Chapter 4

Status and Prospects of Ballistic Missile Defense Sensor Technology

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INTRODUCTION

Much of the public debate on ballistic missile defense (BMD) technologies centers on futuristic weapon systems such as lasers, rail guns, and particle beams. The Strategic Defense Initiative Organization's (SDIO) initial BMD system design, however, does not include any of these exotic weapons.[1] Rather, it calls for space-based interceptors (SBI) to collide with Soviet intercontinental ballistic missile (ICBM) boosters and post-boost vehicles (PBVs), and for high acceleration ground-based missiles to destroy Soviet reentry vehicles (RVs) by direct impact. The sensor systems required to detect, identify, and track up to several hundred thousand targets may be more challenging than the actual kinetic energy weapons: it may be more difficult to track targets than to destroy them, once tracked.

The technical feasibility of a first-phase deployment, then, may depend primarily on major technical advances in the areas of sensors and chemically propelled rockets, and less on the availability of rail-gun or laser weapons systems. Accordingly, this report emphasizes these more conventional technologies.

Nonetheless, the more exotic weapons technologies could become important in second-or third-phase BMD systems deployed in response to Soviet countermeasures. For example, if the Soviet Union deployed fast-burn boosters that burned out and deployed their RVs (and decoys) before they could be attacked by slow-moving chemically-propelled rockets, then laser weapons might be essential to attack ICBMs in their boost phase. These directed-energy weapons (DEW) would require even more accurate sensors, since their beams would have to be directed with great precision. Thus, the required sensor technology improvements might continue to be at least as stressing as weapons technology requirements.

Some of the major sensor and weapon components proposed by Strategic Defense Initiative (SDI) system architects for both near- and far-term deployments are listed in figure 4-1 (also see ch. 3). This chapter describes sensors; weapons, power systems, communications systems, and space transportation required to implement a global BMD system are described in chapter 5. For each technology, chapters 4 and 5 discuss:

- the type of system suggested by SDI architects,
- the technical requirements,
- the basic operating principles,
- the current status, and
- the key issues for each technology.

The systems aspects of an integrated BMD system are discussed in chapter 6. Computing technologies are discussed in chapter 8. Technologies for offensive countermeasures and counter-countermeasures are deferred until chapters 10 through 12 (as of this writing, available only in the classified version of this report).

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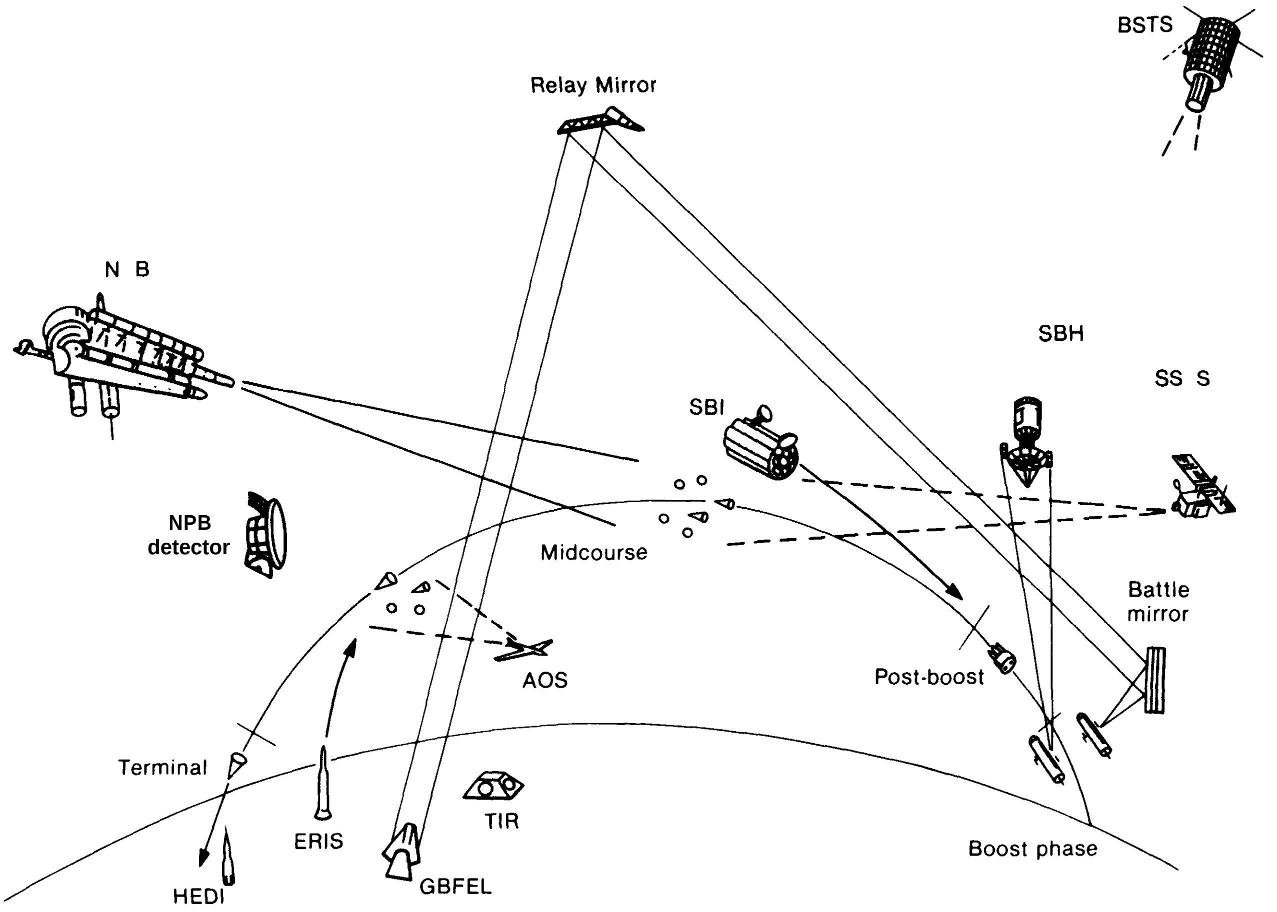
*Some BMD architecture contractors did, however, call for rather exotic beam sources for "interactive discrimination, " in which targets would be exposed to sub-lethal doses of particle beams or laser beams and their reactions measured to distinguish between reentry vehicles and decoys. See section on interactive discrimination.

Recently, SDIO officials have spoken of "entry level" directed-energy weapons that might constitute part of second-phase BMD deployments. The utility of such weapons would depend on the pace and scope of Soviet countermeasures.

Note: Complete definitions of acronyms and initialisms are listed in Appendix B of this report.

Figure 4-1—Major SDI Sensors and Weapons



SDI sensor systems:

BSTS-Boost Surveillance and Tracking System (infrared sensors)
SSTS-Space Surveillance and Tracking System (infrared, visible, and possibly radar or laser radar sensors)
AOS-Airborne Optical System (infrared and laser sensors)
TIR-Terminal Imaging Radar (phased array radar)
NPB-Neutral Particle Beam (interactive discrimination to distinguish reentry vehicles (RV's) from decoys; includes separate neutron detector satellite)

SDI **weapons systems:**

SBI-Space-Based Interceptors or Kinetic Kill Vehicles (rocket-propelled hit to kill projectiles)
SBHEL-Space-Based High Energy Laser (chemically pumped laser)
GBFEL-Ground-Based Free Electron Laser (with space-based relay mirrors)
NPB-Neutral Particle Beam weapon
ERIS-Exoatmospheric Reentry vehicle Interceptor System (ground-based rockets)
HEDI-High Endoatmospheric Defense Interceptor (ground-based rockets)

SENSORS

Sensors are the eyes of a weapons system. In the past the human eye and brain have constituted the primary military sensor system. A soldier on the battlefield would:

- look over the battlefield for possible enemy action (surveillance);
- note any significant object or motion (acquisition);
- determine if the object was a legitimate target (discrimination);
- follow the enemy motion (tracking);
- Aim his rifle (weapon direction), fire;
- look to see if he had killed the target (kill assessment); and
- if not, reacquire the target (retargeting), aim, and shoot again.

Ballistic missile defense entails these same functions of target surveillance, acquisition, discrimination, tracking, weapon direction, kill assessment, and retargeting. BMD sensors, however, must have capabilities of resolution, range, spectral response, speed, and data storage and manipulation far beyond those of the human eye-brain system.

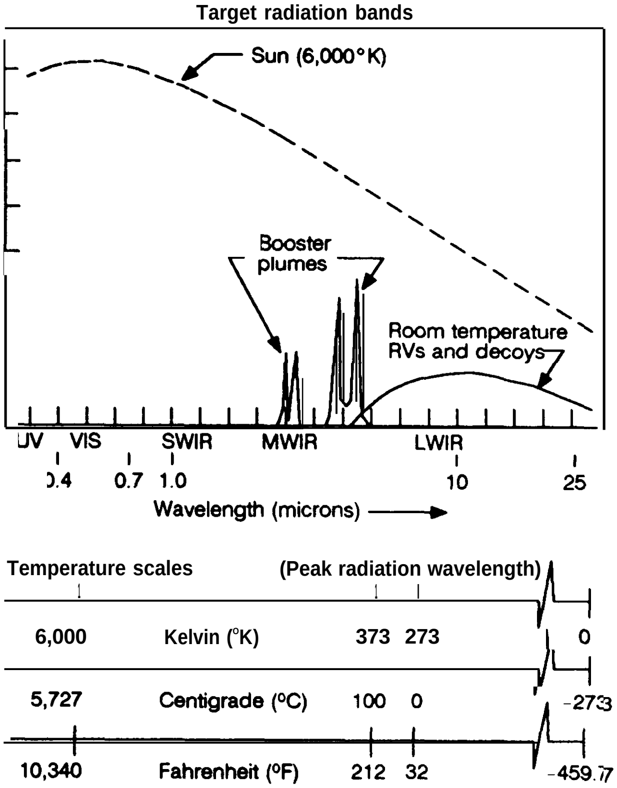
Proposed SDI Sensor Systems

The following sections describe five representative sensor systems. Most of the five SDI system architecture contractors (see ch. 3) recommended some variation of these sensor systems. The primary attack phase and recommended sensor platforms for each type are summarized in tables 1-1 and 1-2.

Boost Surveillance and Tracking System (BSTS)

The BSTS would have to detect any missile launch, give warning, and begin to establish track files for the individual rockets. Most system architects proposed a constellation of several satellites in high orbit.

Figure 4-2.-Relatlons Between Temperature and Electromagnetic Radiation



Very hot sources such as the sun radiate primarily in the visible portion of the spectrum. The hot exhaust gases from missile booster engines radiate primarily in the short and mid-wave infrared (SWIR & MWIR), while colder bodies such as reentry vehicles, the booster body, and the earth radiate at much longer wavelengths in the infrared (LWIR). Therefore different sensors would be required to detect different targets.

Typical BSTS characteristics are summarized in the classified version of this report. Each BSTS would carry a sensor suite that would monitor infrared (IR) emissions from the rocket plumes (see figure 4-2). From their very high altitude, these sensors would have relatively poor optical resolution. Track files could be started, but the Space Surveillance and Tracking System (SSTS) or other sensors at lower altitude might be required to achieve the track file accuracy needed for some BMD functions.[2]

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[2] Space-based interceptors (SBIs), formerly called “space-based kinetic kill vehicles” (SBKKV), which have their own horning sensors, could operate with the resolution given by a BSTS sensor.

b rv d g m BS S D g b m
BM b w p m m CBM w m b m
m d g g m g S b
m A BS S mg m d m g g
b m g m m g

Space Surveillance and Tracking System

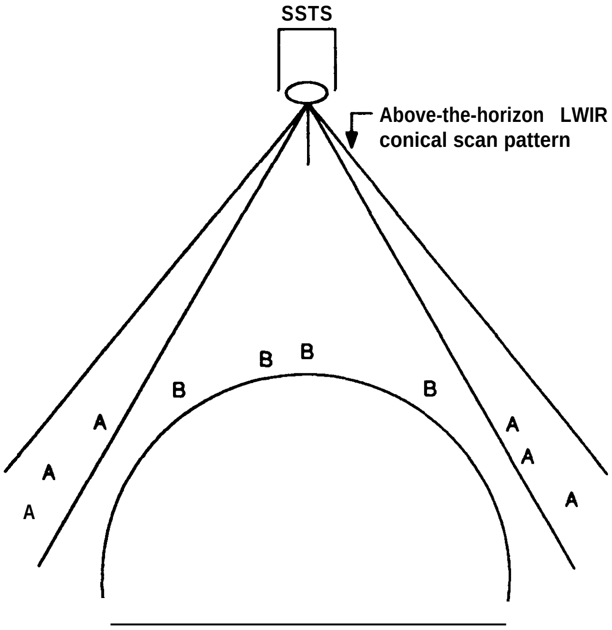
For the equivalent of an SDIO phase-two BMD system all five system architects proposed some type of SSTS at lower altitudes to furnish finer resolution missile tracking and to detect cold RVs and warmer post boost vehicles PBVs against a space background Most of the SSTSs would be out of range for observing Soviet ICBM launches at any given time Therefore several tens of SSTS satellites would be needed to provide continuous redundant coverage of the missile fields which also would supply adequate coverage around the world for submarine-launched missiles.[3] Redundancy would be necessary for survivability and for stereo viewing of the targets. These SSTS satellites might be essential for much of the mid-course battle, so some SSTSS must survive at most locations.[4]

The SSTS satellites would carry one or more long-wave infrared (LWIR) sensors for tracking the somewhat warm PBVs and cold RVs. These LWIR sensors could not detect RVs by looking straight down against the relatively warm earth background. Rather, they would look only above the horizon, in a conical or "coolie hat" pattern which would afford the necessary cold space background for the IR detectors. Thus each SSTS would monitor targets that were far from the satellite. Those targets closest to each SSTS would pass below its sensors, undetected; they would have to be observed by more distant SSTS satellites (see figure 4-3). This problem could be alleviated if sensing at other wavelengths, e.g., in the visible range, were to be feasible.

