MIDCOURSE DISCRIMINATION FOR THE PHASE ONE STRATEGIC DEFENSE SYSTEM

A Report of the BMD Panel of the Army Science Board

February, 1989

Executive Summary

The ability to differentiate adequately between true targets and false ones (discrimination) in the midcourse phase of attacking missiles[1] flight is a key requirement for a successful ballistic missile defense. This ability is of particular importance for the proposed initial configuration of the Strategic Defense System (SDS phase 1) because (1) the preponderance of the reentry vehicle (RV) negations are to occur in the midcourse and (2) the effectiveness of the system is leveraged through selective (adaptive) defense that depends on reliable attack assessment in midcourse.

Discrimination in SDS phase 1 is to be performed remotely by a combination of radar and passive optical sensors, and will be based on hoped-for detectable differences in the emissions, shapes, and motions of the objects in a threat presumed to contain a variety of penetration aids accompanying the RVs.

The BMD Panel of the Army Science Board has reviewed discrimination concepts, the current knowledge of threat characteristics and potential discriminants, the supporting experiments that have been conducted and are being planned, and the major uncertainties and open questions.

Below are some of our observations and suggested actions. The full list of our conclusions and recommendations are too detailed to repeat in this summary, but can be found in the last pages of the report.

o At the current stage, as a result of an inadequate information base, it is not possible to state with confidence whether we can or cannot achieve adequate midcourse discrimination against a probable reactive Soviet threat. Information is inadequate in the following areas:

a) <u>Soviet Penetration Aids</u>
The Soviets have not tested within our view a pen-aids suite that would be effective against SDS phase 1. This means that SDS developers must invent and build presumed Soviet pen-aids and test against them. Our current intelligence systems do not provide information on Soviet

bus deployment characteristics and minimal information on the missile tests on their inland range. This is a major inhibition to our learning about current or future Soviet pen-aids.

b) U.S. Penetration Aids

In trying to estimate the practicality of Soviet pen-aids, we have only very limited experience relative to our own strategic missiles from which to predict the difficulty and the cost in weight and time required to develop penetration devices to the state of operational utility.

c) Optical Characteristics

Good discrimination-related measurements and data are our critical shortfall. Radar information is adequate except for that dealing with bus deployment, but our optical data base for and understanding of some of the important discriminable properties of RVs and the first versions of pen-aids is incomplete and rather poor. We do not, for example, have the ability to model, and hence to predict, the optical signals even from US targets in space because of the anomolous results, in terms of target radiance, spectrum or temporal behavior, from virtually all of our experiments and measurements to date.

The actions required to remedy these information deficiencies are:

a) An integrated SDI discrimination plan and program must be put in place. There is no integrated SDI discrimination plan and funding line keyed to the questions central to discrimination, nor is there an SDI discrimination program as such. It is made up of partially coordinated pieces being carried out by the Army, by the dem/val developers, and as part of some multi-purpose SDIO experiments. The Army's part of the program is a more coherent whole than the other efforts, but even it is not planned as specifically as it needs to be around answering defined, important discrimination questions. In any event, the sum of the pieces making up the SDI discrimination program is undersized and underpinned when considering the crucial role that discrimination is to play in SDS phase 1 and the time that will be required to prepare and carry out some of the important discrimination measurements.

Because of its background in and infrastructure for discrimination work, SDC would be an appropriate manager of the national SDI discrimination program.

b) No DAB Milestone 2 decision criteria have been established relative to discrimination. Such criteria would be useful in providing the necessary focus and explicit objectives for the discrimination program.

c) A much more active field and test program specifically oriented to the discrimination problem must be undertaken. The program should contain several main elements, two of which we would emphasize for near term actions: (1) A frequent series of sounding rocket-based measurements as the best timely means of identifying and resolving many current questions. These include the behavior of optical emissions of test targets, thermal shroud effectiveness, aerosol dispensing, decoy dispensing techniques and motion damping, and the robustness of phase derived range. And (2), one or more flights of a subscale Soviet bus simulator to validate our engineering models of dispensing characteristics and the impact of the thrusters on pen-aids.

(d) The construction of pen-aids for test purposes needs to be a well supported effort managed independently of the SDS system and element developers.

(e) Programs should be promptly initiated to obtain pertinent data on Soviet bus deployments and on inland range activities.

It must be recognized that discrimination is not a problem that can be "solved". Rather it will be a continuing race between the offense and defense to institute, respectively, more effective pen-aids and more capable means to counter those pen-aids to a degree that is adequate to maintain the defense's desired level of effectiveness. It will be a chess game that requires looking ahead several moves, and its effectiveness will probably always be a matter of judgment rather than a demonstrable fact.

I. Terms of Reference

The Chief Scientist of the USA Strategic Defense Command requested the Army Science Board's BMD panel to undertake a review of the Army's program and allied projects directed at midcourse discrimination. Because neither the experimental efforts connected with midcourse discrimination nor the impact of discrimination requirements on the design of the systems elements of the Strategic Defense System (SDS) are limited to independent Army activities, the panel broadened its review to include some examination of relevant Air Force and SDIO programs; and the panel's report is framed in terms of the overall SDI national requirements. The review considered the following.

o The current and presumed reactive Soviet threat o

Potential discriminants and counters

o The status of discrimination-related measurements and experimental information, and their uncertainties

o Measures of discrimination effectiveness

o The discrimination capability of the SDS phase 1 sensor suite

o The planning and management of the experimental projects intended to develop a discrimination data base and resolve important questions.

Limits of the Review

Discrimination issues for SDS go beyond the midcourse phase of reentry vehicle flight. Nuclear obscuration or even decoys are posed as potential boost phase problems. Long sleeves might be added to the post boost vehicles to mask deployments, and thrusted replicas have been suggested to mimic RVs in reentry. These are examples of possible steps to deny true target identification at each layer of a multi-tier defense. But the dominant concern at this stage of SDS development is midcourse discrimination, and it is that subject to which we have limited ourselves.

The evolution of the requirements for SDS and the likely increase in the sophistication of the threat are expected to lead over time to more complex discrimination problems and solutions. Passive and active sensors will have to be augmented with space-based imaging systems and interactive discriminators, and homing hit-to-kill interceptors will have to defeat targets that are spatially more complex. However, this review is limited to the epoch of the initial defense system, involving both passive optical sensors and CONUS based wide-bandwidth radars as the means of discrimination, and a threat including RVs with insulated, irregular shrouds to decouple thermal mass and reduce thermal brightness and to present multiple radar scattering centers, accompanied by a pen-aid suite mainly consisting of light replica decoys and spherical balloons.

Successful discrimination in a threat environment as complex as that postulated for the SDS phase 1 will place great demands on its space- and ground-based data processors and computational subsystems. However, within the limits on our time for this review, we did not attempt to assess the status and adequacy of these technologies, and recommend subsequent consideration of this important question.

