and the target identification is confirmed, attack is initiated with a stand-off weapon. The analysis concludes that all of the SAM units are destroyed in approximately 15 hours, although a few non-targets were attacked because of the small probability of mis-identifying other vehicles as members of a SAM unit. The results would be degraded significantly if Discoverer II did not have the ability to obtain a high resolution SAR image, enabling identification of a stopped target.

Two additional considerations are being implemented in the analysis of mobile target attack. First, it should be possible to track groups of targets moving together more easily than individual targets. SAM units, in particularly, consist of a small group of vehicles with distinctive signatures. This could be particularly important if target classification techniques, such as range profiling, cannot be used. Second, it is possible to concurrently produce MTI and coarse SAR information using the same waveform and dwell period that would be used for MTI alone. This would make it possible to quickly determine whether the loss of an MTI return from a target being tracked is a result of the vehicle stopping or some other reason such as obscuration.

Peacetime Applications

The Discoverer II objective system will significantly improve the capability of the US to conduct a number of missions in peacetime as well as war. For example, in peacetime the system can be used to monitor facilities that are involved in the production, storage and testing of weapons of mass destruction. The nearly continuous presence, deep look capability and MTI mode of the system will make it possible to detect an increase in traffic levels at a facility, or to observe a correlation in traffic fluctuations at production and storage facilities, or between storage and testing sites. The system could also be used for maritime surveillance, including tracking ships suspected of carrying weapons of mass destruction.

Preliminary analyses have been completed to determine the capability of the objective system to detect, classify, and track ships in the Persian Gulf. Initial detection of nearly all ships could be accomplished in approximately 20 minutes. Experimental test data suggests moderate-range-resolution MTI could provide sufficient range profile data to enable ship classification. The objective system will be capable of providing revisit rates required for unambiguous tracking, however, dynamic tasking is required for tracking and classification in moderate to high density ship traffic. An aspect of maritime surveillance that is being investigated is the use of lower radar transmitted power for maritime surveillance, taking advantage of the large radar cross section of ships, and thereby, extending the operating time of a satellite.

The capability to generate a consistent maritime tactical picture can also provide significant advantage for friendly naval forces during hostilities. This can constitute the basis for early warning of all surface-based threats against allied fleets, as well as data for targeting sea and air launched weapons against both ships and land-based targets.

As a third peacetime application, the system could be used to detect the construction of underground facilities. An underground facility can be built by digging out the area and constructing a cover, (*cut and cover*) or tunneling. Cut and cover could be detected by using coarse resolution SAR, e.g., 3m x 3m, to detect the abrupt change in range at the front wall of the opening and the strong reflection from the back wall. Tunneling could be detected by observing the accumulation of dirt brought out of the tunnel or the trucks removing the dirt. Detecting tunneling would, in general, require higher resolution, e.g., 1m x 1m. Other radar modes of operation such as interferometric SAR (IFSAR) could be used to observe a change in elevation. An estimate of the fraction of the objective system resources required to detect underground facility construction using SAR mode in a representative large, medium and small country is shown in Table 1.

These results, as well as all other results reported in this paper, are based on a nominal objective system consisting of 24 satellites in a Walker constellation with 8 planes, each with a 770 Km altitude and 53 degree inclination. The underground facility detection results are based on the assumption that 20% of the total area of a country is suitable for the construction of an underground facility, the remainder being too far from roads, under water, etc. The cut and cover operations are assumed to require three weeks while the tunneling operations are estimated to require three months, and the table entries represent the percentage of system resources required to search the 20% of the area deemed suitable in the time required for facility construction. From the table it can be seen that even for a large country only a small fraction of the total available operating time would be required to detect underground facility construction. Yet to be developed are search strategies that maximize the probability of detection of facility construction while minimizing false alarms.

	Cut and Cover	Tunneling
Country Size	3mx3m Resolution (% of 3 weeks' availability)	1mx1m Resolution (% of 3 months' availability)
Large	2.6	1.8
Medium	0.25	0.19
Small	0.02	0.01

Table 1 System Resources Needed to Detect Underground Facility Construction

DTED-Aided Targeting and Terrain Analysis

Discoverer II's worldwide access for collection of regional digital terrain elevation data, with virtual immunity to terrain masking and a broad diversity of available look angles, will enable new techniques for precise targeting, mission planning, and mission execution. A single SAR image can be registered on DTED data to extract the third coordinate of target location and to virtually remove errors associated with the two dimensions of target location provided in the SAR image. The SAR registration process tends to be sensitive to large differences in the viewing aspects of the images being registered. This problem is overcome by generating a "synthetic" SAR image from the terrain elevation model (Figure 2). Initial demonstration results described in the following paragraph show that this technique can succeed even in the absence of terrain feature data, with the SAR image synthesis being strictly a function of the orientation of individual "facets" of terrain.

In a demonstration of this technique using a highly accurate digital elevation matrix (DEM) for the Lucky Rise region of Fort Irwin, synthetic SAR data was generated from the DEM and matched to separate SAR imagery. For numerous subregions in the SAR imagery, the technique produced geolocation accuracy well under 10 meters.