For some missions, such as cueing DEW sensors, the SSTS might include short-wave infrared (SWIR) and medium-wave infrared (MWIR) sensors to track booster exhaust plumes. This would duplicate to some extent the BSTS function, but with much better resolution.[5] These sensors might have limited fields of view, so that each SSTS platform would require several IR sensors to cover all the threats. These SWIR/MWIR sensors could look down against the Earth background, since they would be monitoring the hot plumes.

Several architects recommended placing laser systems (and some suggested microwave radars) on the SSTS. Lasers might be needed to designate or illuminate targets for homing space-based interceptors (SBIs). Laser radar (Ladar) systems might be required for all of the interactive discrimination systems, just to determine the target's position with sufficient accuracy. This would be particularly true for tracking cold RVs, which could be passively detected mainly by LWIR sensors with inherently poor resolution,[6] or for discriminating and designating an RV in the presence of closely spaced objects (that often are decoys). In any case, a laser radar could supply the range to the target, which is necessary to generate three dimensional track files from a single platform.

Figure 4-3. -Scanning Pattern for Satellite Sensor



"Collie hat" above the horizon scan pattern for the LWIR sensors on the SSTS which could *only* detect the cold RV's against the cold background of space. The targets labeled "A" could be detected by this SSTS platform, whereas the closer targets labeled "B" could not be detected against the warm earth background. These "B" targets would have to be tracked by another, more distant SSTS satellite.

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[3] More recent SDI studies have recommended fewer satellites.

[4] Alternatively, pop-up IR probes on ground-based rockets could observe the midcourse battle. These probes would have to be based at high latitudes to get close enough to observe the beginning of mid-course missile flight. Otherwise, they could be based in the northern United States to view the late mid-course.

[5] An SSTS could not achieve the pointing accuracy needed by DEW satellites; each DEW platform would have to carry its own high-resolution optical sensor. An SSTS constellation might aid the battle manager in designating targets for DEWS.

[6] The resolution angle of a sensor is directly proportional to wavelength; long wavelengths such as LWIR produce large resolution spots in the sensor focal plane, or large uncertainty in the target's location. Therefore shorter wavelength laser radars may be needed to accurately measure target position.

The SSTS might also carry some battle management computers, since the SSTSS would be above the battle and to some extent less vulnerable than lower altitude weapons platforms, and because they would generate most of the track-file information essential for assigning targets to weapon platforms.

The SSTS originally conceived by the system architects for ballistic missile defense now appear too complicated, too expensive, and possibly too far beyond the state of the art of sensor technology for deployment in this century. As a result, there was some discussion in late 1986 and early 1987 of launching early SBIs without any SSTS sensor, placing minimal sensor capability on each SBI carrier vehicle instead. There would probably be no sensor capability enabling SBIs to kill RVs in mid-course.

The phase-one architecture submitted to the Defense Acquisition Board in June and July of 1987 was vague about mid-course sensors: there was a “Midcourse Sensor” (MCS) program, but no system concept. The MCS might consist of SSTS sensors, or ground-based surveillance and tracking (GSTS) rockets or “probes,” or SWIR/MWIR (or other) sensors on some of the kill vehicle carrier satellites. These sensors would apparently locate targets for the ground-based exe-atmospheric reentry vehicle interceptor system (ERIS) interceptors. More recently, an MCS study proposed a combination of the three sub-systems.

The SDIO ended development work on the original SSTS program and let new contracts in mid-1987 to design a less complex SSTS system. The classified version of this report contains the range of parameters specified by the original, more comprehensive system architectures. The new designs could not by themselves furnish precise enough data to direct SBIS to RV targets.

Airborne Optical Adjunct (AOA)

The AOA would test technology for a new sensor addition to terminal defensive systems. The SAFEGUARD BMD system, operated in partial form in the 1970s, relied exclusively on large, phased-array radars to track incoming warheads. There were no optical detectors, The resolution and range of these ground-based radars was adequate (assuming they survived) to direct nuclear-tipped Spartan and Sprint missiles to the general vicinity of target RVs. Such radars would not be adequate as the only guidance for the non-nuclear, hit-to-kill vehicles proposed for SDI: these interceptors would require on-board homing guidance systems.

The AOA would test LWIR technology similar to that in the SSTS program, but deploy it on an aircraft flying over the northern United States. The sensor system has been designed and is being fabricated. Above most of the atmosphere, this sensor could look up against the cold space background and track RVs as they flew through mid-course. Resolution would be relatively coarse: a follow-up system based on this technology might eventually be able to direct ground-based radars, which in turn would hand target track data over to high speed hit-to-kill projectiles. These projectiles would derive their final target position from on-board homing sensors. The AOA aircraft might also include laser range-finder systems to supply accurate estimates of the distance to each target-and possibly to discriminate

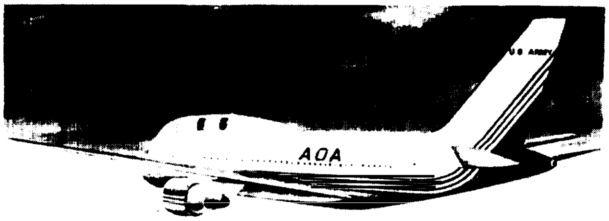

Photo credit: Strategic Defense Initiative Organization

Airborne Optical Adjunct (AOA)

In a strategic defense system, airborne sensors might be used to help identify and track targets and to guide ground-based interceptors to them. The AOA will validate the technology to acquire targets optically at long ranges, and to track, discriminate and hand data over to a ground-based radar. It will also provide a data base that would support future development of airborne optical systems. Sensors have been fabricated and tested and test flights will take place soon. The model shows the sensor compartment on top and the crew stations in the interior of the aircraft.

decoys from RVs by measuring minute velocity changes caused by drag in the upper atmosphere.

System architecture contractors proposed tens of AOA-like aircraft as part of a sensor system. Some proposed rocket-borne, pop-up probes with LWIR sensors for rapid response in a surprise attack until the aircraft could reach altitude.

There is some uncertainty regarding the infrared background that an airborne sensor such as AOA would see. Sunlight scattered from either natural or (particularly) man-made "noctilucent clouds" might obscure the real RV targets. These clouds form at altitudes from 60 to 100 kilometers (km). During a battle, the particles ablating from debris reentering the atmosphere would form nucleation centers. Long-lived ice crystals would grow at these centers, possibly creating a noisy infrared background that would obscure the real targets arriving later. Intentional seeding of these clouds is also a possibility.[7]

Ground-Based Radar (GBR)

Large phased-array, ground-based X-band (8-12 GHz frequency) radars might work in conjunction with optical sensors to track and discriminate incoming warheads from decoys. These radars could receive target track data from those sensors and then use doppler processing to create a pseudo-image of the warheads by virtue of their spinning motion. Nonrotating decoys or decoys with different shapes or rotation rates would produce different radar signatures.

Ground-based radars would also measure the effects of the atmosphere, identifying light decoys that would slow down more than the heavy RVs. These radars might guide or cue the endoatmospheric HEDI and FLAGE-like interceptor rockets and the ERIS exoatmospheric interceptors (see ch. 5).

The GBR concept very recently supplanted the proposed Terminal Imaging Radar (TIR) system in SDIO planning. The latter would have had a much shorter range (thereby not being useful for cueing the ERIS interceptor) and much less resistance to anti-radar countermeasures, such as jamming. Some radar concepts call for deployment on railroad cars to evade enemy attack.

Neutral Particle Beam (NPB) Interactive Discrimination

While several interactive discrimination techniques have been proposed (see section below on interactive discrimination), the NPB approach has thus far received the most attention and development funds.

A series of full space-based tests was planned for the early 1990s, but has been subjected to budgetary cutbacks. A 50-MeV[8] NPB source was to be placed in orbit along with a sensor satellite and a target satellite to measure beam characteristics and to begin interactive tests. The primary detection method would be to monitor the neutrons emmitted by the target after irradiation by the NPB, although gamma rays, x-rays, and ultraviolet radiation might also be useful for indicating whether targets had been hit by the neutral particle beam. The NPB accelerator might be located 1,000 km from the target. The neutron detectors might ride on separate detector satellites closer to targets, although they could be collocated on the NPB platform under some circumstances. A single NPB discrimination accelerator system might weigh 50,000 to 100,000 kilograms (kg), making it the heaviest element proposed for a second-phase BMD.[9] Over 100 NPB satellites and several hundred neutron detector

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[7] See M.T. Sandford, II, *A Review of Mesospheric Cloud Physics,* Report No. LA-10866 (Los Alamos, NM: Los Alamos National Laboratory, October 1986.)

[8] The energy of a beam of particles is measured in "electron volts" or "eV," the energy that one electron would acquire traveling through an electric field with a potential of one volt. The energy of beam weapon particles would be so high that it is measured in millions of electron volts, or "MeV." One MeV is equal to 1.6×10^{-13} joules; each particle carries this amount of energy.

[9] A far-term, robust BMD system might also include very heavy directed-energy weapons.

platforms might be required for a global discrimination system.[10]

Sensor System Requirements

Technical requirements for BMD sensors are discussed below for each sensor function: surveillance, target acquisition, identification, tracking, and kill assessment.

Surveillance and Target Acquisition Requirements

A surveillance and target acquisition system would have to detect the launch of any missile, either ground-based or submarine-based, and render accurate positional information to the BMD weapon system. Some SDI weapon systems would require very high resolution sensors. A laser beam, for example, would have to be focused down to a spot as small as 20 to 30 cm in diameter to produce the lethal intensity levels for projected hardened missiles.[11] A DEW sensor must therefore determine the missile location to within a few tens of cm so as to keep the laser focused on one spot on the target.

As an illustration of what is practical or impractical, note that if the sensor were placed in geosynchronous orbit at 36,000 km, just a few sensor satellites could survey the entire earth. But at this high altitude the sensor's angular resolution would have to be better than 8 nanoradians, or one part in 125,000,000.[12] This high resolution is clearly beyond the realm of practical sensor systems.[13]

Resolution improves directly with reduced distance to the target. Therefore a reasonable alternative-one being examined-would be to place many sensor satellites at lower altitudes. Even a constellation of sensor satellites at altitudes around 4,000 km would not be adequate for directed energy weapons: positional uncertainties for sensor satellites combined with vibration and jitter would preclude the transmission of target positions to weapon platforms with 10-cm accuracy. Therefore each DEW satellite would need its own sensor to provide the final pointing accuracy. Sensor satellites might supply broad target coordinates to each weapon platform.

Homing kinetic energy weapons (KEW) would require less accurate information from a remote sensor: a homing sensor on an SBI itself would give the fine resolution needed in the last few seconds to approach and collide with the target. Still, the SBI must be fired toward a small volume in space where the intercept would occur several hundred seconds after it had been fired. The sensor system must locate each target in three dimensions.

Target Identification or Discrimination Requirements

Ballistic missile defense (BMD) sensors would not only have to detect missile launches, but they would also have to identify targets. Identification requirements would vary considerably during missile flight. During the boost phase, a sensor would first distinguish between missile exhaust plumes and other natural or man-made sources of concentrated heat. Given adequate spatial resolution, a smart sensor with memory could separate moving missiles from stationary ground-based sources of heat. The location of the missile launcher and the missile's dynamic characteristics (acceleration and burn time for each stage, pitch ma-

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[10] Between 100 to 200 flights of the proposed Advanced Launch System (ALS) might be required to lift a full constellation of 100 NPB discriminators into space. For a discussion of the number of elements in a useful NPB system, see American Physical Society, *Science and Technology of Directed Energy Weapons: Report of the American Physical Society Study Group,* April 1987, pp. 152 and 335.

[11] For example, a 90 MW laser operating at one micrometer (μm) wavelength would require a mirror as large as 10 m in diameter to achieve the very high brightness 10^{21} W/sr) required to destroy hardened (i.e., able to resist 20 KJ/cm^2) targets. A 10 m mirror would would project a 20-cm diameter spot at 2,000 km or 40 cm at 4,000 km, which are typical ranges for the proposed directed energy platforms. See chapter 5 on directed energy weapons for more details.

[12] One radian is equal to 57.3 degrees; one nanoradian is 1x10^{-9} radian or one billionth of a radian.

[13] For example, even an ultraviolet sensor, which would have the best resolution due to its short wavelength, would require a 45-m diameter mirror to achieve 8 nanoradian resolution.

neuvers, stage separation timing, etc.) should permit identification of missile type and probable mission. Eventually a low altitude sensor would have to identify the booster body (as opposed to the hot plume), either by geometric extrapolation or by generating an IR image of the booster tank.[14]

The post-boost phase is more complicated. Most missiles carry a PBV or "bus" which may include 10 or more individual warheads in RVs. These RVs are individually aimed at separate targets: the PBV maneuvers and mechanically ejects each RV, one at a time, along a different trajectory. A BMD sensor system might detect heat from a PBV propulsion system as it made these multiple maneuvers. However, PBV propulsion energy is far less than main booster engine energy, making tracking (at least in the SWIR/MWIR range) more difficult in the post-boost phase. Once ejected, cold RVs would be even more difficult to detect and track.[15]

This reduced signal level could be partially offset by arranging the sensor satellite to view its targets against the cold space background instead of the warm and noisy Earth background, as in the boost phase. The sensors would have to look above the horizon, generally limiting detection to distant targets over the Earth's limb. ***Since*** detection becomes more difficult at longer ranges, this above-the-horizon (ATH) detection of cold RVs would be more difficult than sensing very hot booster plumes against the earth background.