We are very much in debt to the following organizations for their helpful inputs to our study: Nichols Research Corp., USAF Ballistic Missile Office, USAF Space Division, MIT Lincoln Laboratory, Sandia National Lab, Jason, Lockheed Missile and Space Company, USA Strategic Defense Command, the Strategic Defense Initiative Organization, and the Johns Hopkins Applied Physics Lab.

The membership of the Army Science Board BMD panel is listed in Appendix C.

II. Background

Over the 30 years in which the US has sought to design a defense against ballistic missile attack, a major question has centered on our ability to devise a credible approach to discriminating, in the midcourse ballistic phase, true targets (re-entry vehicles) in the presence of a presumed class of counter-measures called penetration aids, involving masking, deception, and overloading. Typical of the first is chaff to hide from radar the presence of a target; of the second, the deployment of numbers of replica decoys whose characteristics that can be measured remotely by the sensors of a defensive system (motion, thermal signature, shape at various wave lengths) are sufficiently similar to those of RVs to make identification difficult and blanket interception too wasteful; and of the third, the dispensing of large numbers of light objects such as balloons that are individually discriminable but which saturate the defenses tracking and discrimination system.

One of the several paradoxes of strategic defense is that our decision to proceed with development and deployment may be determined by whether or not we can convince ourselves that we can operate successfully against Soviet pen-aids that we have never seen. To the best of our knowledge, the Soviets do not have operational pen-aids and our observations suggest only a minimal Soviet flight test program. However, there is a consensus among US developers that some forms of pen-aids are within the Soviets technical ability and developing and fielding them is one of the Soviet's main technical options in responding to the Strategic Defense System. Moreover, since the time required to build, test and deploy pen-aids may be shorter than our SDS time table (~10 years) the Soviets may not give us a glimpse of their program and their technical approach until we have settled on the basic characteristics of SDS and made the development decision (Milestone 2.) For SDS to proceed in such a circumstance, it is necessary for its developers to invent for themselves the Soviet pen-aid threat (no doubt providing helpful guidance to the Soviets in the process) and to build such pen-aids and test the SDS elements against them. A decision to develop SDS will rest, in part, on a determination that this surrogate threat adequately encompasses the credible Soviet responses and that the SDS design is flexible enough to accommodate to the actual threat as it emerges and evolves.

III. The SDS Phase One System

SDS phase 1 is not fully defined, but the essential features as they apply to midcourse discrimination are known. For a typical situation, the SSTS will track clusters (usually the objects deployed at each bus stop, including pen-aids and one or more RVs) until handed off to the GSTS which has the resolution to track and discriminate individual objects based on thermal behavior or macro-dynamic differences. The GSTS will in turn cue the GBR to examine uncertain object groups with greater spatial and motion resolution, basing discrimination on refinements of the impact point prediction and of the information on angular motion. The effectiveness of SDS will be leveraged through the use of adaptive defense,[1] which puts a premium on successful discrimination and kill assessment. To achieve the system performance goals with the current SDS phase 1 architecture, roughly speaking the probability of identifying an RV in midcourse should exceed 75% and the number of false targets misidentified as RVs should be less than 25% of the true targets.

The discrimination effectiveness of the system will depend on the details of the threat, the required RV negation in midcourse, and on the assumption of sensor characteristics, and can be estimated only with an architectural model. However, many of these models use measures of discrimination effectiveness that may be overly simplified, and the actual sensor requirements cannot be established adequately without a more detailed simulation of the threat objects (see the later section on Measures of Effectiveness.)

There are many demanding manufacturing and engineering hurdles to overcome to achieve sensors with the capabilities required by SDS, but for discrimination purposes the key ones are navigational accuracy, object identification, and sensor to sensor correlation to fix target coordinates in a highly complex scene; LWIR sensitivity and small pixel size to allow object

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[1] The defense doctrine of preferrential/adaptive defense is based on the idea of ranking the sites to be defended (preference), and, using limited defensive assets, having the ability during the course of the actual battle to select and defend those targets that maximize surviving value or some other criterion (adaptive.) The concept of adaptive defense -- save what is savable -- is sensible, but the implementation of preferrential defense has yet to be tested politically.

detection and resolution at long range; optical band-to-band stability and in-band precision to determine small temperature changes; high framing rate to adequately sample oscillatory signals; high-power wide-bandwidth (and possibly mobile) radar to detect subtle motion differences; and fast algorithms to process the vast amounts of data in essentially real time.[2]

IV. The State of Our Knowledge About Soviet Midcourse Systems

Reentry Vehicles. The US has accumulated quite a lot of radar data on Soviet reentry vehicles in flight tests, and there is confidence in our knowledge of dimensions, mass, spin rate and orientation, and coning angle and rate (precession.) As the Soviets proceed to new RV models, including those that are modified as part of a countermeasure to SDS, our radar observation program should allow us adequately to track these changes. In the case of more detailed information which in some instances we can now measure, such as internal structure, the location of radar scattering centers and the small motions connected with mass imbalance, it is not clear whether we can count on those as discriminants since there are countermeasures, perhaps inadvertently appearing even now, that may deny us these as reliable, real-time discriminants. However, because of the potential usefulness of these smaller scale discriminants, it is important to mount a Red-team experimental program to try to answer this question.

The status of optical data taken against Soviet RVs is essentially the opposite of the radar case: we have none. However, that is just changing. The Queen Match LWIR rocket probes have started to fly, and the airborne LWIR Cobra Eye will soon follow. Efforts have been made over the past years to gather optical information on US and simulated Soviet RVs in space chambers, on rocket probes, and as part of orbital experiments, with variable results. Many, if not most, of these measurements have shown anomalous behavior, which has precluded validating the optical signature code (OSC) model, and in

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[2] The 1987 SDIO sponsored Midcourse Sensor Study devoted considerable effort to examinining the state of technology and its outlook for application to midcourse sensor systems, and is the best specific reference on this subject. We have highlighted in Appendix B some of the top level issues connected with radars and optical sensors which are the central systems for SDS phase 1.

some instances suggested other physics at work not included in the model. The only answer to this situation is better measurements undertaken with some urgency. Understanding and being able to model (predict) the RV's optical behavior is key to addressing the optical discrimination problem.

A conformal thermal shroud with a small α/ε [3] to reduce the RV's signature and to decouple its thermal mass has been invoked as the wooden stake in the heart of optical discrimination. There are limited measurements so far, but the potential of this countermeasure has already played a role in the redesign of SDS phase 1. The recent results from Delta 181 do not confirm the space chamber measurements on shroud effectiveness at a terminator crossing -- possibly indicating a problem for MLI pump down in a space experiment -and point to the need for further experiments with particular attention to the choice and behavior of the shroud to determine the practical limits of this countermeasure.