In addition to its application to precision targeting, DTED supports the planning, rehearsal, and execution of missions. Intervisibility calculations using DTED can identify routes and locations in an area of operations where terrain would protect forces from attack and locations where they would be exposed. Similar intervisibility calculations have been used in a terrain analysis system operated by the US Army, with less precise DTED, to generate terrain-dependent acquisition zones for airborne threats. Terrain analysis of high resolution, high accuracy DTED data can reveal terrain relief features which inhibit the passage of traffic. Terrain analysis is now employed, using terrain elevation data with lower accuracy and coarser resolution, to estimate vehicle mobility speeds. In addition to the importance of this data for planning friendly force maneuvers and anticipating enemy maneuvers, it can be used to improve the accuracy of ground target tracking systems.

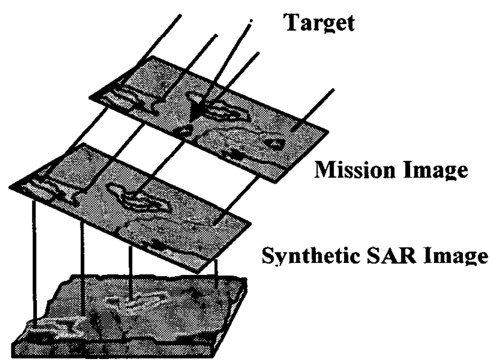


Figure 2 DTED- Aided Precision Targeting

DTED data allows collection and exploitation of data from a variety of other sources to be improved. For example, the terrain elevation data, employed in collection planning tools, can prevent the needless expenditure of time and energy in attempting to image target areas at times when terrain obscures them from view. DTED also allows the position of moving targets to be refined. This technique adds height data to the GMTI location error ellipse and is especially effective when applied to a series of GMTI "hits" collected from different aspect angles. DTED data permits SAR imagery to be orthorectified, so that it presents a less aspect-dependent view of an area. Orthorectification of imagery, in turn, allows the imagery to be combined more effectively with other images and the extraction of knowledge from the series of images.

3. PROCESSING ARCHITECTURE

The Discoverer II program is pursuing technology development and demonstration in key aspects of the program, where advances in hardware, software, or algorithms will provide significant reduction of risk in the development, launch, and operation of the two demonstration satellites. Part of the DII risk reduction effort is focused on developing the processor technology needed to enable real-time operation of the radar. This effort is divided into the two complementary areas of algorithms and architectures for the on-board processor. The on-board processor must provide more than one Tera-operation per second (1 TOPS) of throughput to support the GMTI capability, and must do so within the confines of the satellite weight and power budgets. An efficient approach to attaining this throughput is to use custom VLSI hardware and parallel processing to reduce clock rates and hence, power consumption.

Parallel operation is achieved by dividing the wideband radar signal into parallel subband channels, processing each channel separately, and then recombining the subbands to recover the equivalent, processed wideband signal. As discussed elsewhere, this approach also has additional algorithm benefits.

A key element of the processor is the subband filter and combiner which channelize the data stream into manageable frequency bands for processing by the other subsystems. After processing by these subsystems, the subband combining operation, which completes the pulse compression process over the full system bandwidth, is performed. Then the data stream is downlinked for the final stages of detection, parameter estimation, and tracking. The next two subsections describe the subband filter (channelizer) and present examples of STAP analyses and STAP processing applied to DII surrogate data obtained from a airborne platform.

Subband Filter (Channelizer) Design

The DII sensor concept includes wideband operation to support the HRR-GMTI and SAR modes. The required bandwidths are such that direct implementation of the radar processing functions, particularly adaptive beamforming and STAP, would be prohibitively expensive in terms of requisite throughput. The alternative approach proposed for the DII sensor is to "channelize" the data prior to the other radar processing functions, and implement those functions on a channel-by-channel basis. This concept requires a pair of digital filters, the *subband filter* and the *subband combiner*. Such filters have a long history in the digital signal processing literature ([1], [2]), but the DII processor architecture offers certain opportunities and challenges not typically found in conventional applications.
The principal challenge is derived from the space environment which places a high premium on weight and power efficiency, and demands some degree of radiation tolerance. The opportunities come through the specific radar application intended for the subband filter and combiner. There are computational economies that can be realized by combining portions of the subband filter function with the other processing subsystems.

Figure 3 depicts one realization of the subband filter (analysis filter) using a polyphase filter bank and FFT. The subband combiner structure (synthesis filter) is essentially the left-to-right mirror image of analysis filter. The design takes advantage of the DII-specific application in three ways. First, the polyphase filter accommodates two real input streams by synthesizing a complex data stream using one channel as the real part and one as the imaginary part. Additional savings are realized by including the usual (for non-critically sampled systems) post-FFT modulation function in the internal parallelized subband processing. A final saving comes about by using a co-design process to simultaneously determine the filter coefficients for the analysis, synthesis, and pulse compression filters. The co-design process effectively reduces the number of taps in the synthesis filter by a factor of two.