If the United States deployed a BMD system, Soviet missiles would probably disperse decoys along with nuclear-armed RVs. Decoys might be simple, aluminum-covered balloons weighing 1 kg or less, or they might be somewhat more sophisticated decoys shaped like an RV with similar infrared and radar signatures. Simple decoys might be tethered to an RV within a few tens of meters: defensive sensors would then require higher resolution to separate decoys and RVs. Alternately, an RV could be placed inside a large balloon, a technique known as "anti-simulation": the RV is made to look like a decoy.

The most sophisticated decoys, called thrusted replicas (TREPs) might even have propulsion so they could push into the atmosphere during reentry to simulate the heavy RV's reentry characteristics. The total post-boost and mid-course threat cloud could contain something like 10,000 RVs, hundreds of thousands of decoys, and thousands of burnt-out rocket stages and PBVs, all traveling through space at 7 km/s. In the same trajectories might be literally millions of fragments from boosters destroyed by SBIs in the boost and post-boost phases.[16]

In principle, a BMD weapons system could fire at all of these objects, but the costs would be prohibitive. Therefore the sensors for a second- or third-phase BMD system with mid-course capability would have to *discriminate* effectively between RVs and the many decoys and debris.

In the post-boost phase, there would be some basis for discrimination. A sensor could, in theory, monitor PBV motion during deployment of RVs and decoys. Decoys would produce less PBV motion than the heavier RVs as they were ejected from the PBV. This distinctive motion might be detected, assuming that the Soviets did not cover the PBV with a shroud to conceal the dispersal of decoys, or that they did not appropriately alter the thrust of the PBV as its RVs dispersed.

In the mid-course phase, discrimination would become even more difficult. All the objects would travel together in a ballistic, free-fall flight. Light decoys would not be slowed down by atmospheric friction until they descended to the 100-150 km altitude range—the same altitude range that constrains deploy-

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[14] A booster body, at 3000 K is cold compared to its hot plume, but it is still warmer than the cool upper atmosphere at about 2200 K. An LWIR sensor could therefore image the booster body against the Earth background at fairly long ranges, using wavelengths which were absorbed by the upper atmosphere.

[15] ICBM boosters typically radiate millions of watts per steradian (W/sr), PBVs hundreds of W/sr, and RVs a few W/sr. (A "steradian' is the measure of a solid angle, defined as the ratio of the surface area subtended by a cone divided by the square of the apex of that cone.)

[16] See chapter 10 for details on countermeasures to BMD.

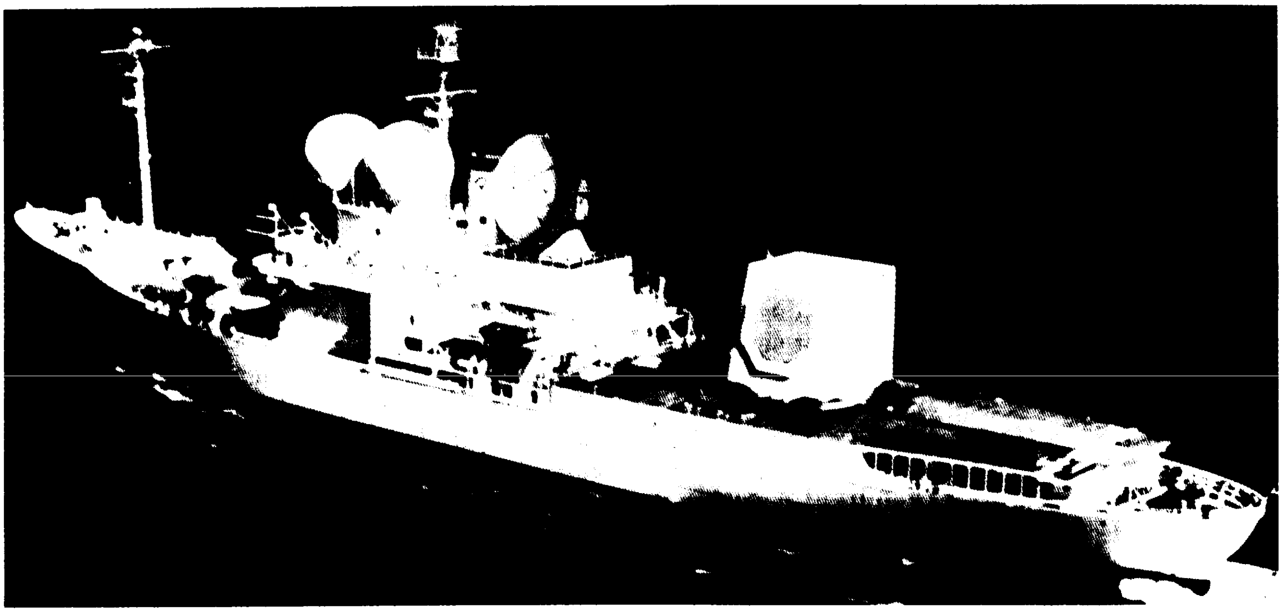


Photo credit: U.S. Department of Defense

COBRA JUDY Radar

A new radar had been developed and installed on the COBRA JUDY ship. This improves the capability of the U.S. for making measurements on reentry vehicles in flight.

ment of rising decoys in the post-boost phase. If decoys had the same signatures or characteristics of RVs as seen by conventional infrared and radar detectors, then conventional discrimination of RVs from decoys would become extremely difficult. Mid-course discrimination is one of the most crucial challenges facing the SDI technology development program.

The BMD sensors would also have to detect and track defense suppression threats such as direct-ascent anti-satellite (DAASAT) missiles or space-based ASATs which might attack BMD defensive assets in space. The sensors should therefore keep track of all of the BMD weapons platforms in a given battle space, allowing the battle manager to determine which objects were likely targets and which weapons should engage the threat.

Target Tracking Requirements

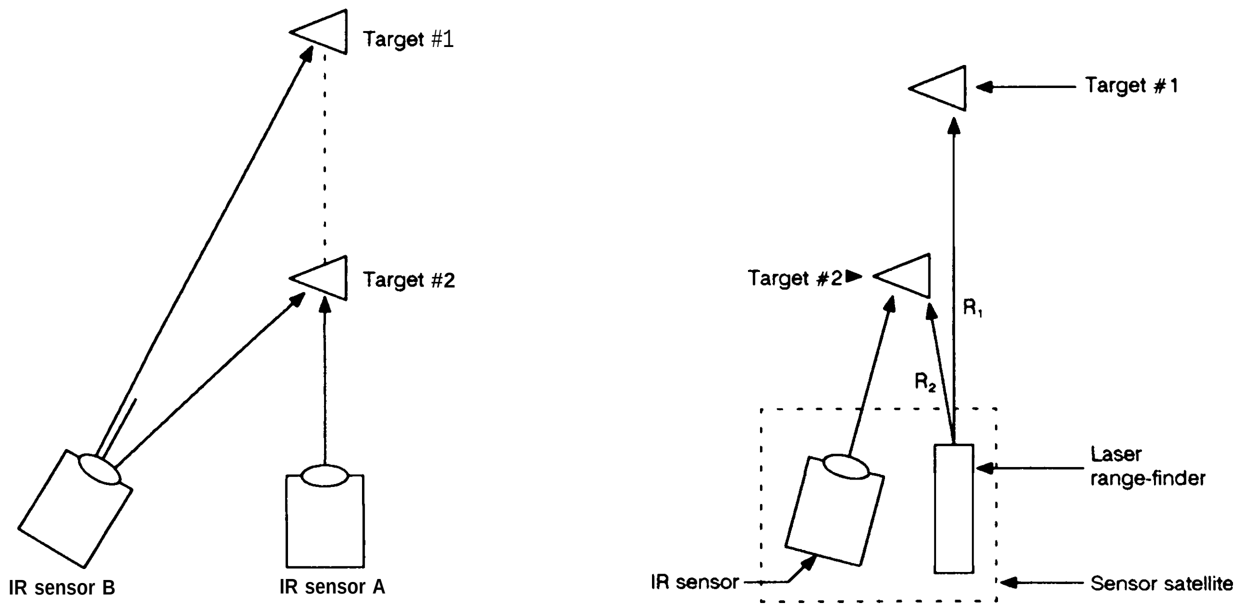
Passive IR sensors on a single BSTS or SSTS satellite could only measure the target position in two angular coordinates. Each target must be located in three dimensions to allow the battle management computer to calculate the expected collision point of weapon and target.

Three techniques could furnish three dimensional data: stereo imaging, ranging, or ballistic trajectory prediction (see figure 4-4). Two or more separated sensor satellites could generate stereo data. This would require a computer to correlate data from multiple sensors and could become very complicated with 40 or 50 sensors generating data from thousands or hundreds of thousands of targets.

Alternatively, a laser range-finder and a passive IR two-dimensional imager together on one satellite could generate three dimensional information. A laser range-finder would determine the distance to the target. With a direct, one-to-one correlation between two target angles from a passive sensor and a third range coordinate from a laser, computational requirements would be reduced by eliminating the need to correlate data from separate platforms.

Finally, for objects traveling in space on a ballistic, free-fall trajectory, Kepler's equations

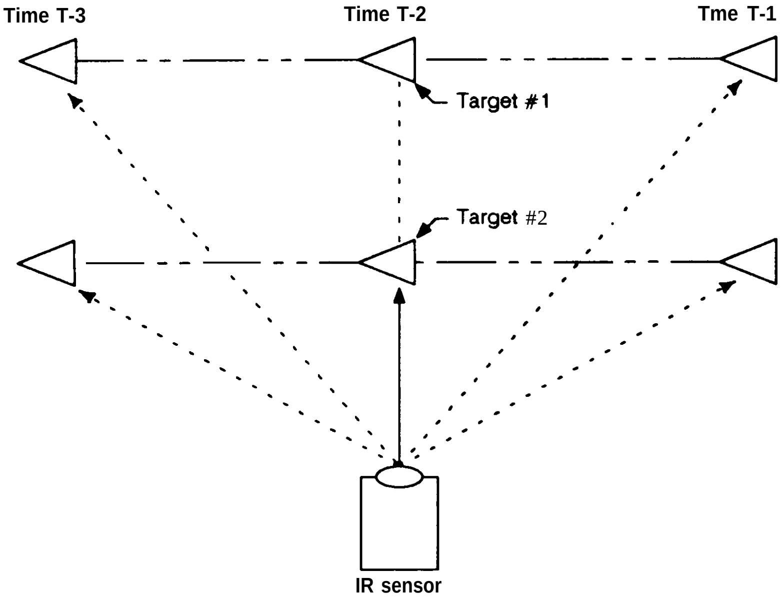
Figure 4-4. - Illustration of Three Techniques for Estimating the Three-Dimensional Position of a Target in Space



Stereo viewing

IR angle/angle plus range finder

Ballistic trajectory estimation (from one passive sensor)



In the first view Sensor A **could not distinguish between Target # 1 and Target #2. Stereo viewing from two or more separate satellites with passive IR sensors eliminates this ambiguity. Relatively complicated software is required to correlate data from each sensor. The other two techniques can predict three dimensional information from one platform, eliminating the requirement for multiple satellite sensor data correlation; a laser range finder determines the range or distance to a target by measuring the travel time for a pulse of light from the platform to the target and back, uniquely determining position with one measurement. The ballistic trajectory prediction approach uses only the passive IR sensor, but requires three or more measurements at different times to compute the target's path through space.**

of motion may be applied: a passive sensor could determine the path of an RV in three dimensions by measuring its two-dimensional position three or more times. This trajectory prediction approach requires more time (hundreds of seconds) to build up an accurate track: this would be adequate for the mid-course phase. It would require more data storage and processing than the laser range-finder technique, but only one passive sensor.

Kill Assessment Requirements

Sensors would also have to determine whether a missile or RV had been disabled or destroyed. Missed targets would have to be retargeted, and disabled targets should be ignored throughout the remainder of the battle. Kill assessment should be straightforward for most KEW projectiles, since their impact would smash targets into thousands of pieces. However, some SBIs might partially damage a booster by clipping anon-critical edge, leaving the bulk of the missile intact. In this case the sensor might judge a missile "killed" if it veered sufficiently off-course to anon-threatening trajectory.

Damage to targets attacked by laser or particle beam weapons might be more difficult to diagnose. A laser beam might conceivably burn through a critical component without detectable damage, yet divert a missile from its intended course. More likely, the laser would disintegrate the missile body, which is highly stressed during acceleration—as demonstrated by a ground-based high-energy laser test at the White Sands Missile Range.[17]

Damage due to particle beams or electron beams might be more difficult to detect. Neutral particle beams, for example, might penetrate several cm into a missile or RV, destroying critical electronic components without any apparent external damage. An RV might be effectively "killed" with respect to its mission at much lower particle beam energy than that necessary to show detectable damage.