One footnote with respect to tethered objects which the Soviets attach to the rear of most of their RVs in flight test. In spite of unresolved arguments over their purpose (probably intended to mask system characteristics for intelligence denial), it is reasonable to assume they will not be present in operational systems in an SDI environment simply because they accomplish little as a countermeasure and they unnecessarily complicate the design of good decoys.

<u>Pen-Aids.</u> Our knowledge about Soviet pen-aids is minimal and tends to rely on inference and mirror imaging (how we might do it.)[4] The Soviets do fragment parts of their bus, drop off objects that accompany RVs but which do not look like RVs on radar, have experimented with putting an RV into a cylindrical canister and with different coatings and surfaces, and have flight tested chaff dispensing. We only have varying degrees of information on these

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[3]The ratio of absorption at visible wavelengths to the emissivity at thermal wavelengths (LWIR.)

[4]Unfortunately, our mirror imaging at this stage must rely more on theory than experience since the US pen-aid program for its offensive forces is limited to chaff and to some earlier preliminary R&D work on aerosols, balloons, and replica decoys.

activities, but none, with the possible exception of the multiple scattering point surface, would appear to be a very effective pen-aid against SDS phase 1.

In attempting to describe the pen-aid potential of a first-level reactive Soviet force, we rely on our estimate of their bus capability and performance, and assume the Soviets can over time build any pen-aid and dispensing system which we can devise for ourselves. The pen-aids that come from these analyses are discussed in the section of this report dealing with countermeasures to discriminants.

Buses. Soviet buses are not part of the midcourse threat, per se, but are important to understanding that threat and its potential. The credibility of pen-aids will be determined in part by bus behavior, particularly with respect to thrust levels and hence plume effects during deployment, stabilization time, tip-off control, volume availability and clearances, and surplus weight capacity. We have very little current data except for two instances when late deployment took place within range of Cobra Dane.

The Gaps in Our Information. For the lack of a good observation platform or location, we obtain little data on Soviet bus behavior or any detailed information on tests conducted on the Soviet inland range, where the first R&D flights of pen-aids will presumably be carried out (or might even be underway now.) Both of these intelligence shortfalls can impact SDS since we will have to rely more on our technical estimates of the Soviet reactive threat than on observations, and may over or under design as a result.

There are certain options for improving our ability to monitor bus characteristics and inland range activities, which, though expensive, are important to pursue. Because these steps will require perhaps three or four years to implement, they should be initiated as quickly as possible if they are usefully to support the SDS design effort.

V. Basic Discriminants

Impact Point Prediction. Assuming MARVs are not in the Soviet inventory, a first order discriminant is to disregard midcourse objects on non-threating ballistic trajectories (including those directed at targets not in the preferentially defended set.) The utility of this discriminant will depend on the accuracy with which the midcourse sensors can determine the state vectors of objects in track and on the dimensions of the keep-out zone of each of the sites in the target set. The ground-based radar should provide IPP to perhaps 100m. For the case of hard targets, such as silos, where the keep-out is measured in hundreds of meters, and for decoys with probably cross-track velocities of a meter per second, this discriminant may be quite useful. The efficacy of this discriminant will depend on the care with which pen-aids are dispensed, but because of plume interaction, may turn out to be very useful.

Thermal Behavior. The thermal emission of a target will depend on a number of its characteristics, but two features are prime candidates for discrimination: the change of signal with aspect as a means of discerning shape (RV vs spherical balloon, for example), and thermal mass which provides different heating or cooling rates, particularly notable at a terminator crossing, for a heavy RV and lighter objects. The efficacy of the two discriminants will depend on the ability of the offense to deny them through shape matching (replica decoy) and thermal isolation to match surface temperature behavior.

Motion. Unless considerable effort is put into matching the mass distribution of decoys, into the decoy dispensing mechanism, and into thruster plume avoidance or compensation, the angular motions of decoys and RVs will differ, with decoys because of their lesser inertia having a greater spread in those motions. These differences may be large enough that the variation in the optical signature, and certainly the radar return, will permit a very useful degree of discrimination. A problem for this discriminant, however, is that the details of the effect will become known reliably only with observation of Soviet test flights of decoys, which may be several years hence for the ranges we currently monitor. The efficacy of this discriminant will depend on the ability of the offense to match angular motions (Project Verify indicated one possible but incomplete approach) or to actively damp them, or to deploy RVs with a random angular motion component that tends to mask this discriminant (anti-simulation.)

Visible/UV. Optical sensors operating in the visible and ultraviolet regime have the advantage of longer acquisition range and better spatial and temporal resolution than typical LWIR space sensors. Since a large majority of ICBM trajectories have sunlit portions, measurements of reflectivity and motion may be a supplemental form of discrimination, though susceptible to many of the same countermeasures noted above.

Other Discriminants. Other, more subtle discriminants have been suggested, such as emissions from the outgassing products of RVs, as evident in shuttle glow, or plasma effects in the ionosphere. The experimental discrimination program should include an examination of these and other possible effects.[5]

Some discrimination concepts are treated on a special access basis and we did not review them. Obviously one cannot rule out novel or surprising techniques but special access can also obscure bad physics, and we caution that these programs deserve special scrutiny.

Multi-Spectral Measurements. By considering discriminants separately, as above, the advantage of multi-spectral measurements does not emerge. While the offense may be able to counter any particular discriminant adequately, defeating all of them simultaneously greatly increases his problem. This advantage cannot be fully quantified, but engineering experience strongly

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[5] In considering other forms of discrimination, most versions of interactive discrimination have been consigned to later phases of SDS because of the greater demands of the physics and technology involved. However one form, dust dispersal, seems to be feasible within the phase one period. The concept proposes the fly out of a ground-based launcher to place one or several dust clouds on intersecting trajectories with threat clusters. Though feasible in principle, this approach has not been given much consideration primarily because of cost. Large payloads and well controlled dispensing tend to lead to an expensive system; moreover, the current SSTS would not have the resolution to provide the requisite discrimination measurements, and delaying until within range of GSTS or GBR could substantially reduce the battlespace. For the purpose of this report we have set aside dust discrimination; however, if the discriminants discussed above turn out to be inadequate because of successful countermeasures, dust discrimination may become important. For that reason, a small program on dust dispensing and analysis of engineering concepts should be part of the overall discrimination program.

supports the concept of a defensive system using multiple sensors with differing characteristics, augmented by analytical and software techniques for data correlation and signal identification. The incorporation of radar, multi-band LWIR, and visible/UV sensors in SDS phase 1 is a good approach.