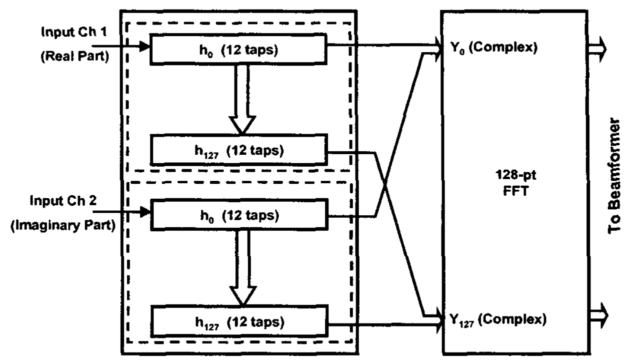


Figure 3 Polyphase Filter and FFT Architecture

Polyphase Filter and FFT Chip Set

To meet the challenge of space-based applications, the polyphase filter and FFT chip set have been implemented using a 0.25 micron CMOS process. The polyphase filter chip is implemented as a dual set (for two input streams) of 128, 12-tap filters. Each filter includes a variable delay function to facilitate time-delay steering of the antenna. The filter accepts real input samples, and uses 12-bit coefficients to yield a 16-bit complex output stream. With two input data streams at nominal design rates, the chip provides over 30GOPS of throughput. Extrapolating measurements of test chips implemented with a similar process, and assuming a 1 volt supply voltage, suggest that power efficiencies of 25-50 GOPS/Watt are attainable for DII.

The FFT chip performs a 128-point FFT every 200nsec using block floating point arithmetic with 16-bit coefficients. This amounts to an equivalent throughput of more than 20GOPS. Extrapolating from test chip measurements, a power efficiency of 25-50GOPS/Watt is projected with a 1-volt power supply. Details of this design are described in [3].

The subband channelizer is a key element in the processor technology (algorithms and architecture) needed to support real-time, multi-mode operation of the DII sensor, and its realization in power-efficient, custom VLSI hardware will be a key enabling technology for the DII program.

4. SPACE-TIME ADAPTIVE PROCESSING

Space-Time Adaptive Processing Approach

A key challenge for DII is the detection of slow-moving ground targets (GMTI) in background clutter. To maintain system affordability, the radar antenna size needs to be modest (nominally 2.5 x 16m). This design is only a factor of two longer than the JSTARS antenna. However, combining the modest antenna size with the satellite velocity (~7 km/sec), means that mainbeam clutter often interferes with targets of interest. Space-Time Adaptive Processing (STAP) is employed to counter this interference and maximize system performance. Of the many possible STAP implementations described in the literature, a variant of the "filter-then-adapt" approach has been analyzed in detail. Specifically, PRI-staggered, post-Doppler, beam-space [4] STAP, using channelized data from the subband filter is used. Extensive system performance studies suggest that four input beams, and three output beams are sufficient to suppress clutter, detect targets, and perform angle estimation. This architecture, shown in Figure 4, includes the Doppler filter DFT because of its intimate connection to this STAP realization. The figure also depicts the single-stagger (delay) applied to the input data prior to the DFT operation.

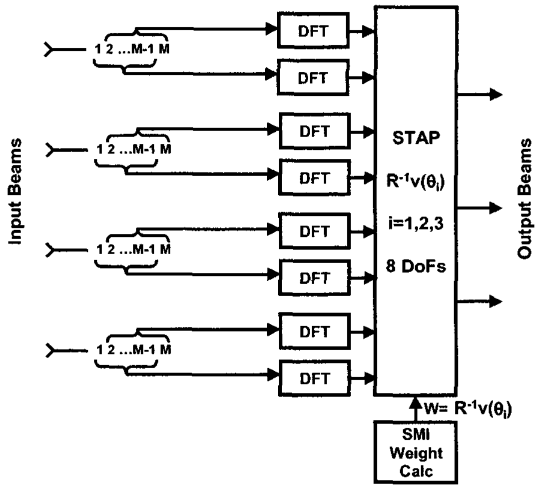


Figure 4 PRI-Staggered, Post-Doppler, Beam-Space STAP

Space-Time Adaptive Processing Results

This architecture has been studied in the context of DII, not only analytically, but also via simulation and application to airborne radar data. Some examples of these analyses and experiments are shown below. Various error effects, such as range ambiguous clutter, internal clutter motion, and sample covariance matrix training strategies have been examined to determine their performance impact. A key metric of GMTI performance is signal to interference and noise ratio (SINR) loss, which indicates the loss in detection performance relative to the noise-limited case (referenced to 0 dB). For example, Figure 5 depicts SINR loss due to range ambiguities at shallow (6 degree) grazing angles. In this figure, azimuth is measured in the local-level plane, with 90 degrees being perpendicular to the satellite velocity vector.

The impact of internal clutter motion (ICM) is depicted in Figure 6 for four wind velocities and two azimuth directions, for CNR=25dB. ICM has relatively little impact on SINR loss at broadside (azimuth=90 deg.), but close to the velocity vector (azimuth = 10 deg.), the change in SINR loss is especially dramatic for low velocity targets.

Finally, Figure 7 shows an example of an airborne data collect employing both the GMTI (left) and SAR (right) modes of operation. The data was taken over Phoenix, AZ, and hence includes strong urban clutter. Detected targets are indicated with circles. The GMTI output demonstrates the efficacy of STAP processing as several targets were detected near the mainbeam clutter ridge which runs vertically through the center of the data. The results of laying these targets onto a SAR map are shown on the right-hand portion of the figure.

Space-time adaptive processing is envisioned as part of the architecture needed to suppress background clutter. The examples of STAP analysis efforts show performance in the presence of range ambiguities and internal clutter motion. The capability of the STAP approach to clutter suppression is demonstrated in the results obtained in processing of the surrogate airborne radar data.