On the other hand, NPB system designers could increase particle beam fluence to levels that would assure electronics destruction (say 50 joules/gram (J/g) —only 10 J/g destroys most electronics) as long as the target were hit. Kill assessment would then become "hit assessment": if the beam dwelled on the target long enough to impart 50 J/g, then the electronics could be judged "killed." With this approach, NPB weapons would be effectively lethal at lower energy levels than that needed for melting aluminum or causing structural weakness (500 to 1,000 J/g). Relying on this indirect kill assessment would require confidence that the Soviets had not shielded critical internal electronic components from NPB radiation.

Table 4-1.—Summary of Typical Sensor Requirements

Surveillance:		
Coverage	**Global**	
Targets	**ICBM's, SLBM's, direct ascent ASAT's, space mines, and one's own BMD assets, including all sensor and weapons satellites and launched SBIs**	
Target Discrimination:		
Boost Phase	**ICBM/SLBM/DANASAT**	
Post-boost & mid-course	**PBV, RV, light decoy, replica, thrusted replica, & debris**	
Terminal	**RV & thrusted replica**	
Tracking:		
Targets	**ICBM's**	**1,400-2,000**
	SLBM's	**1,000-1,500**
	DANASAT's:	**1,000-16,000**
	PBV's	**2,400-3,000**
	RV's	**8,000-15,000**
	Decoys	**hundreds of thousands**
Track file	**position, velocity, & acceleration in 3-D**	
Kill assessment:		
KEW	**destruction**	
Laser	**destruction**	
NPB	**hit assessment or other**	

SOURCE: Office of Technology Assessment, 1988.

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[17] The mid-range infrared advanced chemical laser (MIRACL) at White Sands Missile Range in New Mexico was aimed at a strapped-down Titan missile second stage. The missile was mechanically loaded with 60 psi of nitrogen gas to simulate the 4-g load and propellant conditions that it would experience in an actual flight. After approximately 2 seconds of exposure to the laser beam, which had a power greater than 1 megawatt, the Titan booster completely ruptured, shattering into fragments as heating of a roughly 1 m^2 area destroyed the mechanical integrity of the booster skin.

Sensor Technology

Three types of sensors might satisfy portions of these BMD requirements: passive, active, and interactive. Passive sensors rely on natural radiation emitted by or reflected from the target. Active sensors, such as radars, illuminate the target with radiation and detect the reflected signal. "Interactive sensors" (a term unique to the SDI) would use a strong beam of energy or cloud of dust-like particles to perturb targets in some measurable way (without necessarily disabling it) so that RVs could be discriminated from decoys. For example, the cloud might slow down light decoys much more than heavy RVs, or penetrating particle beams might create a burst of neutrons or gamma rays from RVs but not from balloons.

Passive Sensors

How Passive Sensors Work.—Passive sensors detect military targets either by measuring their natural emission, or by detecting natural light reflected from the targets. A typical sensor is similar to an ordinary camera. An optical element (the lens) forms an image, and alight sensitive surface records that image (the film).

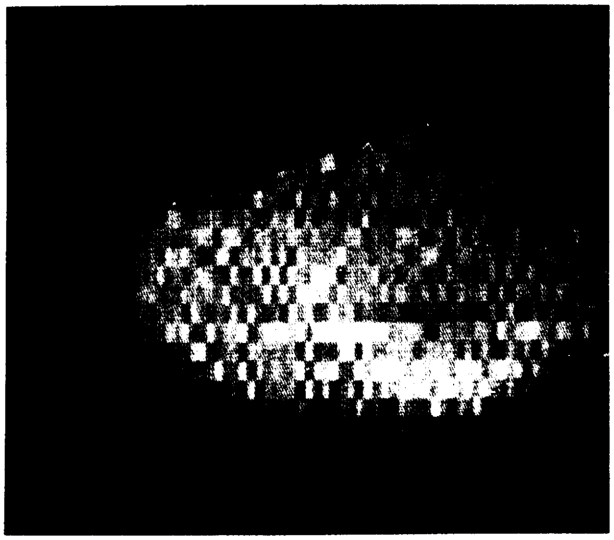

Photo credit: U.S. Department of Defense, Strategic Defense Initiative Organization

Infrared image of the moon from SDIO's Delta 181 experiment. That experiment took measurements of a rocket booster and other objects in space to gather information about the kinds of sensors that would be needed in a space-based ballistic missile defense system. This may be the first long-wave infrared image acquired from a platform in space.

In BMD infrared sensors, the optical lens would be replaced by a system of reflecting mirrors and the camera film by an array of discrete optical detectors in the focal plane which convert the optical image into electronic signals for immediate computer processing. Many detectors are required to record a detailed image. In a sense each detector substitutes for one grain of photographic film. Some sensors use a stationary two-dimensional "staring" array of detectors, in direct analogy to photographic film. Others mechanically scan the image across an array of detectors that may be either two-dimensional or linear.

Infrared Sensors.–Ordinary photographic cameras record the visible light reflected from a scene. For BMD, the IR energy emitted by the target (particularly the hot exhaust gases ejected from a missile booster engine) is abetter source of information.[18] The sensor images the infrared radiation from the target and background onto a photosensitive array of detectors. These detectors generate a series of electrical signals that are processed by computers to detect and track the target.

There are three distinct target classes for the BMD mission: missiles with their rocket engines firing, post-boost vehicles with much lower power engines, and cold objects such as RVs and decoys in space." Each type of target demands different IR sensors. Hot exhaust gas from a booster engine radiates primarily in relatively narrow bands of short wavelength IR. The exact wavelength of this radiation is

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[18] All objects with a temperature above absolute zero(–273 C) emit energy in the form of electromagnetic waves, such as light waves, infrared waves, microwaves, etc. For example, the human body continuously radiates infrared waves. To an infrared camera, we all "glow in the dark": our bodies would be recorded on infrared film as a group of "hot spots, even if the picture were taken in absolute darkness. Similarly, any target emits energy which can, in principle, be detected with appropriate sensors, provided only that the target is warmer (or colder) than the background scene.

[19] The RVs do heat up from friction as they enter the atmosphere.

determined by the particular gas constituents. The primary emission bands for gas plumes are near the water vapor and carbon dioxide lines at 2.7 micrometers[20] (in the short wave IR or SWIR) and at 4.26 µm (in the middle wave IR or MWIR).[21]

Other specific radiation lines may help identify some Soviet booster plumes: this will be investigated in the SDI research program. These plumes radiate hundreds of thousands to millions of watts per steradian (W/sr) of energy. Post-boost vehicles also have propulsion systems, but their smaller motors radiate only hundreds of W/sr.

Reentry vehicles remain near “room temperature” (20 o *C* or 2930 K) in mid-course, until they are heated by the friction of the atmosphere on reentry. The maximum radiation for room temperature objects is near 10 µm in the LWIR. Infrared detection of RVs is difficult because of their low level of radiation (typically a few W/sr) and poor contrast against the earth background. That is, the earth is also near “room temperature, ” with strong emission in the 10-pm band. An IR sensor cannot “see” a red target against a red background. The sensor would generally have to wait until the target RV was above the horizon to view it against the cold (4 o K) temperature of space. The sensor system would also have to filter out the IR energy from planets or bright stars in the field of view.[22]

The technical feasibility of detecting relatively cold RVs against a space background was demonstrated on June 10, 1984, when an LWIR sensor on board the Army’s Homing Overlay Experiment (HOE) missile successfully detected a simulated RV over the Pacific Ocean.[23] The sensor guided the HOE projectile into a collision course, destroying a target launched earlier from Vandenberg AFB in California. This test demonstrated an ability to detect and track a single approaching RV in space at relatively close range. (The initial HOE missile trajectory was specified by radar signals from Kwajalein until the missile LWIR sensor could acquire the target.)

Tracking thousands of RVs and possibly hundreds of thousands of decoys with space-based sensor satellites from distances of 5,000 to 10,000 km would be more challenging, particularly if the RVs were encapsulated in balloons and decoy balloons were tied (tethered) together or to an RV.

Three-Color Infrared Sensors.–Depending on the offense’s countermeasures, discrimination of RVs from decoys might be improved if the object temperatures could be measured accurately. Long-wave IR sensors that detect one narrow wavelength band cannot determine temperature. That is, a warm object with low IR emissivity[24] could produce the same radiance at one wavelength as a cooler object with high emissivity, as illustrated in figure 4-5. However, the shape of the blackbody (non-reflecting object) radiation curve as a function of wavelength is distinct for objects at different temperatures. This suggests that two or more LWIR sensors operating at different wavelength bands within the 8- to 24-µm region could estimate the temperature ofµpace objects, independent of their general emissivities.

Most SDI architects recommended three-color LWIR detectors to measure energy in three separate wavelength bands or “colors.” Note that this complicates sensor design and

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[20] One micrometer (µm) is one millionth (10 ‘o) of a meter.

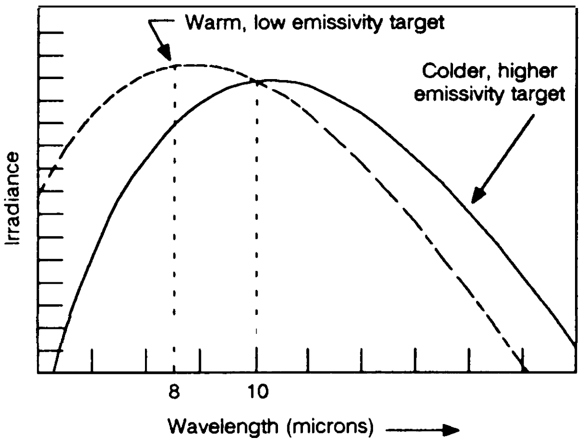
[21] Atmospheric water vapor and carbon dioxide attenuate mOSt of the IR radiation from a missile plume in the early stages of flight. However, the higher temperature and pressure of the water and CO_2 in the plume produce a broader IR spectrum than the atmospheric absorption bands. Infrared energy will therefore leak through on both sides of the 2.7 and 4.3pm lines, even from rockets close to the surface of the Earth.

[22] The Air Force has used a star as the “target” for tests of the U.S. F-15 launched ASAT, which uses a LWIR sensor to home on its target.

[23] To place this experiment in perspective, it should be noted that this RV was significantly brighter than the radiance expected from current RVs, while the Soviets may take steps to further reduce IR emissions.

[24] The emissivity of any object indicates its ability to radiate energy. Emissivity is defined as the ratio of the energy radiated at any wavelength to the amount of energy radiated by a perfect blackbody at the same temperature. (A “blackbody” absorbs all energy reaching its surface.) Thus an object with low emissivity will radiate less energy than a higher emissivity object, even though they are both at the same temperature.

Figure 4-5.-Spectral Response of Two Objects at Different Temperatures



One LWIR sensor measuring only the 10 micron energy would record the same signal intensity for both targets; they could not be distinguished. The different temperatures can be detected by adding a second color measurement at 8 microns, revealing more of the shape of the spectral emission curves. Three-color LWIR sensors are recommended for even better temperature discrimination capability.

construction. Each "pixel" must be measured by three different detector elements. Detector manufacturing and signal processing tasks are increased.

Cooling.—If an LWIR camera were operated at room temperature, then the entire camera enclosure would radiate LWIR energy and fog the film or saturate the IR detectors with noise. Sensitive IR cameras must therefore be cooled to reduce stray radiation. In particular, the mirrors that form the IR image must usually be cooled to keep IR noise generated by mirror radiation small compared to other background radiation. Cooling further complicates the task of building large, light-weight mirrors for space-based sensors. The degree of cooling necessary depends on the temperature and radiation levels of the expected targets.

Some detectors themselves must also be cooled—typically to the range from 4° K to 78° K—to reduce the self-generated thermal noise that would mask photon-generated signals from targets of interest. One key SDI task is therefore to develop space-qualified cryogenic coolers that could operate for many years in space. The current goal is to reach life-times

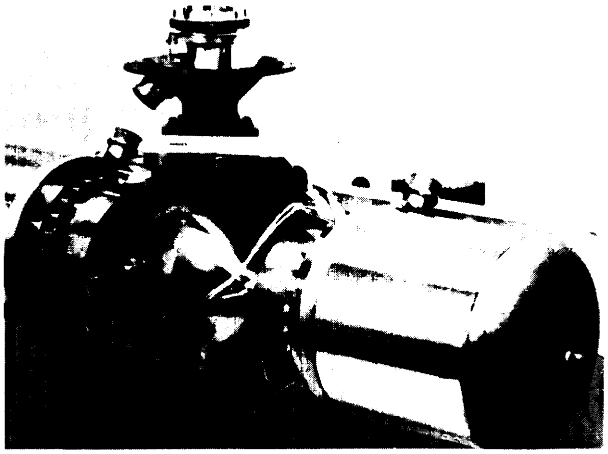


Photo credit: U.S. Department of Defense, Strategic Defense Initiative Organization

Cryocooler for space applications. Many of the advanced "heat-detecting" infrared sensors necessary to identify and track missiles and warheads in space must be cooled to work properly. Special refrigerators called cryocoolers would produce the needed very low temperatures. Cryocooler life, reliability, and performance experiments designed to demonstrate the ability to cool long-wave infrared detectors have been conducted.

of 7 years, and at least one type of cryogenic refrigerator has demonstrated this ability in accelerated life tests.[25]

UN/Visible Sensors.—Some SDI contractors have proposed the use of visible or even ultraviolet (UV) sensors, primarily to achieve better resolution with realistic optics dimensions.[26] For example, a 28-cm diameter UV mirror at 0.3 pm could achieve the same resolution as a 400-cm (4-m) diameter mirror operating at 4.3 µm. However, this gain is not free: reducing the wavelength increases the fabrication difficulty. Mirrors must be polished to within one-tenth to one-twentieth of the operating wavelength. Thus an MWIR mirror at 4.3 µm must be polished to within at least 0.43 µm of the prescribed surface figure, while a UV mirror must be polished to an accuracy of 0.03 µm or better.