VI. Countermeasures

Inventing countermeasures to SDI is a popular game in the techno-political community, often with little regard for technical difficulty and cost impact (in terms of weight and volume penalties, and time required) which our own limited experience in developing pen-aids for US offensive systems has shown to be substantial. SDI has on many occasions been pronounced dead-on-arrival because of postulated countermeasures and presumed SDI response (or lack thereof.) However, so far, those who are prepared to suspend judgment on the feasibility of SDI until engineering information and measurements on both countermeasures and defense systems performance begin to be available have prevailed and the program has maintained its political support.

Our review touched on those pen-aids discussed below, and did not consider one of the often noted potential counter measures, viz, nuclear effects from a precursor attack or salvage fuzing. In midcourse, the short duration of nuclear induced optical background and the variety of viewing directions available to the optical sensors does not make nuclear detonations very effective as a means of blinding sensors, and a blackout fence against radar requires the diversion of a sizable number of weapons. However, with respect to longer term and extended nuclear background effects, there remain major uncertainties in the effect of atmospheric heave and the optical clutter of nuclear striation. A well supported program of research on these questions is important. Direct nuclear effects on the functioning of sensors in space is part of the troubling problem of survivability, and is not dealt with in this report.

Chaff and Aerosols The dispensing of chaff and aerosol clouds around RVs and non-RVs (possibly little more than the dispensors themselves) can create radar and LWIR (reflected earth shine) signals great enough to mask the presence or absence of an RV in each cloud. The advantage of masking is that it may be a simpler than attempting to achieve an adequate degree of matching between the motion and thermal properties of RVs and decoys, or other means of denying discriminant information. And masking becomes easier as RV's RCS and temperature are lowered as countermeasures. US experience suggests these are achievable pen-aids: chaff dispensing is an established capability and an earlier program on LWIR aerosol dispensing was advancing when it was cancelled by USAF BMO. Further work will be required to confirm the reliable dispensing of LWIR aerosols, and their effectiveness will have to be tested at shorter wavelengths to counter the addition of visible and UV sensors to SDS.

Chaff and aerosols are not considered main elements of the SDS phase 1 threat, and this may be an important oversight. We recommend that a project be initiated to assess the practicality of dispensing chaff and aerosols with densities appropriate for masking GBR and GSTS resolution cells, and to determine if this is a reasonably near-term countermeasure.

<u>Traffic Balloons</u>. The concept of traffic balloons involves a large number of small, light-weight packages (perhaps 100) dispensed from the bus at each deployment station (over a period of some 20 seconds), with each package subsequently inflated into a spinning and probably spherical balloon having RV-like dimensions. The surface of each balloon may differ in terms of painted patterns and α/ε. Any one of the balloons may be discriminated from an RV in their midst by brightness, aspect change, thermal history, or rotational dynamics, but in aggregate there will be overlap in the signal distributions from true and some of the false targets, requiring more and lengthier measurements to achieve good statistical separation. The question is whether this places so great a demand on the sensors[1] spatial resolution and framing rate, and on the data processor, discrimination algorithm, and track file (and possibly on the inter-sensor communication system) as to exceed the design of a practical defense. The information we received in our briefings suggests that this pen-aid has been fully modeled and that SDS phase 1 can reduce the number of such false targets to an acceptable few without saturating its data system. Our only comment is that the history of BMD discrimination is spotted with contrived threats and threat responses - see the section of this report on that subject - and it would be advisable to look critically at those models to assure oneself that the details of the threat are as demanding as practicality permits, and to

assure that the data processing loads are within the capabilities of practical space and probe systems.

Light Replica Decoys. A particular concern for midcourse discrimination are light replica decoys: each being 2-5% of an RV weight and having the same shape, surface in terms of optical, thermal, and radar properties, and dynamics (spin rate and orientation, coning angle, precession rate and amplitude), as a typical RV. At each station perhaps 10 of these decoys would be deployed as rigid objects (possibly in the so-called Dixie cup style) or in canisters to be subsequently inflated. In their idealized form they would be indiscriminable by the planned SDS sensor suite and too numerous to intercept. However, whether that ideal can be achieved is an open question. A high degree of thermal isolation of RVs will have to be demonstrated and the Delta 181 results seem to indicate this may not be straightforward. A stressing problem for the light replica decoy may be unwanted motion produced by the impingement of the bus thruster plume on the rigid decoy or the inflation impluse on the canistered decoys. Laboratory measurements in the first case and the Delta 181 experiment in the second case indicate a discriminable motion can be induced, though the use of small attitude rate reducers may mitigate the effect. These clearly are very important questions that need to be answered, and the unfunded program to build and fly a reduced-scale replica of a Soviet bus, along with other supporting experiments, are critical first steps to obtaining the engineering data that is required.

It has been suggested that a long bus sleeve could protect decoys from significant plume effects, but that threat is not part of the SDS phase 1 epoch. Another suggestion is to turn off the bus thrusters during deployment and rotate the bus before re-ignition. US experience indicates that this can be done, however, it might lengthen the total busing time and increase vulnerability to SBI attack. This last point should be generalized. While mitigating one problem, many proposed counter measures would have a deleterious effect on some other performance feature of the offense. It is important to examine and evaluate countermeasures - and counter counter- measures too, for that matter -- in terms of overall system impact to avoid trading off one problem for another.

Anti-Simulation. As we discuss later, discrimination is usually a statistical judgment and the deviation from the norm is an important parameter in trying to separate true and false targets with acceptable reliability. Anti-simulation is a counter measure that undertakes to spread these distributions and increase their overlap. It is often invoked as a step the Soviets would take to avoid localizing their RVs in a multi-dimensional signature space, but can also apply to pen-aids to offset unpredictable or uncontrolled conditions, such as, the tip-off errors of traffic balloons, the variable viewing geometry of the defenses sensors, and differences in season and time of day. Anti-simulation countermeasures will have to be evaluated on a case-by-case basis and accepted to the extent they are practically achievable without significant penalty.

CSOs and Enveloping Balloons. SDS has opened itself to a particular counter-measure by relying on hit-to-kill midcourse interceptors, namely, closely spaced objects[6] or large enveloping balloons around the RV. In both cases the homing sensor of the interceptor might not be able to discern and target the RV. There is some consideration being given to flying a large sweeping net on a precursor missile to prep the threat for the follow-on interceptor, but for SDS phase 1 it is felt that the controls necessary to achieve CSOs or large enveloping balloons will place this threat into a later time period.

Defense Enforced Countermeasures We may, as the developers of the defense, tend to overestimate the effectiveness and ease of Soviet countermeasures. The cost and engineering difficulties and the offensive compromises may in fact be considerable. We should not forgo any discriminant on the grounds that when studied in isolation it could, in principle, be countered. Within the bounds of affordability, SDS should incorporate measurements of essentially all potential discriminants, and put the onus on the offense to try to defeat them.

[6] CSO's are objects near the RV within one resolution cell of the tracking sensor but separated by distances greater than the kill radius of the interceptor and its lethality enhancer. Typical separations would be 10-100m.