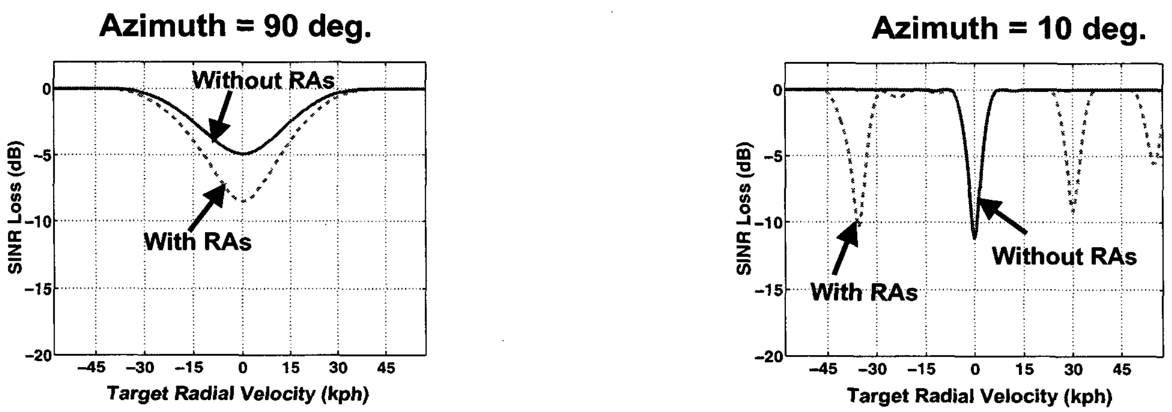


Figure 5 SINR Loss Due to Range Ambiguities (RAs) for 6 Degree Grazing

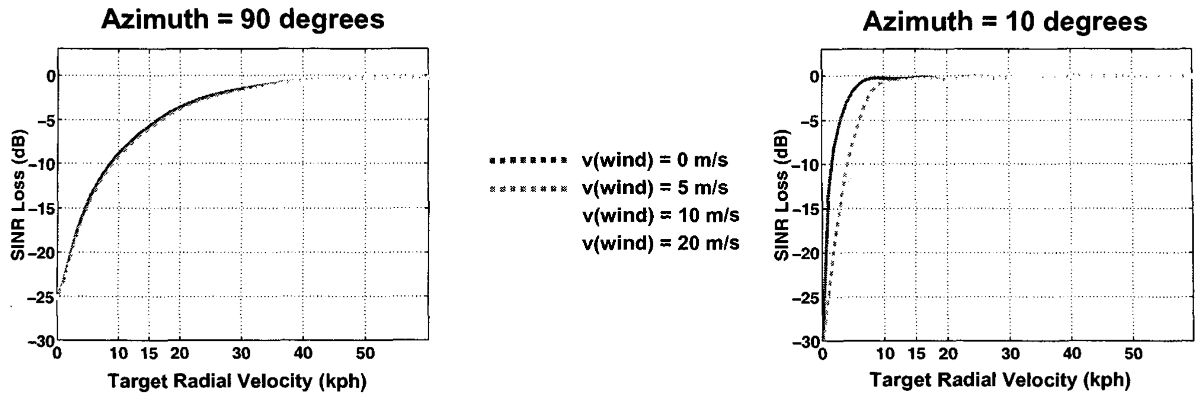


Figure 6 SINR Loss for Internal Clutter Motion, CNR=25dB

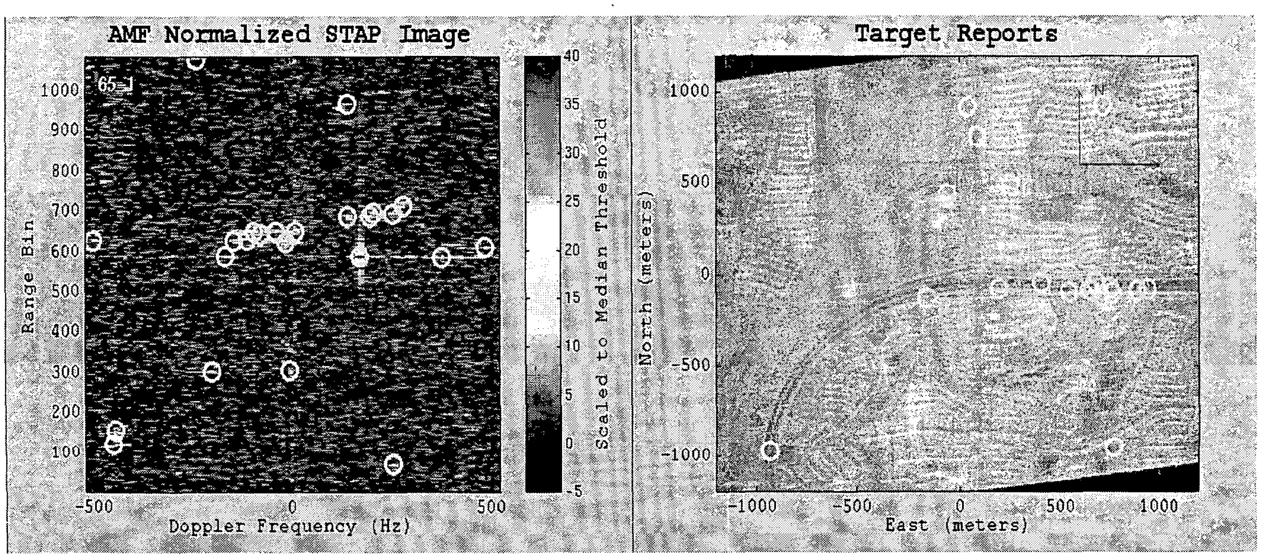


Figure 7 GMTI and SAR Processing of Airborne Data

5. GMTI TRACKER

Tracker Approach

The Discoverer II System uses a Bayesian multiple hypothesis ground target tracking algorithm. The Bayesian approach provides an integrated framework for combining all available target, environment, and sensor information, and solving the joint problem of correlating sensor reports for a target and estimating the kinematic state of each target. The multiple hypothesis approach uses information from one or more subsequent frames of sensor data to determine the best match of sensor reports in the current frame to tracks.

Figure 8 shows a high-level functional block diagram of the D-II GMTI Tracker. It processes radar MTI data from all satellites in the D-II constellation on a frame-by-frame basis. The block labeled *Create Feasible Hypotheses* (1) groups reports which potentially originate from targets moving in formation, (2) forms potential 'road reports' which specify the location of the MTI reports if they originated from road-following targets, (3) postulates transitions of road following tracks to off-road tracks and vice-versa, and (4) forms feasible associations of road reports and MTI reports in the current frame with target tracks postulated in earlier frames.

Feasible report associations are limited to those that are statistically close to the predicted track in both kinematic measurement space (i.e., range, azimuth, Doppler measurements) and attribute measurement space (i.e., range-extent along line-of-sight vector).