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[25] Hughes Aircraft has demonstrated operation of a magnetic gas cooler system with an accelerated test simulating 7 years' life.

[26] The resolution of a sensor is limited by diffraction spreading of the optical image. This diffraction spreading is proportional to the wavelength of light used to form the image; shorter wavelengths produce less image spreading, yielding better resolution or sharper images.

Visible or UV sensors might detect energy from rocket plumes, although the visible radiation from liquid-fueled missiles is minimal. The atmosphere attenuates UV below an altitude of a few tens of km, but a post-boost vehicle propulsion system may generate adequate UV radiation. To see RVs, however, these sensors would have to rely on the reflection of natural radiation (sunlight, moonlight, or Earthlight). Alternatively, they could be used in an active mode with a laser designator illuminating the target (see next section).

Current Status of Passive Sensors.–Passive infrared sensors operate today in early warning satellites. A few satellites at geosynchronous orbit, some 36,000 km above the earth, monitor the entire globe, searching for missile launches from the Soviet land mass or from the oceans. Several heat-seeking tactical missiles such as the air-to-air Sidewinder and the ground-to-air Maverick missile also employ infrared sensors. This same sensor technology supplied the terminal guidance for two successful space hit-to-kill experiments: the anti-satellite (ASAT) experiment in which a missile fired from an F-15 aircraft destroyed a satellite in space and the Homing Overlay Experiment.

Today's operational infrared sensors have relatively small optical systems, typically 20 cm or less in diameter, and focal plane arrays of a few thousand detectors. Most detectors are fabricated from bulk silicon and could not survive in a nuclear environment. Relatively few large detector arrays are built each year, and the United States does not yet have the manufacturing technology to build large arrays economically.

Key Issues for Passive Sensors.—This report has identified five key issues for passive sensor technology development (see table 4-l). While driven by the space-based system requirements, these same sensor functions would be required for effective ground-launched weapons systems. Whether the sensors rode on airborne or space-based platforms, these issues would have to be resolved to produce a robust BMD system.

Mirror Size.—A sensor system mirror must be large to collect enough energy, to resolve closely spaced objects, and to accurately direct weapons systems (see box 4-A). The mirror size needed is determined by sensor operating wavelength, distance to target, and target positional accuracy required by the weapon system. The resolution of any optical system is given approximately by the wavelength divided by the diameter of the aperture multiplied by the range.

Typical mirror sizes for adequate spot resolution from a passive sensor at 3,000 km altitude are shown in figure 4-6.[27] To provide adequate aiming information to homing kinetic energy weapons, sensor resolutions from 10 m

Table 4-2.—Key Issues for Passive Sensors

	KEW	DEW	Current status
Mirror size (m)	about 0.1	about 1 (UV/visible)	0.1-2.4
Number of detector elements (resolution limited)			
Geo/staring	10^{6}-10^{8}	N/A	many tens of thousands
Geo/scanning	10^{4}-10^{0}	N/A	
3,000 km/staring (1 °FOV)	10^{3}-10^{5}	10’	
3,000 km/scanning	10^{3}	10^{5}-10’	
Detector manufacturing capacity	10^{8}-10^{9}/yr	10^{7}-10^{8}/yr	IO^{6}/yr
Signal processing			
Rates	10%	10^{10}/s	several x 10^{7}/s
Memory	1 X 10^{7}	1 x 10^{8}	8x 10^{7}

SOURCE: Office of Technology Assessment, 1988.

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[27] Fig. 4.6 assumes a perfect, diffraction limited optical system. In practice other factors-such as vibration, imperfect mirror quality, and thermal distortions-would degrade resolution. This figure, therefore, represents the minimum allowable mirror size for a spot. Tracking resolution may only require mirrors a factor of 10 smaller, as noted in the text.

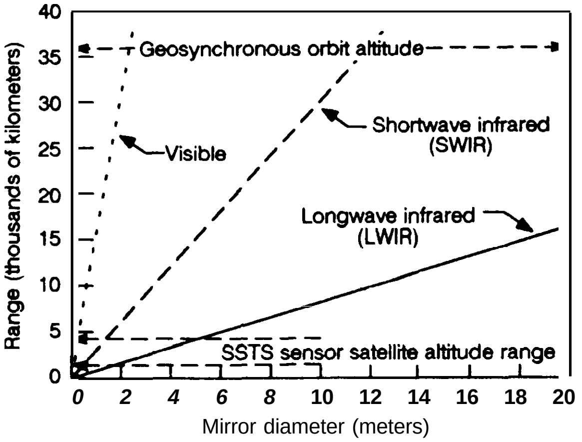
Box 4-A.—Sensor Resolution Limits

The resolution of any electromagnetic sensor (or its ability to separate two closely spaced objects) is limited by two factors: diffraction and detector element size. The image formed by the sensor optics cannot faithfully reproduce the actual scene. An infinitesimally small point in the scene will have a finite size in the image due to diffraction or spreading of the light beam. This spreading increases with distance, so diffraction will limit the useful range of any sensor as shown in figure 4-6a.

The optical system projects an image of the scene onto the detector array. The size of each detector element in this array must be equal to or preferably smaller than the optical resolution size to preserve the diffraction-resolution of the figure in the electronic signal. If the detector elements are too large, then they will further limit the system resolution.

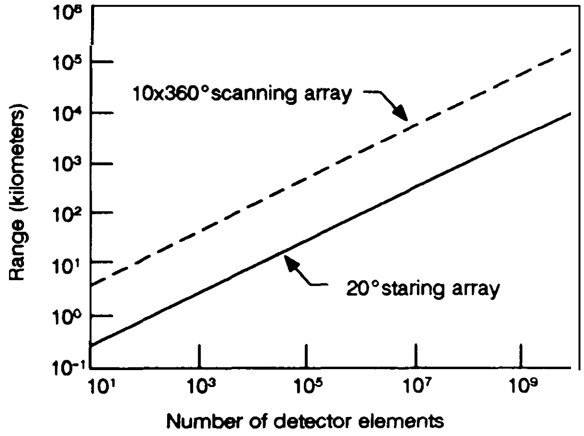
For a fixed field-of-view, as the distance between the scene and the sensor increases, then each detector element covers a larger area in space: the resolution decreases with range, the same dependence as diffraction spreading of the optical image.

Figure 4-6a.-Diffractlon-Llmited Range for Ten-Meter Resolution



Sensor range as a function of mirror diameter to produce a 10-meter resolution element at the target, for three different wavelength sensors. Two point targets separated by 10 meters at these ranges could just be resolved by mirrors of these sizes.

Figure 4-6b. - Range Limited by Number of Detectors for Ten-Meter Resolution



Range of LWIR sensors as limited by the number of detector elements in the focal plane array. The staring array is a fixed, two-dimensional array with a 200 field-of-view. The scanning array covers a 10° by 360° "coolie hat" pattern, with 10 rows of elements scanning each point in the image. Both arrays detect three different LWIR bands. The scanning array could use just one row of detectors to sweep out the image. However, to improve signal-to-noise ratio, most designs utilize more than one row and "time delay and integrate" (TDI) circuits to average the signals from many rows.

up to 1 km maybe adequate, depending upon the sensors and the divert capability of-the interceptor. As shown in figure 4-7, mirrors of 1-m diameter or less are adequate for any visible or IR wavelength. Furthermore, a 1-m mirror operating at 2.7 µm would yield 10-m target accuracy from 3,000 km.[28]

Track resolution, however, imposes a less stringent requirement than the spot resolution for a single "look." Data from many "looks" can be combined, using statistical techniques, to achieve up to a tenfold improvement. Therefore, proportionately smaller mirrors are needed for predicting tracks.

Directed-energy weapons would require much better resolution than SBIs, since they

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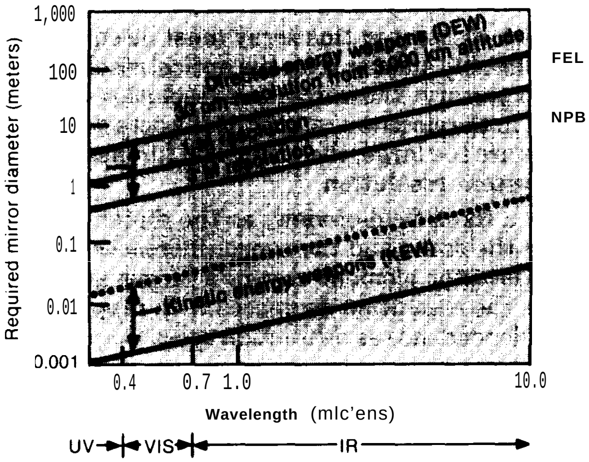
[28] The primary water vapor emission line from missile exhaust plumes is at 2.7 pm.

Figure 4-7.—Mirror Size Plotted v. the Operating Wavelength of a Sensor System



Mirror size plotted v. the operating wavelength of the sensor system, assuming a 3,000 km range to the most distant target, for indicated spot resolution. Note that the *tracking* resolution can be up to a factor of 10 better than the resolution calculated for one "look," based on diffraction limits. Therefore, the tracking may only require mirrors up to 10 times smaller than indicated in the figure.

For homing kinetic energy weapons, moderate-sized mirrors (well under 1 meter in diameter) would be adequate for all wavelengths. Directed-energy weapons such as high power lasers would require sensors with very large mirrors operating in the visible or even ultraviolet region of the spectrum. Thus all DEWS would have to use a low-resolution LWIR sensor to point a second UV/visible active sensor or laser on each weapons platform to achieve the necessary accuracy.

SOURCE Off Ice of Technology Assessment, 1988.

must be focused to a small spot without the benefit of a homing sensor at close range. LWIR sensor mirrors to direct DEWS would have to exceed 10 m in diameter. Therefore a DEW sensor would probably have to operate in the SWIR or MWIR, visible, or even ultraviolet (UV) wavelengths.[29] Laser beam weapons would demand the highest accuracy to take full advantage of their small spot size and therefore high intensity on target, typically on the order of 30 cm at 3,000 km or 0.1 microradian. Neutral particle beams, as currently envisaged, would have about one microradian divergence, producing a 3 m spot at 3,000 km, so NPB sensors could be about 10 times less accurate than laser beam sensors.

Number of Detector Elements per Array. – Each passive sensor would need many detector elements for both adequate resolution and high signal-to-noise ratios. For example, a staring array sensor on a BSTS satellite at geosynchronous orbit (36,000 km) could need well over a million detector elements to afford coarse resolution at the surface of the Earth. This requirement could be reduced to hundreds of thousands of detector elements by scanning the IR image over a smaller array of detectors, so that each detector sampled many resolution elements in the IR image.

Many detector elements would also be necessary to yield adequate signal-to-noise ratios: the electrical signal produced by IR radiation from a target would have to exceed the signal from all sources of noise. Competing IR noise could come from the background scene such as the Earth or stars, from the mirrors and housing of the sensor system, and from the internal electrical noise of the detector elements. The signal-to-background-noise ratio could be maximized by distributing the background from a fixed field-of-view over many detector elements.[30] For the most stressing task of detecting cold RVs above the horizon against atmospheric background at a tangent height of 50 to 80 km, sensors would need at least several hundred thousand detector elements to generate adequate signal-to-noise ratios.[31]

Current IR focal plane arrays on operational military sensors for tactical elements have up to 180 detector elements. Some other operational systems have several thousand, and experimental arrays with many more than 10,000

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[29] This might be satisfactory for boost-phase kills, but cold RV's in mid-course could only be detected with LWIR sensors. Hence a future laser BMD system designed to attack RV's would have to use a coarse LWIR sensor for detection, then a separate laser designator at shorter wavelength to illuminate targets for tracking by a second UV or visible-light sensor. This complexity, combined with the durability of RV's as a result of their ablative shield needed for reentry, makes the use of laser beams for killing RV's in mid-course very doubtful.

[30] Ideally, each detector element should be the same size as that of the target image. If the elements were twice this ideal size (half the total number of detectors in the array), then each element would collect twice the background noise with no increase in signal: the signal-to-noise ratio would be cut in half. For many long-range BMD missions, the detector element would be much larger than the target image.

[31] These numbers of detectors are based on the assumption that the sensor mirrors are cooled to the800 to 1000 K range so that IR radiation from those mirrors does not dominate the noise, and that the detectors are fabricated with low noise.

Photo credit: General Electric Company

Sensor focal plane array of 128 by 128 detector elements. These elements convert light energy into electrical signals. Focal plane arrays are the electro-optical equivalent of film in a camera. Some SDI sensors may require focal planes containing hundreds of thousands of detector elements.

elements have been fabricated. The focal plane array (FPA) for the planned Airborne Optical Adjunct (AOA) experiment will have a 38,400-element three-color FPA.[32] However, none of these detectors was designed to the radiation hardness needed for BMD sensors.