VII. Measures of Effectiveness

Discrimination does not lead to a bipolar answer except in special circumstances. Even the best operational data will be imprecise because of measurement error, systematic but unpredictable variability of the source, and finite sampling time. The results of operational discrimination measurements are not expected to give a yes or a no on an object by object basis, but to provide degrees of maybe. This fact, plus the potentially large numbers of RVs and pen-aids in an all out attack (perhaps 10^4 and 10^6, respectively), mean that the measures of discrimination effectiveness will necessarily be expressed in statistical terms. Lacking a body of data from actual measurements, it has been common practice to make some idealized assumptions about the statistical description of RVs and pen-aids, namely to assume the variability of a discriminant feature is single-mode and stochastic, and to characterize discriminability as the separation between the norms of the RV and pen-aid Gaussian distributions of that feature, measured in units of the standard deviation of the RV distribution - the well known K factor. (In instances where there are multiple simultaneous discriminants, each is considered stochastic and discriminability is measured by the Bhattacharya distance.) With this model it is then usual to compute the requisite K factor to achieve desired upper bounds on "false alarms" (to avoid interceptor exhaustion on false targets) and on "leakage" (to have an acceptable survival rate among sites being attacked). This K factor becomes the design goal for the system sensors.

This approach to modeling discriminant measurements and their effectiveness was reasonable as an entry level concept but must be used with caution in generating specific discrimination requirements for sensors or as the parameter around which the SDS architecture is developed. The offense may deliberately transform the distribution functions of the discriminant features from the assumed Gaussian by design changes to RVs and pen-aids[7] (e.g., balloon decoys may have varying amounts of reflective and emissive surface areas, giving rise to a temperature distribution function which is not Gaussian.) This

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[7] Note that even if the offense is successful in transforming the distributions of the discriminant features to be non-Gaussian, to be effective as a countermeasure a substantial overlap must be maintained between the distribution characterizing the RVs and the pen-aids.

procedure (one application of anti-simulation) requires more detailed analysis to determine discrimination effectiveness than that determined by the K-factor. Simulations of targets and full end-to-end engagement models should play a part. (We understand the Army is beginning to take this approach, but this awareness has not spread throughout the SDI community.) The key point, however, is that the modeling of the RV and pen-aid parameters used in the simulations must be realistic, which means they must ultimately rely on intelligence data and information from US flight tests. The development of sensor design parameters will have to be based on the assumption that the offense will use, whenever possible, anti-simulation techniques.

There are a number of discrimination algorithms in various states of use with little obvious coordination between them. This can create differing answers and confusion. It may be premature to settle on a single construct, but one benchmark algorithm for cross checking and some standardization would seem advisable.

VIII. The Discrimination Measurement Program

The Experimental Program. Measurements have been made over the years of the optical and radar characteristics of test objects intended to simulate Soviet targets. While the radar results are reasonably consistent, the LWIR data is almost invariably anomalous in terms of radiance, spectrum, or temporal behavior. FAIR, DOT, HOE, Have Jeep, Delta 181 all had results that were at odds with the best model (OSC) describing optical emissions. Attempts (usually unsuccessful) to understand the sources of the surprises have been made more difficult by the frequent lack of in-flight calibration.

The multi-year plan for future measurements is described in detail in Appendix A. As we have commented elsewhere, the magnitude and schedule of the program are not commensurate with the urgent need for firm discrimination results nor do the plans adequately recognize the difficulty, based on experience, in generating understandable results. We are not at the stage of refining our understanding but are still trying to describe and understand the basic phenomenon. Four observations are:

- The experiments need to be better designed and monitored, including the test targets, so that there is a better chance of isolating the sources of anomalies. In-flight calibration must be included in all experiments.

- In trying to identify the source of problems in a complex experimental environment it is useful to separate and hold fixed as many experimental parameters as possible. This is best accomplished on a step by step basis in a series of systematically planned, relatively inexpensive experiments. The Army's sounding rocket program (SRMP) - with recurring costs in the neighborhood of $3 million each - would seem to be an appropriate experimental platform, and should be scheduled for six or so flights a year until basic phenomenon are identified and understood. These test flights can be augmented with piggyback experiments on rides of opportunities on US missile test ranges.

- Expensive (>$200M) multi-purpose orbiting experiments such as Delta 181 and the MSX (currently in the planning phase) have distinct pluses and minuses for answering the important questions connected with discrimination. They provide simultaneous measurements among a number of sensors that can provide useful and possibly revealing correlations, and with its longevity in orbit MSX may be able to gather good statistical information on a number of target types under a variety of conditions. Some disadvantages are (1) if the satellite or one of its key instruments fails, some years may lapse before a follow-on can be flown (or afforded); (2) there is less flexibility, which may be important in trying to track down sources of anomalous behavior when during the course of the experimental campaign one may want to change experimental instruments or parameters such as wavelengths, bandwidths, time constants, dynamic ranges; and (3) in attempting to meet the objectives of several quite different experiments, any one of them may be compromised. The failure of Delta 181 to obtain LWIR radiance data, which is key to the optical discrimination of SDS phase 1, is an example of the last point.

- Had that data been the purpose of the experiment, its execution would have been different. MSX may be susceptible to the same problem as it tries to balance between sensor and optics tests, long-term tracking, on-board data processing and analysis dem/val, the gathering of optical background data, and performing measurements to diagnose the optical behavior of test objects.

- The Army's EDX is a systematic set of experiments, but at one flight a year is not adequate to meet the most urgent discrimination data requirements of the SDS phase 1 decision schedule.

- Induced motion may well turn out to be a prime discriminant for SDS phase 1, but it will take time to prepare and test this in a series of flights. The discrimination program should include the construction of a replica subscale Soviet bus to validate our engineering model of dispensing characteristics and plume interaction and its mitigation.

Target Specification and Standardization. There has been an a la carte approach to the selection and building of dedicated RVs and pen-aids for discrimination measurements, which can create a problem in relating results among experiments as well as to the SDS phase 1 threat. Because of the experimental nature of the measurements at this stage, there may have to be flexibility in the choice of test objects. But as a minimum they should be explicitly described, explained and related to the accepted threat as part of a discrimination master test plan.

There is an effort within SDIO to specify test objects for the dem/val flights, but it does not reach into the discrimination program. At an appropriate point, the discrimination program should also use a standardized target set.

Data Management and Dissemination. Data taken from past discrimination experiments have undergone varying degrees of analysis, correlation, and archiving. A major effort was made five years ago (the LEAD study) to look comprehensively at the LWIR data available at that time, and to quantify our knowledge and uncertainties. No comparable baseline compendium has been prepared by the discrimination community for radar observations of RVs and buses, but a recent Lincoln Laboratory report provides a great deal of that information.[8] Subsequent and planned future measurements - hopefully substantially expanded -- will make the management and accessing of such information a daunting problem, requiring a systematic approach not only to the formatting and archiving but to the reduction and analysis of the information into forms that can explicitly guide SDS architectures and sensor designs. The SDC ARC is now housing the Delta 181 data and is a good first step.