The block labeled *Update Tracks* updates the target kinematic state (i.e., position and velocity) and target attribute state (i.e., target length and width) using the measurements of range, azimuth, Doppler, and range-extent contained in the MTI report associated with the track. Off-

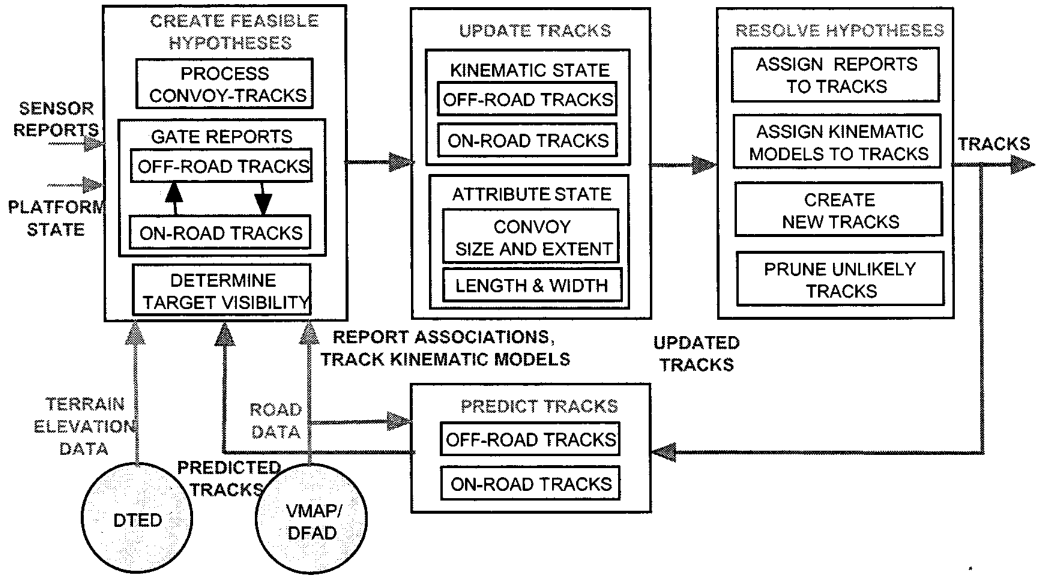


Figure 8 Functional Block Diagram of Discoverer-II GMTI Tracker

road tracks are constrained to lie on the ground, and on-road tracks are constrained to lie on the ground and along a road segment. The block labeled *Resolve Hypothesis* selects the most likely set of track hypotheses for an earlier frame based on how well the MTI measurements match the postulated track hypotheses in the subsequent frames. The remaining track hypotheses are pruned away. The block labeled Predict Tracks predicts the kinematic state of all targets to the time of next MTI frame. Off-road tracks are predicted based on the estimated velocity, and on-road tracks are predicted based on the estimated speed but constrained to lie on roads. When predicted on-tracks pass through intersections, predicted tracks are placed on each of the links emerging from the intersection. Digital road information (such as those available from NIMA) are used to predict on-road tracks and to project MTI reports on to roads. Digital terrain information is used to estimate the height of the target above the ground, and to predict regions in which targets will not be detected by the radar because of terrain obscuration.

Tracker Results

Figure 9 shows the test target trajectories for one of the experiments at Camp Navajo in Arizona. A total of five test targets were operated on roads in the test area. The types of targets are shown in the figure. The 5-ton truck and the HMMWV operated on the same road (4 St.), and the remaining targets operated on separate roads.