Detector Radiation Hardness.—Ballistic missile defense sensors must withstand radiation from distant nuclear explosions. Current detectors are fabricated from relatively thick bulk materials such as silicon or mercury cadmium telluride (HgCdTe) which are susceptible to radiation damage. Other materials, such as gallium arsenide or germanium, or thinner detector structures would be needed to achieve radiation hardness goals. Impurity band conductor (IBC) detectors, which are only 10 to 12 µm thick, can withstand 10 to 100 times more radiation than common bulk silicon detectors. Arrays with up to 500 IBC elements have been fabricated in the laboratory.

The electronic readout from FPAs must also be resistant to radiation damage. In the past, charge-coupled devices (CCD) were used to read out large detector arrays. To reduce susceptibility to radiation damage, researchers are butt-bonding switching metal oxide semiconductor field effect transistor (MOSFET) readouts to the detectors.

Detector Manufacturing Capacity.–Industry produces about 1 million IR detectors per year. Many of these are small linear arrays of 16 to 180 elements each, used for tactical IR missiles or scanning IR imaging systems. The "Teal Ruby"[33] experiment bulk-silicon array is the largest built so far. Production would have to increase by one or two orders of magnitude to satisfy the ambitious BMD goals: very large, radiation-hard, low-noise arrays would be required. For example, just one BMD sensor would require several, perhaps up to 10, times the current annual production capacity—and there could be many tens of sensors in a second-phase space-based BMD system. The SDIO has programs underway intended to

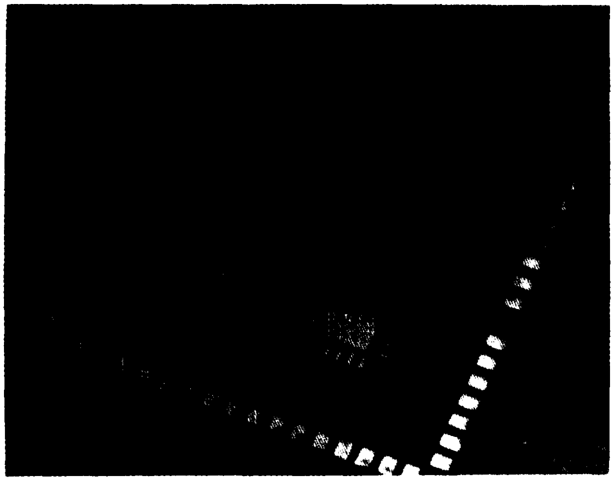

Photo credit: U.S. Department of Defense, **Strategic** *Defense Initiative Organization*

Impurity **Band Conduction Long-Wave Infrared Detector Array**

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[32] *See Aviation Week and Space Technology, Nov.* 10, 1986, P. 87.

[33] Teal Ruby is an experimental satellite designed to detect aircraft from space with an LWIR detector array.

achieve these improvements in manufacturing capability.

Conversion from laboratory fabrication to full-scale manufacturing of the new IBC detectors-assuming they continue to be the preferred detector–could limit BMD sensor deployment. Industry Performance in converting to the manufacture of bulk silicon IR "common module" arrays in the early 1980s was not good. Producing arrays of just 60, 120, or 180 elements once held up the completion of M-1 tanks that use forward looking IR (FLIR) sensors.

Manufacturing yield (the ratio of the number of acceptable arrays to the number manufactured) for IR detectors would have to be improved. The overall yield (including read-out) for the Teal Ruby array was about 2 percent. Since yield was so low, every element had to be individually tested at cryogenic (10° K) temperatures: testing might be the limiting manufacturing process. The SDIO has initiated programs to address this problem in fiscal year 1988.

Signal Processing Improvements.–Projected signal processing rates for BMD sensors would exceed current space-ebased operational capabilities by factors of a few hundred. Current operational signal processors can handle up tens of millions operations per second (MOPS), while BMD signal processing requirements might exceed 10 billion operations per second, or 10 giga-OPS (GOPS).

Projected on-board memory requirements for BMD sensors vary from 10 million to 100 million bytes of information. Reaching these memory and processing goals by the 1990s seems likely, given the progress in very high speed integrated circuits (VHSIC).

Power consumption of signal processors must be reduced. The AOA experiment will require less than 10 kilowatts (KW) of power to drive a 15 GOP processor, or over 1.5 MOPS/W. Hardened VHSIC technology offers the promise of many times less power consumption (40 MOPS/W) and good radiation resistance.

Active Sensors

How Active Sensors Work.—Active sensors illuminate the target with radiation and monitor reflected energy. In general, active sensors have the advantage of adequate illumination under all conditions: they do not have to rely on radiation from the target or favorable natural lighting conditions. They suffer the disadvantage, under some circumstances, of being susceptible to jamming or spoofing: the opponent can monitor the illumination beam and retransmit a modified beam at the same frequency to overpower or confuse the receiver. At the very least, the illumination beam can alert the enemy that he is under surveillance or attack. This might be a concern for surveillance and tracking of defense suppression weapons such as direct-ascent or orbiting ASATs.

Microwave radar, an active sensor used so successfully in tracking aircraft, might support some phases of BMD, particularly for terminal defense. These ground-based radars might use advanced data processing techniques to generate pseudo-images of RVs to distinguish between RVs and decoys, as described below. Conventional microwave radar has two serious limitations for most space-based BMD functions: limited resolution and large power requirements. Because of the large antennae, large power requirements, and survivability issues, microwave radar is not a prime candidate for BMD space applications.[34] However, the SDIO still believes that microwave radar might be included in future BMD systems.

SDI researchers are also investigating laser radar or 'ladar" for applications such as measuring the range to a target and discriminating RVs from decoys. In principle, ladar is equivalent to radar with much shorter (opti-

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[34] The SDIO had considered developing shorter millimeter wave radar to provide better radar resolution and lower power require ments. With reduced funding, support for millimeter radar has been reduced. Distributed antenna arrays are also being considered to provide space surveillance of aircraft and cruise missiles for the Air Defense Initiative.

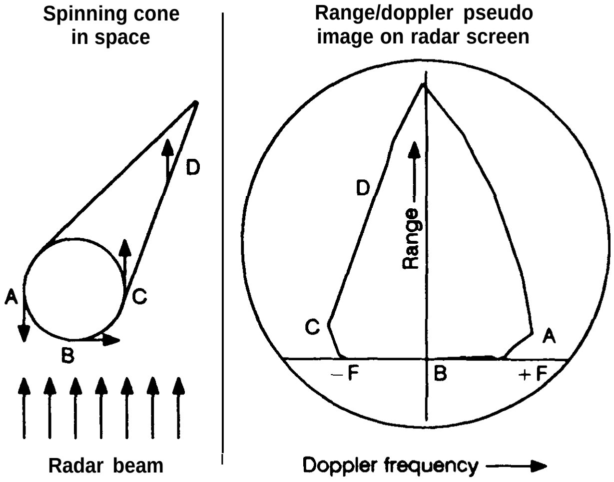
cal or infrared) wavelengths. With shorter wavelength, ladars generally would give better resolution with less power and weight. Ladars cannot operate in all weather conditions on earth. They are therefore better suited for space applications.

Imaging Radars.– If an object is moving relative to a radar, then the radar return signal is shifted in frequency, similar to the Doppler frequency shift of a train whistle as it passes by a stationary observer. For objects that rotate, such as spinning satellites or reentry vehicles, pseudo-images can be generated by processing the doppler frequency shifts of radar signals stored over time. This is a process similar to synthetic aperture radar, sometimes called inverse synthetic aperture radar (ISAR).[35]

Consider a conical RV spinning about its axis (figure 4-8). The tip of the cone has no significant motion due to rotation, and little doppler frequency shift. The back edge of the cone has a large motion (proportional to the radius of the cone and the angular velocity of the RV) and a large doppler frequency shift. A plot of range to target versus doppler frequency shift will therefore resemble the shape of the RV for most orientations of radar beam to spinning RV.[36]

The resolution of range/doppler pseudo-images does not depend on radar-beam spot size. The beam floods the target area, so precise beam pointing is unnecessary. Range resolution is inversely proportional to the bandwidth of the transmitted signal. For example, a one gigahertz[37] bandwidth radar signal could have a range resolution capability of 15 cm. Resolution in the cross-track direction (corresponding to the radius of the spinning cone) is limited by the minimum doppler frequency shift that can be detected, radar wavelength (smaller is better), and the rotation rate of the RV (larger is better).[38] For microwave radars, typical doppler frequency shifts are in the tens to hundreds of hertz. Many radar pulses must be stored and analyzed to measure these low frequencies, which requires substantial data processing.

Figure W.-I Illustration of an Imaging Radar Viewing a Spinning Conical Target



Point "A" on the base of the cone has the most motion toward the radar, producing the largest doppler frequency shift. The echo from this point would appear at point 'A" on a radar-generated plot of range versus doppler frequency shift. Point "B", at about the same range as point "A", is moving perpendicular to the radar beam, and will have no doppler frequency shift; its echo would be plotted as shown. Similarly, point "C" is moving away from the radar, and would have a negative doppler frequency shift. Finally, points along the cone such as point "D"have lower frequency shifts, since they are closer to the spinning axis. The resulting range-doppler plot will therefore resemble the conical target.

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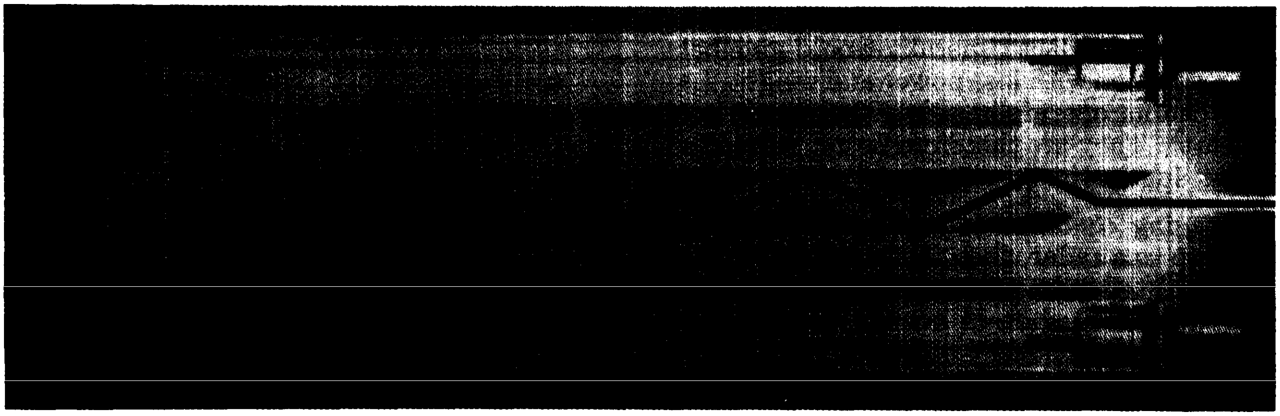
[35] An airborne synthetic aperture radar system generates an image of the ground by measuring the doppler frequency shifts of all return radar signals. Targets directly ahead of the radar aircraft have maximum Doppler frequency shift because the relative velocity between the ground and the aircraft is a maximum. Targets perpendicular to the aircraft flight path have no relative motion toward the aircraft and no Doppler frequency shift. By storing all the radar returns and processing data over time, a pseudo image of the ground is generated.

[36] If an imaging radar were boresighted along the trajectory of an RV, there would be no doppler frequency shift and no image. Conversely, if the radar looked perpendicular to the RV flight path, there would be no information on the length of the RV: any range spread would be due to the radius of the cone, independent of length. For other radar look angles between these extremes, the doppler frequency shift would be proportional to the sine of the look angle, and the range spread would be proportional to the cosine of that angle.

[37] Gigahertz is a unit of frequency equal to one billion cycles per second.

[38] Note that doppler (cross-track) *resolution* of these pseudo images is not equivalent to *positional accuracy.* Object details on the order of a few cm may be resolved in these images, but the cross-track position of the object will not be known to better than the radar beam width, which might be tens of kms wide.



m m S m g
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Ladar.—The short wavelength and very short pulse-length of a laser might prove very useful for several BMD functions. A laser radar or ladar system would illuminate the target cloud with a pulsed beam of light. An optical receiver would detect the reflected echoes, in direct analogy to a microwave radar. Various types of ladars could supply one-dimensional range to the target (a laser range-finder), or they could generate 2- or 3-dimensional images.

Several modes of imaging operation are possible:

- Scanning beam or "angle/angle" mode: a pulsed laser beam is focused and scanned over the scene. A single optical detector records the time sequence of reflections from each returned laser pulse, and a three dimensional map of target position is generated in computer memory. Ladar resolution would depend on the beam spot size, which could be as small as 3 m at 3,000 km with reasonably sized optics.[39] Very short-wavelength lasers are preferred to minimize spot size. The range resolution would be on the order of 1.5 m with 10-nanosecond long laser pulses, which are commercially available.
- Focal plane array: a passive imager, similar to the IR sensors, records the scene illuminated by a laser. The laser is the "flash lamp".
- Doppler ladar: the optical analog of a microwave Doppler imaging radar might be feasible if lasers with adequate coherence could be built. Doppler resolution of a coherent ladar could be excellent. A 30-cm RV rotating once per second would generate a 3.8 megahertz (million cycles/second—MHz) frequency shift in the ladar return signal, compared to only 60 hertz for an X-band imaging radar. Since the resolution of this pseudo-image would be independent of spot size, there would be no need to operate at short UV or visible wavelengths. This fine image resolution would not, however, yield good positional information. A narrow beam (short wavelength) angle/angle ladar would be required for good angular resolution.