In a perversion of priorities, there is an unfortunate tendency to stint on the funding of the analysis of data often taken in costly experiments. We suggest two steps to avoid or mitigate this problem in the future.

- The test plan for all experimental and dem/val projects that can produce useful discrimination results should include a specific plan and funding profile for analysis of that data. By making this requirement explicit at the front end of a project, it will strengthen ones claim at the back end when enthusiasm and attention have moved on.

- The Army should prepare and circulate an SDI discrimination data management, analyses, and dissemination plan. A convincing plan, including funding objectives, marketed to and hopefully adopted by SDIO, could lead to a useful, relatively complete national data base, and also may lessen the need to make the case, project by project, for data analysis support.

A centralized data analysis program would be intended to maximize the understanding of discrimination phenomenology that can be derived from any given experiment and provide a comprehensive information base. However this centralized analysis should not substitute for the sensor developers also working with original data, which can be important to the details of the system design.

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[8] LL Technical Report 830: Discrimination for BMD. November 1988

The Planning and Management of the SDI Discrimination Program. Firstly, there is no integrated SDI discrimination program. Organizationally it appears once in the national effort, as a division within the sensors directorate under the BMD Program Manager of the Army's Strategic Defense Command. Elsewhere it is an implicit part of other technology development projects or of the system elements dem/val projects (where it is not dealt with *very* profoundly.) It is part of five separate SATKA work packages. As a consequence, there is no SDI discrimination plan that lays out objectives, questions, problems, measurement schedules, budgets or decision criteria that support the requirements and time table of SDS phase one. With SDS's latest architecture relying even more on midcourse interception and hence midcourse discrimination, this state of affairs should be changed. Our suggestion is that since the Army has the background in midcourse discrimination and the only coherent (but limited) current experimental program, it should prepare a plan and propose to take the lead for a national program to support the midcourse discrimination requirements of SDI, and to submit and market this to the director of SDIO. The plan should be directed very explicitly at the resolution of the basic questions for midcourse discrimination -- a partial list is suggested below - and should describe well defined protocols for ground, probe, and space based measurements, target monitoring and control, and modeling that are designed to provide unambiguous answers.

- OSC validation, and possibly modified to capture other effects.
- Decoy dynamics produced by bus thrusters or inflation, and the effectiveness of a practical ARR
- Effectiveness of thermal shrouds
- Dynamics and thermal behavior of balloons designed to stress the discrimination capabilities of SDS's sensors.
- Robustness of phased derived range to detect microdynamics
- Aerosol dispensing

- UV/visible behavior

It has been (long) hoped that developers of the US offensive forces would independently provide a range of credible pen-aids developed for their own use, and that this technology would augment the Army and SDIO efforts. Our meeting at USAF BMO made it clear that for budget reasons this will not happen and the pen-aids to test SDS will have to be conceived and built within the SDI program, hopefully making use of the residual expertise at BMO and its contractors.

One final thought on the approach to the management of the discrimination program: in spite of the best of intentions and commitment to integrity, there is an inherent conflict of purpose and interest between those responsible for the system architecture and element development, and those responsible for challenging the capabilities of the system to perform against stressing countermeasures. To mitigate this conflict and to be persuasive to an agnostic external community, it is advisable to establish and maintain the discrimination and countermeasures program as a well-supported, well-managed, separate and independent activity.

IX. Contrived Solutions

During our review we were exposed to two examples where the midcourse discrimination problem was supposedly solved, but both would require the cooperation of the offense. In one case thermal leakage through the small but finite conductivity of a particular thickness of thermal shroud would over time permit the true target to be identified, but as the Army has shown, a slightly thicker shroud would deny that discriminant, assuming MLI can be made to work practically in space as it seems to in a space chamber. In the other case the Soviets would have to maintain distinctly different coning angle distributions of RVs and replica decoys.

Discrimination seems to be a very tough problem and in such circumstances contrived solutions will arise, particularly if there is a sense of urgency about the need for getting on with the program as a whole. But this is obviously not an acceptable basis and those responsible for the program must examine with care proposed solutions for discrimination in order not to be misled.

On the other side, those who invent supposedly indiscriminable threats must be made to confront equal scrutiny and skepticism. The engineering difficulties of creating such threats in large numbers are daunting, and in our estimation will probably not be accomplished in the period of the first reactive threat.

X. DAB Milestone 2

Pace and Funding. The Army's current experimental discrimination plan, involving a few flights a year over the next six years, is a sensible set of measurements that would be appropriate to a moderate cost research program aimed at developing the data base on BMD discrimination, such as existed prior to SDL However, this program seems risky and inadequate for providing the key if not crucial (with the increasing emphasis on midcourse) information for an SDS development decision by the early 1990s. The field test data and the understanding resulting from discrimination measurements should be the underlying bases for the design of the SDS sensors dem/val. But instead the two programs are moving in parallel, with the particular sensor concepts and designs being selected essentially on the assumption that discrimination will prove tractable, and with a very sizable investment being made in sensor construction and test. It is too late to suggest altering the sensor schedule, but the pace of the discrimination program can - and must - be increased. As a starting point the sounding rocket program should have flights every other month and the Soviet replica bus project funded immediately. These and other steps will of course increase the cost of the discrimination program, but by amounts that are small compared to sensor development effort.

Decision Criteria. There is an understandable desire not to over specify the decision criteria for DAB Milestone 2 of SDS phase 1. This Milestone is distant in time, the objectives and threat may change, and a welter of new engineering information will emerge over the intervening years. On the other hand, without specific goals, the discrimination program may lack focus and possibly not be in a position to provide convincing information to facilitate a Milestone 2 decision. As far as we can tell, the Milestone 1 decision was made with little supporting information to demonstrate the existence of a latent solution to midcourse discrimination for a stressing but practical threat.

We suggest the following as a partial list of answers which the discrimination program should provide by the time of Milestone 2.

- The optical and radar description of Soviet RVs that have been flight tested, including the variability of the signatures.

- The same information on other objects in the threat cluster, including of course any pen-aids.

- A best estimate of the Soviet countermeasures program, including any information on bus-decoy interaction.

- A simulation model that accurately characterizes signatures (and their variability and statistics) of Soviet threat objects, including a description of empirical factors not having a ready physical explanation.

- Results of US test flights of simulated, postulated Soviet pen-aids, reduced to deterministic models that can be incorporated into system architectural and engagement models.

- A model-derived prediction of the performance of SDS phase 1 against the accepted threat, using the above RV and pen-aid models, with some reasonably high confidence level (perhaps > 80%.)