Radar data was collected for the targets from an airborne platform. The platform operated South of the test area, and the targets were observed at a grazing angle of 15 degrees. MIT-Lincoln Laboratory processed the radar data to generate high-resolution MTI reports. Each MTI report contained range and azimuth measurements (converted to geodetic coordinates), Doppler measurement, and platform position in geodetic coordinates. The cumulative set of MTI reports generated for a period of 30 seconds is shown in Figure 10. Notice that, in addition to the reports for the test targets, the radar occasionally generates false alarms. MIT-Lincoln Laboratory has indicated that some of these false alarms may be due to azimuth ambiguities. That is, an actual moving vehicle outside the region of interest can "fold into" the region of interest.

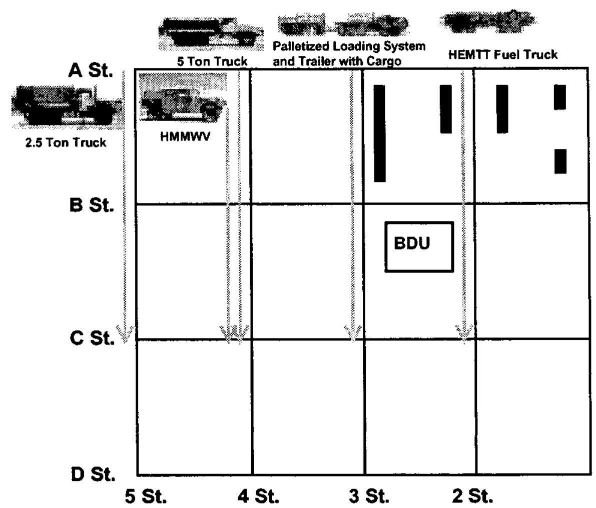


Figure 9 Camp Navajo Test Setup

The MTI reports were processed by the D-II GMTI Tracker, and the generated tracks are shown in Figure 11. Each of the five targets was successfully tracked by the D-II GMTI Tracker. The figure shows that the speed and spacing of the tracks are consistent with the targets sketched in Figure 9. The average position error for the tracks is less than three

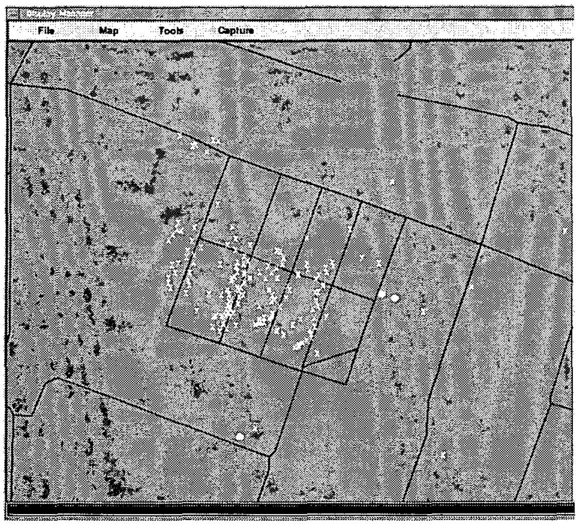


Figure 10 MTI Reports for Test Scenario

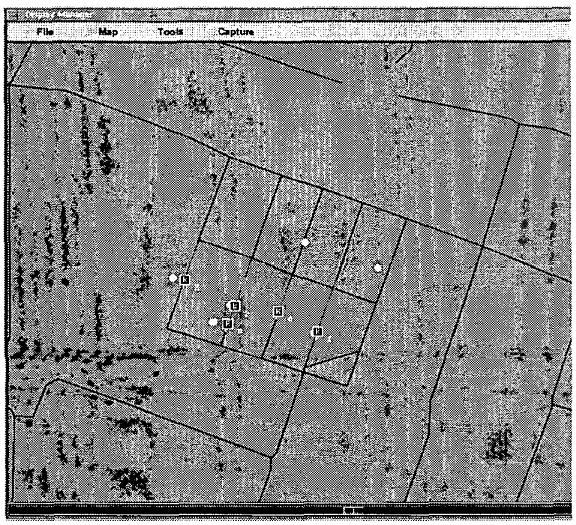


Figure 11 Tracks Generated by the D-II GMTI Tracker

meters, there are no breaks in the target tracks, and the targets are tracked for more than 80% of the time.

6. Digital Terrain Elevation Data

The collection of precision digital terrain elevation data (DTED) poses special challenges for Discoverer II. The goal is to collect at accuracy levels up to DTED Level 5, characterized by one-meter post spacing (resolution), five-meter absolute height and location accuracy, and one-third meter relative height accuracy.

DTED Methodology

DTED can be generated from radar imagery with either stereo SAR or IFSAR techniques. In the case of stereo, accuracy depends on the *stereo angle* between the two slant planes. This angle determines the amount of differential layover that will be present between objects elevated above or below a reference height, as shown in Figure 12. The stereo angle is the angle between the slant plane normals of the two collections and is a resultant of differences in both grazing angle and Doppler cone angle. Stereo SAR height extraction techniques are based on registration of individual patches of area composed of numerous pixels. This presents system designers with a tradeoff between post spacing and relative height accuracy. Stereo SAR generally requires many pixels to be averaged to accomplish the measurement of elevation at each post, making it difficult to achieve high accuracy in conjunction with fine resolution, as necessary to meet the DTED Level 5 specification.