Active Discrimination.–A ladar might be very useful for discriminating between RVs and decoys as they were ejected from a PBV. The PBV would perceptibly change its velocity as each heavy RV was discharged, but not as light decoys were dispensed. A ladar could be designed with the spatial resolution to resolve independently the PBV and the RV or decoy and, in theory, to measure the differen-

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[39] A $0.5\ \mu m$ laser with a 60-cm mirror would produce a diffraction-limited spot 3 m in diameter at a distance of 3,000 km.

tial velocities before and after each deployment.[40]

Light decoys might inflate as they left the PBV. A high resolution imaging ladar could in principle observe this inflation and so identify balloon decoys.[41] A precision doppler ladar might also observe small vibration or nutation (wobbling) differences between an RV and a decoy. Light decoys might vibrate at tens to hundreds of kilohertz (kHz), heavier RVs at less than a few kHz. Over tens of seconds, the nose of a spinning RV also nutates a few millimeters: a very high resolution ladar might detect this motion, but long integration times and high data storage rates would be necessary.

Current Status of Active Sensors.—Active sensor technologies have been tested and deployed in some form since the radars of World War II. Considerable development remains, however, before active sensors will be ready for advanced BMD systems.

Phased-array Search Radars. -Ground-based phased-array radars are currently deployed in both the United States and the Soviet Union to detect objects in space and give early warning of missile attack. The “PAVE PAWS” radars now at Otis AFB on Cape Cod and at Beale AFB near Sacramento have two large faces each, with active areas 22 m square, providing 2400 coverage. Each face has 1,792 active antenna elements, with provisions to upgrade each face to 31 by 31 m active areas with 5,354 elements. Two additional PAVE PAWS radars are being built in Georgia and Texas.

The United States plans to replace the three existing Ballistic Missile Early Warning System (BMEWS) mechanically scanned radars at Clear, Alaska; Thule, Greenland; and Fylingdales Moor in England with phased array radars. The old Distant Early Warning radars will also be replaced by *52* new phased array North Warning System (NWS) radars. These radars, along with the mothballed phased array radar near Grand Forks, North Dakota, might supply RV target coordinates to an ERIS exoatmospheric interceptor system.[42]

Imaging Radars. —Several radars have been operated in the rangedoppler imaging mode since the early 1970s. These ground-based radars are used to image satellites, RVs, and other space objects. MIT’s Lincoln Labs operates an L-band and an X-band imaging radar at Millstone Hill in Massachusetts.

Ladars.—Ladar systems have not been placed in operation, but they have been tested. In 1981 MIT Lincoln Laboratories built the “Firepond” CO, ladar, which had a 15 kW peak power and 1.4 kW average power. With a one microradian resolution, this ladar could detect targets spaced 3 m apart at a distance of 3,000 km. This ladar has been reactivated for the SDI program. It will be operated in the range-doppler mode to investigate RV imaging in a ground-based field test. Two other lasers are planned. One will have a very short (nanosecond), high peak power pulse to yield good range resolution. The other will use a lower peak power, frequency-chirped pulse. To recover good range resolution, this chirped pulse is compressed electronically in a data processor. This same pulse compression technique has been used successfully to reduce the peak power required in more conventional microwave radars.

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[40] Consider a PBV with 10 RVs. The PBV velocity would change very little if a light decoy were ejected. Ejecting the first RV, if it weighed l/15th of the remaining PBV weight, would cause the PBV to slow by l/15th of the RV-PBV separation velocity. That is, if the two objects were designed to move apart at a 15cm/sec rate, then the PBV would slow down by 1 cm-dsec and the RV would speed up by 14 cm/sec after separation. Later RV'S would cause the PBV to slow down more, as the ratio of RV to remaining PBV weight increased. The ladar would therefore need a velocity resolution of 1 cm/sec in this example.

[41] One Countermeasure to block the observation of decoy inflation (as well as differential velocity detection) would be to inflate the decoys under a long shroud, although there is some concern that the PBV rocket plume might interfere with a shroud. Alternatively, decoys and RVs could be tethered together so that their rotation would confuse the sensor, which could not keep track of each object (see ch. 10.)

[42] SDIO's phase-one Strategic Defense System plans one or more optical sensors for cueing ERIS interceptors. However, Lockheed-the ERIS developer–and others have proposed an “early deployment” version of ERIS that would utilize existing radars. The computing capabilities of these radars would have to be improved to handle hundreds of targets. The systems would be susceptible to electromagnetic pulse, microwave jamming, and blast damage in the event of nuclear war. At this time, phased-array radars are the only sensors available for early deployment of ERIS-like BMD systems.

Work is also proceeding on diode-pumped glass lasers, excimer lasers, and bistatic CO_2 ladars. Glass lasers are typically pumped with flash lamps, resulting in very low efficiency (typically less than 0.2 percent), since the spectrum of the flash lamp does not match the absorption bands of the Nd:glass material. By pumping the Nd:glass laser with an array of incoherent laser diodes, efficiency can be increased significantly and the thermal distortion which normally limits these lasers to very low repetition rates can be controlled.

Excimer lasers have the advantage of generating UV radiation, which demands the smallest mirrors for a given resolution.

Key Issues for Active Sensors.—Current SDI phase-two concepts call for ground-based radars for directing late mid-course and terminal defense. Space-based ladars are suggested for boost-phase ranging, to observe PBV deployment, and for determining accurate target position during mid-course discrimination. Ladars might also be used for air-borne ranging to assist terminal defense. Issues for these active sensors include the following.

Ground-based Radar.-Ground-based radars would have to be large, phased-array devices to focus adequate energy on many targets. Two key issues would be survivability and data processing. Surge fuses at each radiating diode in the array could probably protect large antennas from nuclear burst-generated electromagnetic pulse (EMP). Shielding the structure and building could protect interior electronics. Most EMP energy would be below 150 MHz, so radar radio frequency (RF) circuits at 10 GHz could be safe.

However, these antennas would be susceptible to in-band radiation from dedicated jammers. It might be a challenge to design effective electronic counter-countermeasures to protect these large and critical assets from electronic jamming by Soviet satellites. Some system architects have suggested that these radars be mobile, possibly on railroad cars. Mobility might reduce susceptibility to jamming.

Data processing might also be challenging. Consider an X-band (3-cm wavelength) radar. Its data processor might have to handle 5 million bits per second of incoming data for each of 5,000 antenna dipoles, or a total of 25 billion bits per second for the entire radar.[43] These data must be stored and processed to determine the direction to each target (by phasing the receiving array) and a Fast Fourier Transform (FFT) operation would have to be performed on each range bin to measure doppler frequency shift over many pulses.

Doppler imaging radars might be fooled if RVs (and decoys) were covered with "fronds," —strips painted with irregular patterns of volatile material. Attached at various places on an object, these strips would move about at random in space as the volatile material evaporated. This motion would give different parts of the target different doppler velocities independent of their positions on the RV or decoy cone. Such extraneous frequency shifts might confuse the radar processor, obscuring the image of the RV body.

Ladar Active Discrimination. –Significant advances would be required in ladar technology before it could be utilized to observe PBV deployment of RVs and decoys. Key issues would be resolution, beam steering, and data processing to handle the expected traffic.

Direct angle/angle ladar imaging of PBVs would take very large mirrors.[44] The alternative would be doppler processing to improve cross-track resolution. While microwave syn-

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[43] This data rate assumes that radar bandwidth is 1 GHz to yield a 15-cm range resolution. The radar tracks each target to within 100-m accuracy before hand-over to an image mode processor, which maintains a sliding range gate 100 m wide about each high-speed target. The radar pulse repetition rate is set by the highest expected doppler frequency shift produced by RV rotation. For clear images of a 20-cm radius RV rotating at 3 hertz, the pulse repetition frequency (PRF) must be 500 hertz or higher. (This imaging doppler radar would be highly ambiguous with respect to RV velocity, which would require MHz type PRFs to measure actual velocity.)

[44] To image a 30-cm diameter RV, a ladar designer would like 10 resolution elements across the object to resolve shape or details, or 3 cm resolution. Thus, an impractically large 60-m mirror would be required for 3 cm resolution at 3,000 km range with a visible laser.

thetic aperture radars have been successfully operated for over 20 years, this process has not been extended to optical wavelengths. Building stable but powerful space-based lasers with the coherence necessary for doppler processing would be a major challenge.

Interactive Sensors

The consensus in the SDI technical community is that passive and active sensors may not be adequate to discriminate between RVs and decoys in the future. The Soviet Union probably has the necessary technology to develop decoys and real RVs with nearly the same infrared and radar signatures. Decoys would not be extraordinarily difficult to fabricate and disperse in space, and they would weigh only a small fraction of an RV. There is a serious question whether, once dispersed, they could be distinguished from real RVs by any passive or active sensor. If not, the offense could overwhelm a space-based or ground-based mid-course defense system with literally hundreds of thousands of false targets.

Mid-course decoy discrimination would become crucial if the Soviets could:

- deny a phase-one boost-phase defense through countermeasures such as moderately fast-bum (e.g., 120- second) boosters, and
- deny significant post-boost kills by moving to faster PBV deployment times or to single warhead missiles.

If an initial U.S. deployment of kinetic energy weapons could no longer destroy many ICBMs in the boost or post-boost phase, and if directed-energy weapons were not yet available, then mid-course discrimination would become indispensable to a viable BMD system.

There would be two possibilities for effective mid-course discrimination under these circumstances: ladar discrimination during post-boost decoy dispersal, or interactive discrimination after the RVs and decoys were released. As discussed in the preceding section, ladar detection during decoy deployment would be very challenging. Moreover, simple measurement of RV and PBV recoil velocities might be thwarted completely if the Soviets could disperse decoys and RVs simultaneously in pairs. Even fine doppler imaging would be foiled if the Soviet PBV could obscure the deployment operation with a shroud. This would leave interactive discrimination as the main approach to keeping BMD viable in the long term.

How Interactive Discriminators Would Work. —In interactive discrimination, a sensor system would perturb each target and then measure its reaction to determine if it were a decoy or an RV. For example, a dust cloud of sufficient density and uniformity could be placed in front of a group of objects. The resulting collisions would slow down light decoys more than heavy RVs. A ladar would monitor the change of velocity of all objects, thereby identifying real RVs.

Two general classes of discriminators have been proposed: kinetic energy and directed energy perturbers.

Kinetic Energy Discriminators. —Two methods have been proposed to project particles in front of an oncoming cloud of decoys and RVs: rocket-born particles and nuclear-explosion-projected particles. A rocket-borne cloud would be limited to late mid-course, unless the rockets were fired from submarines or based in Canada or the Arctic. Presumably one rocket would be necessary for the cylindrical cluster (or "threat tube") of RVs and decoys emanating from each PBV. To slow down decoys measurably, a rocket would have to carry enough mass to cover the full lateral extent of the threat tube with a sufficiently dense cloud. A ladar would have to measure velocity changes *in* the 10-cm/sec to l-m/see range.

Directed-energy Discriminators. -Several forms of directed energy have been proposed for interactive discrimination. They would all have the advantage of long range, extending the discrimination capability back to the beginning of the mid-course if not to the post-boost phase.

The laser is the best developed directed-energy perturber currently available, although further development would be needed to produce lasers with the brightness required for interactive discrimination. Lasers could heat unknown targets (called "thermal tagging"). Alternatively, a short pulse of laser light could change the velocities of targets (called "impulse tagging").

In thermal tagging, a laser of the appropriate wavelength would heat a light-weight decoy more than an RV—assuming they both absorbed laser energy and radiated IR (thermal) energy to the same degree. A separate IR sensor, possibly mounted on SSTS satellites, would then detect the warmer decoy.

Pulsed lasers could shock the unidentified objects. Energy would be deposited in microseconds instead of the milliseconds taken by thermal tagging. A high-power pulse would boil away material perpendicular to the surface of the target. The reaction of ablation products would cause the target to change velocity. A heavier RV would recoil less than a decoy, providing amass-dependent indicator. A separate ladar would monitor the change of each object's velocity.

The SDIO has chosen the neutral particle beam (NPB) as the most promising interactive discrimination perturbation source. The particle beam source is derived from well-established particle accelerators used for several decades in physics research experiments around the world. A neutral particle beam could be composed of hydrogen atoms,[45] accelerated to velocities about half that of the speed of light. Since the particle beam would be relatively broad, on the order of 2 microradian beam width, it would not require the pointing accuracy of 50-nanoradian-wide laser beams.

These energetic particles would be deposited several cm deep inside an RV.[46] As they were absorbed, these particles would produce gamma rays and neutrons. Neutron or gamma-ray detectors on many satellites-located closer to the targets than the accelerator—might monitor the emissions coming from a massive RV. Light weight decoys, in contrast, would not emit much radiation.

High energy particles must be electrically neutral to propagate through the Earth's variable magnetic field (charged particles would bend in unpredictable paths.) But a particle must be charged to be accelerated. Therefore the NPB would first accelerate negatively charged hydrogen ions. After acceleration to a few hundred MeV (million electron volts) energy, this beam would be aimed toward the target by magnetic steering coils. Once steered, the charged beam would be neutralized by stripping off the extra electron from each particle. Thin foils or gas cells are currently used to neutralize beams in laboratory experiments.

A relativistic (i.e., near-speed-of-light) electron beam could also be used as a discriminator. The detector in this scheme would monitor x-rays from the more massive RV. Such a system might be ground-based, popping up on a rocket to monitor the mid-course phase. The main advantage would be the avoidance of space-based assets for interactive discrimination. However, an e-beam discriminator would need some air to form a laser-initiated channel, so it could only operate at altitudes between 80 to 600 km.