- A description of what is certain and what is uncertain, arguable, or simply not understood, and the possible impact of the latter on the achievement of the phase 1 performance objectives.

XL Conclusions

Primary Points

1. The ability of SDS phase 1 to achieve adequate midcourse discrimination is an unresolved question. Extant optical data is anomalous relative to our best model, and there is uncertainty about the robustness of radar-measured motion discriminants. Since more than a decade of discrimination measurements has not provided answers, the current effort seems to be risky and inadequate to rely on for the key if not crucial (with the increasing emphasis on midcourse) information for an SDS development decision by the early 1990s. Only a full fledged measurement program, including intelligence gathering, will provide answers.

2. There needs to be an integrated discrimination program and plan that relates objectives, experiment selection, schedule, and funding, and is managed independently from the SDS development effort. A national manager is required.

3. The pace and funding of the aggregate discrimination effort is too slow and too little to provide the information for a confident DAB Milestone 2 decision. Some important components of the discrimination program, such a Soviet bus simulation and enhanced intelligence gathering, will require some years to put into place.

4. Some broad criteria relative to discrimination requirements need to be established for Milestone 2 in order to provide goals and a time table for the discrimination program to achieve results essential to a well-founded decision.

5. Good, practical countermeasures to SDS will be difficult for the Soviets to build and involve their own engineering challenges,

and could potentially have a significant negative impact on the offense's performance. The SDS should make that problem as hard as possible by maintaining the multi-spectral sensor approach of SDS phase 1. The addition of visible and UV sensors would be sensible.

6. Misleading or contrived solutions to discrimination must be guarded against.

Intelligence

1. Measurement systems and locations need to be established to allow the monitoring of Soviet bus characteristics and dispensing actions in flight, and to observe the Soviet inland range where, presumably, the pen-aids test program will be conducted.

Measurements

1. Above all, the information base, derived from measurements, on which discrimination concepts will be decided needs to be developed. The current information is incomplete and unreliable.

2. Experiments need to be better designed and controlled to isolate the sources of the unpredicted behavior that has plagued almost all the LWIR measurements to date. In-flight calibration must be routine. The data base must be expanded to cover visible and ultraviolet wavelengths since such sensors are candidates for a supplementary role in SDS phase 1.

3. The flight test targets must be instrumented and monitored to correlate their motions and emissions in enough detail to provide a basis for understanding the results of the measurements taken by the remote sensors. Target specifications and standards

should be adopted so results can be compared from experiment to experiment.

4. The design and construction of realistic simulated Soviet pen-aids is an important part of the discrimination program. Some technical and conceptual help may be obtained from USAF BMO, but with their very restricted budget, they will not be an independent source of pen-aid test targets.

5. In trying to identify the source of problems in a complex experimental environment it is useful to separate and hold fixed as many experimental parameters as possible. This is best accomplished on a step by step basis in a series of relatively inexpensive experiments. The Army's sounding rocket program (SRMP) - with recurring costs in the neighborhood of $3 million each ~ would seem to be an appropriate experimental platform, and should be scheduled for six or so flights a year until basic phenomenon are identified and understood.

6. Large, multi-purpose experiments can provide inter-sensor correlation and statistical information, but are relatively inflexible and may tend to compromise the objectives of any given measurement.

7. Bus induced motion ~ or that from decoy inflation - may be a particularly useful discriminant. It is important to make test flights to observe these effects and their possible mitigation by an active attitude rate reducer. A subscale Soviet bus should be built and flown to validate our engineering model of dispensing characteristics and the dynamical behavior of pen-aids after passage through the bus plumes.

8. Specific measurements are needed to ascertain (1) the usefulness of anti-simulation as a means of effectively defeating those discriminants on which SDS is based, (2) the ability of an MLI shroud to decouple the thermal mass of the shrouded object over

ballistic flight times, and (3) the robustness of microdynamics as a measurable discriminant.

9. Among the potential pen-aids, masking against radar and optical sensors by chaff and aerosols may be both practical and effective. Chaff dispensing is an established ICBM capability for the US. The remaining question is the weight penalty to maintain enough scatterers in a GBR resolution call. An experimental program should be immediately initiated to test aerosol dispensing and determine its effectiveness as an optical countermeasure to the SDS phase 1 optical sensors.

Data, Modeling, and Measures of Effectiveness

1. LWIR data on flight objects is almost all anomalous in terms of radiance, spectrum, or temporal behavior relative to the best predictive models. It would be impractical to rely on most potential optical discriminants when our physical understanding of thermal emissions is so incomplete or in error. There may be other effects involved that are not included in the models.

2. Data from past discrimination measurements are in varying states of archiving and analyses. A plan for a national SDI discrimination data base is particularly needed with the prospect of greatly increased data generation. The Army's effort to be the data center for Delta 181 seems to be a good model, and an Army proposal to SDIO to be the repository for all discrimination information would be a sound idea.

3. Adequate funding of data analysis must be secured. It should be emphasized in the original plan for any experiment, and be an element of the funding of a national SDI discrimination data base.

4. There are a number of discrimination algorithms being used, which can lead to conflicting results and conclusions. It is not time

to try to standardize to one algorithm while the bases for discrimination and the SDS sensors suite are still fluid; however, having one benchmark algorithm to facilitate intercomparisons is appropriate.

5. The use of the present K-factor as the only measure of effectiveness in modeling an SDS architecture or establishing sensor requirements is questionable. The idealized assumptions behind the K-factor are probably not valid for the circumstance of SDS phase 1 (adaptive defense with a limited number of interceptors in a target rich environment), and the dominant variability of most signals may well be under the control of the offense. A detailed physical model of the discriminate characteristics of the threat objects should be used in the end-to-end system simulations to compare with the results of model calculations based on K-factor assumptions.

6. Background effects for SDS optical sensor from long term nuclear effects (atmospheric heave and striations) need to be the subject of further study.

Other Points

1. Some misleading answers to the discrimination problem have been proposed and must be guarded against by thorough scrutiny and independent review. Discrimination concepts that are pursued as special access (SAR) projects deserve particular attention since the review mechanism is necessarily limited. The appropriate attitude toward discrimination solutions, or toward proposed indiscriminable pen-aids for that matter, is skepticism.

2. Two areas deserving attention but which we did not have time to examine are the purported effectiveness of bulk filtering, including assuring oneself that the selected traffic balloon threat (in terms of optical and thermal characteristics) is truly stressing within the

bounds of practicality, and the availability of real time data processing to support the implicit SDS requirements.

3. Since dust interactive discrimination might be the ultimate discrimination fallback for SDS phase 1, there should be a small program on dust dispensing and analysis of engineering concepts.

XII. Recommendations

A fairly large number of recommendations have emerged from our study. However, we are reluctant to offer a menu of these of daunting length and detail, and instead direct the reader to the preceding conclusions where most are evident. There are some recommendations, though, which represent the actions we feel are crucial, and these are distilled below.