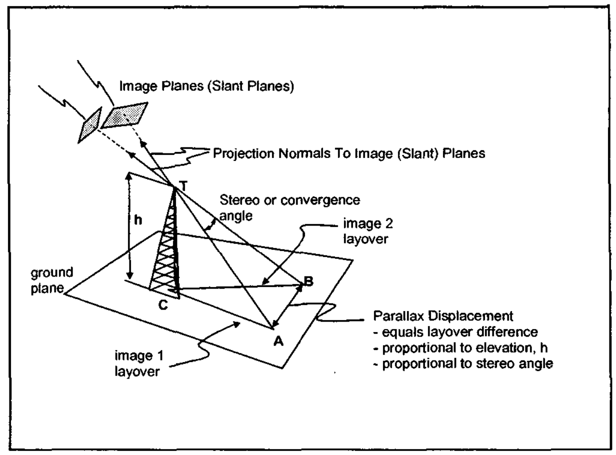


Figure 12 Stereo SAR Geometry

IFSAR relies on two mutually coherent collections separated by a carefully controlled cross-track separation, the interferometric *baseline*. In IFSAR processing, an estimate of terrain height is extracted by observing the phase difference between corresponding signals in the two antennas. The phase difference is generated from the path length difference that results from terrain relief. Figure 13 shows the collection geometry for IFSAR.

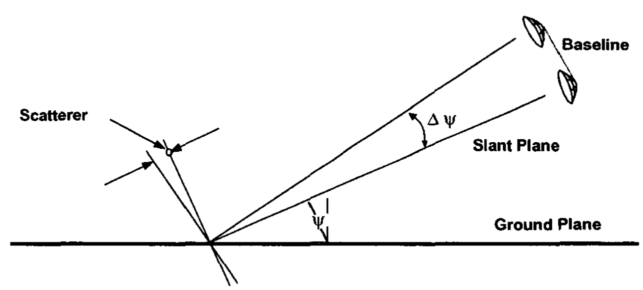


Figure 13 IFSAR Collection Geometry

The baseline length is a critical determinant of IFSAR accuracy. With excessively short baselines, small phase measurement errors will result in large terrain height errors. Excessively long baselines will result in loss of coherence between the two images, as the viewing angles diverge enough to result in differences in the scene complex reflectivity. Preliminary analysis suggests that baseline lengths of approximately five kilometers will be needed to provide the goal level of relative accuracy. With baselines of this length, goal-level terrain height accuracy can be achieved by using significantly fewer pixels per terrain post than is possible with stereo techniques. IFSAR thus provides the best possible simultaneous accuracy and resolution.

Terrain elevation can be estimated from IFSAR using simultaneous collection of the two images by two separate SAR channels (*single-pass*) or by sequential collection by a single or different SAR sensors that image the scene at different times (*two-pass*). Satisfactory IFSAR results require mutual coherence between the image pair, so the scene microstructure and moisture content must be nearly identical for the two collections. Consequently, there is a risk of decorrelation for two-pass collections. This can result from foliage motion or growth, moisture changes due to evaporation or precipitation, or microstructure changes due to wind or precipitation. Depending on the terrain cover, climate, and weather conditions, the likelihood of decorrelation ranges from moderate to virtually certain.

The five-kilometer baseline needed to reach accuracy goals is not practically achievable on a single satellite, especially a low cost satellite. The need to perform the two collections on separate satellites, but at virtually the same time, has lead to the identification and analysis of several potential configurations for two-satellite "paired orbits."

The processing used in IFSAR is illustrated in Figure 14. The input SAR phase histories are collected with a small difference in grazing angle (typically a tenth of a degree.) The grazing angle difference is generated by two antennas separated by a baseline on the order of several km that is perpendicular to the satellite velocity vector. SAR images are formed separately for each phase history, and registered with each other on a sub-image basis. The subtraction of complex-valued returns from the two images results in an interferogram which contains information on the relative height of pixels in the scene. This relative height information is cyclical, modulo 2π, and must be "unwrapped" to generate unambiguous height information. The final scaling procedure is performed to determine the total image bias in integer multiples of 2π of height, and the resulting height information is orthorectified and resampled.

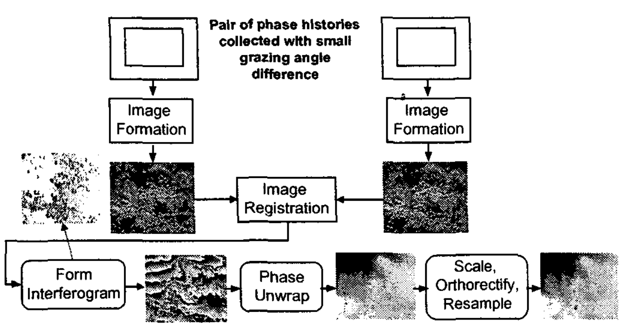


Figure 14 Interferometric SAR Processing

A aircraft outfitted with X-band radar systems, the CV-580 Data Collection System, was used to collect interferometric SAR imagery with baselines to generate differential grazing angles similar to those that would be used in a space-based system. Data was collected at each of three antennas mounted along a line perpendicular to the aircraft flight track: one in the fuselage, and one on each wingtip. The aircraft is shown in Figure 15.