Current Status of Interactive Sensors. -Interactive sensors have not yet been built for any military mission. All the concepts described above have been invented to solve the severe discrimination problem unique to mid-course ballistic missile defense.

Key Issues for Interactive Discrimination.—The overriding issue for interactive discrimination is effectiveness in the face of evolving Soviet countermeasures. There are some common issues for any discriminator and some issues unique to each approach.

Laser Radar. –Any discriminator would require a high resolution laser radar to accurately locate and identify each object in space. One

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[45] An NPB could also utilize deuterium or tritium, the heavier isotopes of hydrogen. These heavier isotopes would experience less divergence in the beam neutralization process after acceleration. Tritium, the hydrogen isotope with two neutrons, must be produced in a nuclear reactor and is radioactive with a half-life of 12.3 years. Deuterium, the non-radioactive hydrogen isotope with one neutron, would most likely be used.

Another approach calls for cesium instead of hydrogen atoms in a "momentum rich beam. " A heavy cesium beam would impart a velocity change to the target, so it is more analogous to a laser impulse tagger than to a hydrogen NPB.

@The electron on each hydrogen atom would be stripped off, leaving the proton which penetrates into the target.

Table 4-3.—Key Issues for Interactive Sensors

For all discriminators:
- **Laser radar required for accurate target location: (corner cube reflector is inexpensive countermeasure.)**
- **Rapid retargeting: 3-50 targets/second**

For NPB accelerator:
- **Voltage and duty cycle must be increased without increasing beam emittance**
- **Beam expansion**
- **Beam sensing must be developed**
- **Beam pointing system must be developed**
- **Beam propagation in space**
- **Space charge accumulation**
- **Accelerator arcing in space**
- **Weight**

For NPB neutron detectors:
- **RV detection with nuclear precursor background**
- **Missed target indicator**

For laser thermal tagger:
- **Moderate to high power pulsed lasers**
- **Thermal shroud on RV**

For laser impulse tagger:
- **Needs ladar imager to tell orientation**
- **High to very high average power, microsecond-long pulsed lasers**
- **Thruster-compensated RVs**

For dust cloud tagger:
- **Dispersal of dust cloud**

SOURCE Office of Technology Assessment, 1988,

possible countermeasure to ladar would bean inexpensive corner-cube reflector on each RV and decoy. This corner cube would essentially swamp the ladar receiver: the beam would be returned on itself and the ladar would be unable to measure target characteristics. A counter-countermeasure would be a bistatic ladar with a laser transmitter on one platform and a light detector on a separate satellite not far away. Reflected energy from a corner cube would travel harmlessly back to the transmitter; thus failing to blind the receiver. Bistatic operation would be feasible, but it would complicate system design, construction, and operation.

Beam Steering.—A directed-energy interactive discriminator would have to steer its beam rapidly from one object to the next. Beam steering requirements are set by the number of expected targets and the number of directed-energy satellites within range of those targets. Typical estimates are that hundreds of thousands of RVs and decoys might survive the boost phase defense.[47] Assuming that mid-course discrimination of sophisticated decoys must be completed in 15 minutes, then each platform would have to interrogate 3 to 50 targets per second. The directed-energy source would have to be steered accurately from one target to the next in less than 20 to 300 milliseconds. This would be a formidable challenge.

NPB Accelerator.–Neutral particle beam accelerator development faces many key hurdles. Beam energy must be increased by a factor of 20, which should not be difficult. Duty cycle and beam diameter must be increased by a factor of 100 without degrading beam quality or emittance—a more challenging task. An accelerator would have to operate in space without electrical breakdown or arcing that would short out its electrical system. Communications and electronic controls would have to operate even with electrical charge buildup in space. An NPB would have to propagate over long distances in space with little divergence. To point accurately at targets, it would have to be effectively boresighted to an optical system.

These same issues would have to be resolved for an NPB weapon accelerator. A weapon-grade NPB would probably dwell longer on each target to assure destruction of at least the internal electronics, but might otherwise be very similar to one designed for interactive discrimination. A more detailed discussion of NPB accelerator issues appears in the DEW section of chapter 5.

Neutron Detection.–Calculations indicate that large neutron detectors placed on hundreds of separate satellites near the targets could detect the neutron flux from RVs. The offense might intentionally detonate nuclear weapons in space before an attack to saturate these neutron detectors. With sufficiently high particle-beam energy (on the order of 200 MeV),

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[47] An interactive discriminator would not have to interrogate all objects in space. Unsophisticated decoys, discarded booster stages and other debris could probably be identified by passive or active sensors. With adequate battle management to keep track of extraneous objects, the process of "bulk filtering" would eliminate these objects from the interactive discriminator's target list.

the energy of some neutrons ejected from an RV would be higher than that expected of neutrons emanating from nuclear detonations. Therefore an energy threshold circuit would eliminate most of the signal from the latter source, allowing identification of the neutrons from RVs.

Another issue is how to confirm that targets had been hit by an NPB, since the neutron detectors would receive no signal from decoys. How would a system distinguish between decoys and RVs which were missed by the beam? One possibility, being tested in the laboratory, would be to monitor each object with a UV sensor on the assumption that the outer surface of the RVs (and the decoys) would emit UV light when struck by the particle beam. This UV sensor simply would confirm that the particle beam had hit a target.

If based on current technology, neutron-detector platform weights would be excessive. Each platform would weigh up to 30 tonnes. System designers hope that lighter detector elements and power supplies can reduce this weight to 5 tonnes per platform by the mid-1990s. If this goal were achieved, then the several hundred detector satellites could be orbited with about 100 launches of the proposed Advanced Launch System.

Laser Thermal Tagger.–Very high power lasers would be required to tag space targets for an interactive discriminator. A laser thermal tagger, like all interactive sensors, would require a separate laser radar to locate targets precisely. For example, cold RVs (and decoys) would have to be tracked by long-wavelength LWIR passive sensors. These sensors could only determine a target's position to within 18 m, assuming a 2-m sensor mirror at 3,000 km.[48] But the interrogating laser beam might have a spot size of only 1 or 2 m. A more accurate laser radar would be required to guide an HF laser beam to the target.

Detecting small temperature rises on several hundred thousand objects would also stress LWIR sensor technology. Monitoring closely spaced targets would demand large LWIR mirrors. For example, to distinguish objects spaced 10 m apart, a sensor 3,000 km away would need a 4-m mirror. Steering this large mirror to, say, 15 targets per second would be another major challenge.

Decoys might be modified to respond to thermal tagging as an RV would. Due to their lower mass, decoy surfaces should became hotter than RV surfaces after laser illumination. However, the outer layer of the decoys could in principle be built to absorb less laser light or to emit more IR heat. These decoys would then reach the same temperature as an RV after exposure to laser light. Or, an RV could simply be covered by an insulating blanket that would decouple the exterior thermal response from the internal RV mass. It appears that laser thermal tagging would have limited usefulness against a committed adversary.

Laser-impulse Discriminator.–The energy density required for laser impulse discrimination would be in the range of 7 to 30 times more than for thermal tagging. In addition, the laser pulses would have to be very short, on the order of microseconds instead of milliseconds, which makes the peak laser power extraordinarily high. This high peak power would be difficult to generate and handle, since mirrors and other optical components would be susceptible to damage by the intense pulses. While less powerful than proposed laser weapons, lasers for impulse discrimination would still be a major development.[49]

Laser impulse discrimination might be countered by equipping RVs or decoys to react deceptively. Small thrusters on RVs might cause them to move as a decoy would under a laser impulse. Alternatively, thrusters on relatively sophisticated decoys might counteract the laser impulse.

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[48] A single target could be located to within less than the 18-m LWIR resolution element by a process called "beam-splitting": the target is assumed to be in the center of the IR signal waveform. If there were two targets or a target and a decoy within the 18-m resolution element, however, then the sensor would falsely indicate one target located between the two objects.

[49] The primary measure of a laser's effectiveness as a weapon is beam "brightness," the average power radiated into a given solid angle. An HF laser impulse tagger would be brighter than any laser built to date, but still a factor of 2 to 200 less bright than that needed for BMD against a responsive Soviet threat.

All interactive discriminators would probably require an imaging ladar to provide adequate resolution both to hit targets with a probe beam and to measure target response accurately. A laser impulse discriminator would bear the additional burden of determining target (and particularly decoy) orientation. The orientation of a conical decoy, for example, could affect its reactive motion in response to the laser pulse.

Dust-cloud Discriminator.–The key issue for a dust cloud discriminator is how to position the cloud accurately in front of the oncoming RV-decoy constellation at the proper time. If the particles were dispersed too widely, the required amount would become excessive. If clustered too closely, they could miss some decoys. As with any discriminator, a precision ladar would be required to measure velocity changes accurately.

Laser impulse discrimination might be countered by equipping RVs or decoys to react deceptively. Small thrusters on RVs might cause them to move as a decoy would under a laser impulse; alternatively, thrusters on relatively sophisticated decoys might counteract the impulse.

SENSOR TECHNOLOGY CONCLUSIONS

Phase 1

1. A boost surveillance and tracking satellite (.BSTS) could most probably be developed by the mid-1990s. Short-wave and middle-wave infrared (S/MWIR) sensors, could provide early warning and coarse booster track data sufficient to direct SBI launches.[50]
2. Space surveillance and tracking system (SSTS) satellites would not be available for tracking individual RVs and decoys before the late 1990s. The ability to discriminate possible decoys in this time frame is in question. Smaller but similar sensors for a phase-one system might be placed on individual SBI platforms or on ground-based, pop-up probes.
3. An airborne optical system could probably be available by the mid-1990s to detect and track RVs and decoys with IR sensors (although not to discriminate against a replica decoy above the atmosphere). However, its utility may be limited in performance and mission:
   - Performance may be limited by the vulnerability and operating cost of its aircraft platform, and IR sensors might be confused during battle by IR-scattering ice crystals formed at 60 to 80 km altitude by debris reentering the atmosphere.
   - The relatively short range of airborne IR sensors would limit the AOS mission to supplying data on approaching objects for endo-atmospheric interceptor radars, and possibly for exe-atmospheric interceptors a short while before RV reentry. Airborne IR sensors, unless very forward-based, could utilize only a small portion of the time available in mid-course for discrimination and therefore could not take full advantage of the fly-outrange of ground-based exoatmospheric interceptors.

   In any case, an Airborne Optical System is not now included in SDIO phase-one deployment plans.
4. Effective discrimination against more sophisticated decoys and disguised RVs in space is unlikely before the year 2000, if at all.

Phase 2

5. By the late 1990s at the earliest, a space surveillance and tracking system (SSTS) might furnish post-boost vehicle (PBV) and reen-

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[50] One uncertainty is the protection of the BSTS sensors from future airborne or spaceborne laser jarnmers which could permanently darnage IR detector elements during peacetime.

try vehicle (RV) track data with long-wave infrared (LWIR) above-the-horizon (ATH) sensors suitable for directing SBI launches in the mid-course. New methods would be needed for the manufacture of large quantities of radiation-hardened focal plane arrays. Another issue is the operation of LWIR sensors in the presence of precursor nuclear explosions (including those heaving atmosphere into the ATH field of view) or other intentionally dispersed chemical aerosols. Effective mid-course SBI capability is unlikely before the late 1990s to early 2000s.

6. There are too many uncertainties in projecting sensor capabilities and the level of Soviet countermeasures to specify a discrimination capability for SSTS. It appears that Soviet countermeasures (penetration aids and decoys) could keep ahead of passive IR discrimination techniques:
   - Passive IR discrimination could be available by the mid-1990s, but probably would have marginal utility against determined Soviet countermeasures.
   - Active laser radar (ladar) imaging of PBV deployment offers some promise of decoy discrimination, provided that the Soviets did not mask dispersal of decoys. Space-borne imaging ladars probably would not be available until the late 1990s at the earliest.
   - Laser thermal tagging of RVs is unlikely to be practical given the need for complex, agile steering systems and given likely countermeasures such as thermal insulation of RVs and decoys.
   - Laser impulse tagging is even less likely to succeed in this phase because high-power pulsed lasers would be required.
7. Ground-based radar (GBR) might be available by the late 1990s to direct interceptors to recentering warheads. There maybe some questions about its resistance to RF jammers. Signal processors may have difficulty handling large numbers of targets in real-time.

Phase 3

8. Accurate IR sensors, UV ladar, or visible ladar would have to reside on each DEW platform.
9. Interactive discrimination with neutral particle beams (NPB) appears the most likely candidate to reliably distinguish decoys from RVs, since the particles would penetrate targets, making shielding very difficult. Before one could judge the efficacy of a total NPB discrimination system, major engineering developments would be required in: weight reduction, space transportation, neutral particle beam control and steering,[51] automated accelerator operation in space, and multi-megawatt space power.

It is unlikely that a decision on the technical feasibility of NPB discrimination could be made before another decade of laboratory development and major space experiments. Given the magnitude of an NPB/detector satellite constellation, an effective dismimination system against sophisticated decoys and disguised RVs would not likely be fully deployed and available for BMD use until the 2010 to 2015 period at the earliest.

10. Nuclear bomb-projected particles might also form the basis of an effective interactive discriminator, if reliable spacebased ladar systems were also developed and deployed to measure target velocity changes. There are too many uncertainties to project if or when this approach might succeed.

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[51] Since the particle beams are invisible, novel approaches would be required to sense the direction of the beam so that it could be steered toward the target.