1. There must be an explicit, integrated SDI discrimination program and plan which describe the major technical discrimination questions that require answers and the steps that will be taken to provide those answers, plus information on schedule, funding, and management. Because of the SDC's experience and program base, responsibility for the national SDI discrimination program would be sensibly placed with SDC. We believe that SDC should undertake to persuade the director of SDIO of the need for such a program and the appropriateness of SDC as its leader. We think SDC can best make its case by preparing a strawman national discrimination plan to illustrate to the director the concept and the magnitude of the effort, and to demonstrate SDC^{f}s understanding and initiative.

2. Some evangelism will be required to make the SDS phase 1 developers understand that the pace and funding of the aggregate discrimination effort is not in keeping with the fundamental nature of the problems faced by SDS: the paucity of optical data and the history of still unresolved surprises, the time that will be required to prepare and carry out some of the important discrimination measurements, and the likely magnitude of the Soviet countermeasures response. We recommend SDC undertake that role.

3. To provide focus and explicit objectives for the discrimination program, the DAB Milestone 1 implementing directive should establish the minimum criteria that the discrimination program should meet to support a Milestone 2 development decision. An example of such criteria are in the body of the text in Section X.

4. In addition to orbital and full range tests, the field experiment and test program for discrimination should contain (1) a frequent series of sounding rocket-based measurements as the best timely means of identifying and resolving current questions, which include the behavior of optical emissions of test targets, thermal shroud effectiveness, aerosol dispensing, decoy dispensing techniques and motion damping, and the robustness of phase derived range, and (2) one or more flights of a subscale Soviet bus simulator to validate our engineering model of dispensing characteristics and the impact of the thrusters on pen-aids.

5. Intelligence capabilities must be put into place so that the US can monitor (1) Soviet bus characteristics and dispensing actions, and (2) the details of the ballistic test flights on the Soviet inland range.

Glossary

ARR	Attitude Rate Reducer
BMO	U.S. Air Force Ballistic Missile Office
CONUS	Continental United States
CSO	Closely-spaced Objects
DAB	Defense Acquisition Board
DOT	Designating Optical Tracker
ERIS	Exo-atmospheric Re-entry Intercept System
FAIR	Fly-along Infrared
GBR	Ground-based Radar
GSTS	Ground-based Surveillance and Tracking System
HOE	Homing Overlay Experiment
ICBM	Intercontinental Ballistic Missile
IPP	Impact Point Prediction
LEAD Study	Long-wave Infrared (LWIR) Exo-atmospheric Discrimination Study
LREP	Light-weight Replica Decoy
LWIR	Long-wave Infrared (when applied to BMD systems, generally refers to the band of approximately 5-30 micrometers)

MARV	Manuevering Re-entry Vehicle
MLI	Multiple Layer Insulation
MSX	Midcourse Experiment Optical
OSC	Signature Code Re-entry
RV	Vehicle Special Access
SAR	Required
SATKA	Surveillance, Acquisition, Tracking and Kill Assessment
SBI SDC	Space-based Interceptor
ARC	U.S. Army Strategic Defense Command Advanced Research Center
SDIO	Strategic Defense Initiatives Organization
SDS	Strategic Defense System
SSTS	Space Surveillance and Tracking System
TDI	Time Delay and Integration
UV	Ultra-violet

Appendix B
Looking Ahead at LWIR and Radar Sensors Technologies

Infrared Sensors

The present discussion is devoted to sensors of the SDI type. These include such instruments as SSTS, GSTS, ERIS, HEDI, BSTS, AOA and related devices. The infrared system consists of a telescope baffle, a telescope, a focal plane array, a cooling device, and electronic processing. Together, they form a system that provides a certain detection range and a discrimination potential. It is these we wish to assess in terms of the limits of the system.

The environment is a harsh one. It is space with its many background radiations, but it is also space with a nuclear environment that requires extraordinary measures for survivability. We need to consider: the capability of the detectors, the telescope systems, stray light rejection and size.

It would appear that in the near future detector arrays can be made with large numbers of elements all of which are photon noise limited. The present situation is that detectors can be made with almost any small degree of internal noise. Examples are doped silicon detectors, used for systems like SSTS. The limit is how cold the array needs to be made. The present limitation in the noise domain then is the amount of stray light that gets to the focal plane and the sampling noise. The present limit on this noise is approximately 100 electrons per sample. Samples must be rapid in order to discriminate against the nuclear radiation pulses. The next limit is sunlight and earthshine scattered onto the focal plane by way of the mirrors and baffles of the telescope. There are design stratagems for reducing these effects, but they entail tradeoffs. The mirror material that is most immune to the ravages of nuclear radiation is beryllium. Unfortunately, beryllium does not take as good a polish as the more conventional materials. There are developments afoot to reduce the heating and film-spoiling effects of the radiation, and comparable activities in refining beryllium. Thus, the devices which have space as a background and no atmospheric paths, with their attendant path radiation, can be improved by improving the mirror materials and coatings and the sampling noise. Of course, the advent of bigger arrays will help as well. There are other alternatives in this area of application. They include, as indicated, the use of a larger number of detectors, but such increases are limited by scanning techniques and the limitations of the performance of wide-angle optical systems. Designs to date seem to be limited to >10 μrad over a full field of about 20°. The required fields are larger and there must be scanning. Step scan could be used or time delay and integration. Current techniques of TDI seem to be limited to about 25 times. An additional source of noise is the radiation from the optics and the structure of the telescope. It is kept to an acceptable level by sufficient cooling.

For systems like this, the future is clear. Detector arrays can be made better if not larger. Sample noise can be reduced. Then the optics will have to be colder and the mirrors smoother - but still radhard. The optics can be made colder by straight forward but expensive and weighty engineering. The mirrors may be made better by some advances in the technology of beryllium, silicon carbide and closely related materials.

There is another entirely different route that has not been pursued very vigorously. The optics can be made much larger. Whereas the range goes as the fourth root of the noise reduction, it goes directly with the area of the collector. The issue then is to make very large optics, perhaps erectable in space, to collect enough target photons. Then the problems of sampling noise, colder optics and baffling are all ameliorated, but the construction, erection and alignment of such optics become the issues.

Other systems, like BSTS and HEDI are limited by other noises. They view, in the BSTS case, the clouds and the ground and in the HEDI case, a very hot airstream. The issues are the development of discriminants for BSTS and the development of a viable window for HEDI.

In all of these applications, information about the target characteristics is absolutely essential. As the sensitivities are increased, they can be used for additional detection range or for better discrimination by using narrower bands. But the use of more or narrower bands is useless unless the properties of the targets and the decoys are well understood. How can the wheat be separated from the chaff if we don't know what wheat and chaff look like?

William L Wolfe