The SAR imagery was processed interferometrically to extract terrain height information, and posts where the correlation level was less than 0.7 were masked out. These areas were generally due to shadowing or layover from trees. The resulting DEMs were compared with high accuracy DEMS based on data collected over the same areas with an airborne LIDAR system. For about half of the test areas, height differences of less than 30 cm (1σ) were obtained, indicating relative height accuracy near the DTED Level 5 goal with 1 m post spacing. For one area the Level 5 goal was exceeded. Several of the areas containing significant tree cover generated larger differences. Figure 16 shows a DEM of the Van Vleck area with accuracy approaching DTED Level 5.

Figure 15 CV-580 Data Collection System

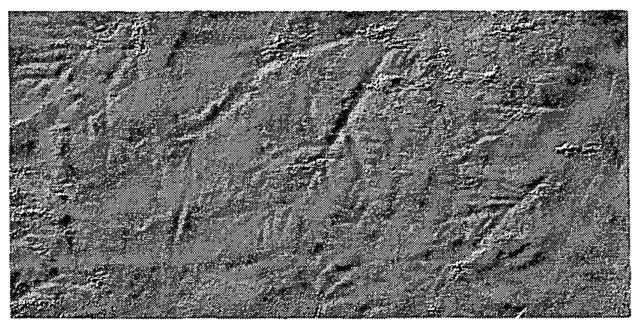


Figure 16 High Accuracy Shaded Relief DEM

7. Conclusion

The Discoverer II (DII) objective system offers numerous significant advantages to the tactical warfighter. The space-based capability offers worldwide access for surveillance without delays usually associated with the deployment of aircraft assets and with virtual immunity to terrain masking. Scenario analysis indicates that DII surveillance will make a vital contribution to the tracking and destruction of enemy mobile missile launchers. In peacetime, DII can track vehicle movements associated with weapon production storage, and test facilities; track maritime traffic over relatively broad areas, and provide cues to indicate the construction of underground facilities. Digital Terrain

Elevation Data (DTED) enables precision targeting and supports military operations planning.

The subband channelization architecture used in the signal processing and the associated high-speed, power efficient hardware are key enabling technologies for providing the needed computational throughput within the power levels suitable for space applications. A 30Gflop chip set capable of wideband channelization and processing of complex signals, which computes a 128 point FFTs every 200nsec, will be fabricated. Measurements of chips fabricated using a similar process indicate that 25 to 50 GOPS per Watt power efficiency can be expected.

Analyses of the performance of space time adaptive processing (STAP) provide projections of the effects of range ambiguities and internal clutter motion. Processing of airborne surrogate DII data shows that the STAP clutter suppression techniques are effective in detecting moving targets. The GMTI tracker is based on a Bayesian multiple hypothesis algorithm that provides an integrated framework for combining all available target, environment, and sensor information. The tracker employs DTED and road information, as well as range profiling to enhance precision targeting and confuser deconfliction. Tracker results from airborne DII surrogate DII data show successful tracking of four ground targets with a high degree of position accuracy. SAR stereo and interferometric SAR (IFSAR) techniques for collection of DTED data are described. Only the IFSAR approach is expected to yield accuracy and resolution at or near the DTED 5 goal. Airborne IFSAR testbed results near the DTED 5 level are presented.

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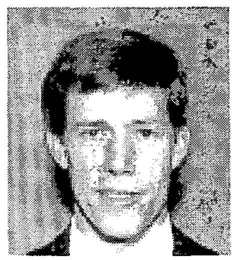
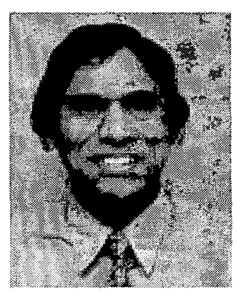
Anthony Filip *is in the Air Defense Technology Division at MIT Lincoln Laboratory. Since receiving his PhD from MIT, his professional focus has been on applications of digital signal processing techniques to a number of radar and electro-optical surveillance systems. He led the development of the programmable signal processor for the Space-Based Visible (SBV) instrument currently flying on the Mid-Course Space Experiment (MSX) satellite launched in 1996, and now a contributing sensor in the Air Force space surveillance network. His current research is focused on system engineering and signal processing algorithms for the Discoverer II space-based radar system.*



John Koss *is a research engineer with ERIM International. He has participated in key roles in the development of space-based and airborne interferometric SAR systems, and has performed numerous analyses of infrared and radar system performance in tactical and strategic applications. John led the development of early prototype laser radar target classification software and developed test procedures for Pershing II radar antennas. He is presently working with the Discoverer II Joint Program Office to define and develop terrain elevation mapping capability. John earned a B.E. in Electrical Engineering from Youngstown State University and a M.S.E.E. from the University of Akron.*



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George Pappas *is vice president at Amron Corporation responsible for support to the Defense Advanced Research Projects Agency (DARPA). He is currently providing Systems Engineering and Technology Assistance in the areas of concept of operations, utility analysis and tracking to the Discoverer II Joint Program Office. He recently served as Chief Scientist for the DARPA/Navy Unmanned Undersea Vehicle Program. He has also developed computer simulations to assess the performance of anti-submarine warfare and underwater mine countermeasures systems. He has a B.S. and Ph.D. in physics from the State University of New York at Buffalo.*