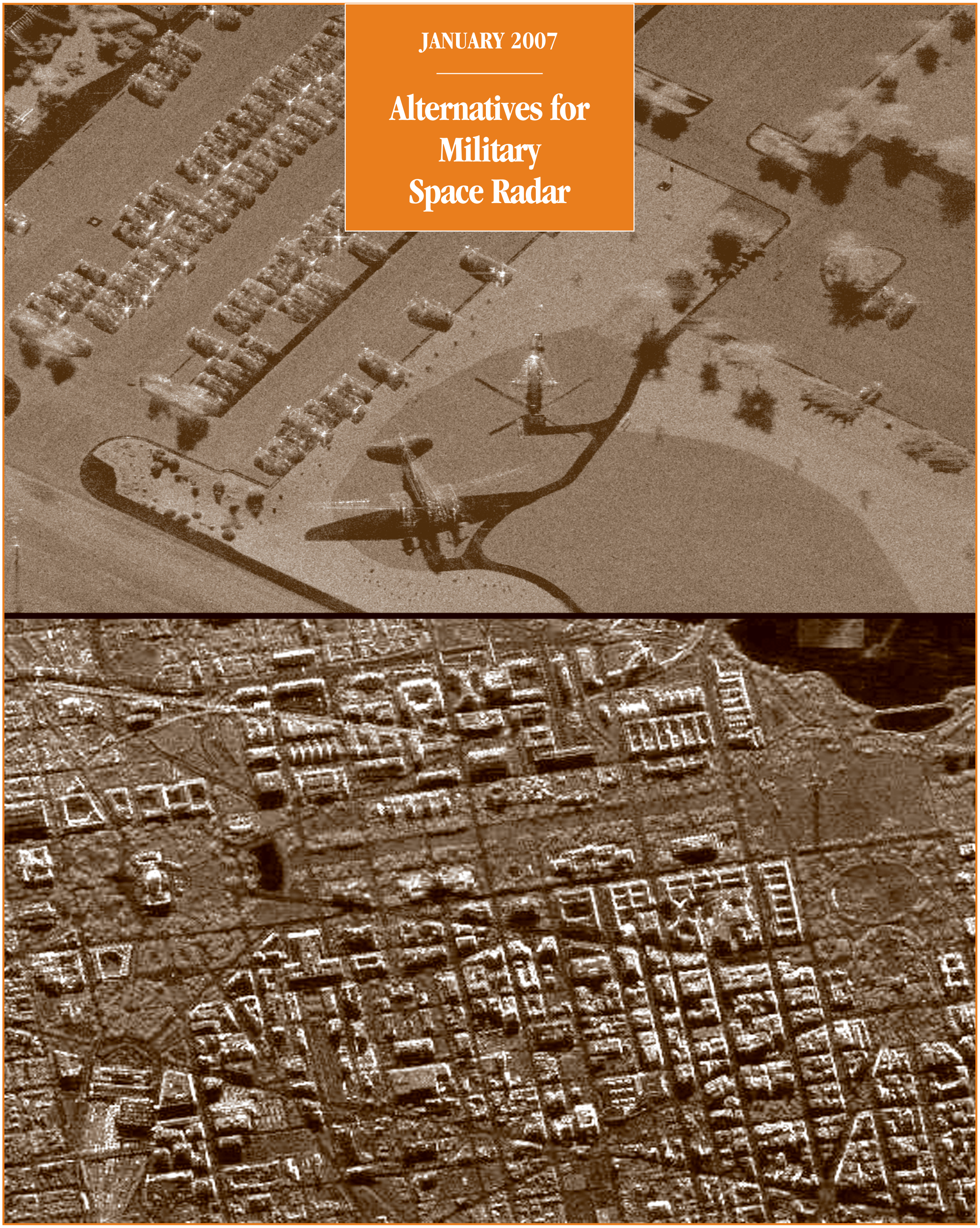
CONGRESS OF THE UNITED STATES
CONGRESSIONAL BUDGET OFFICE

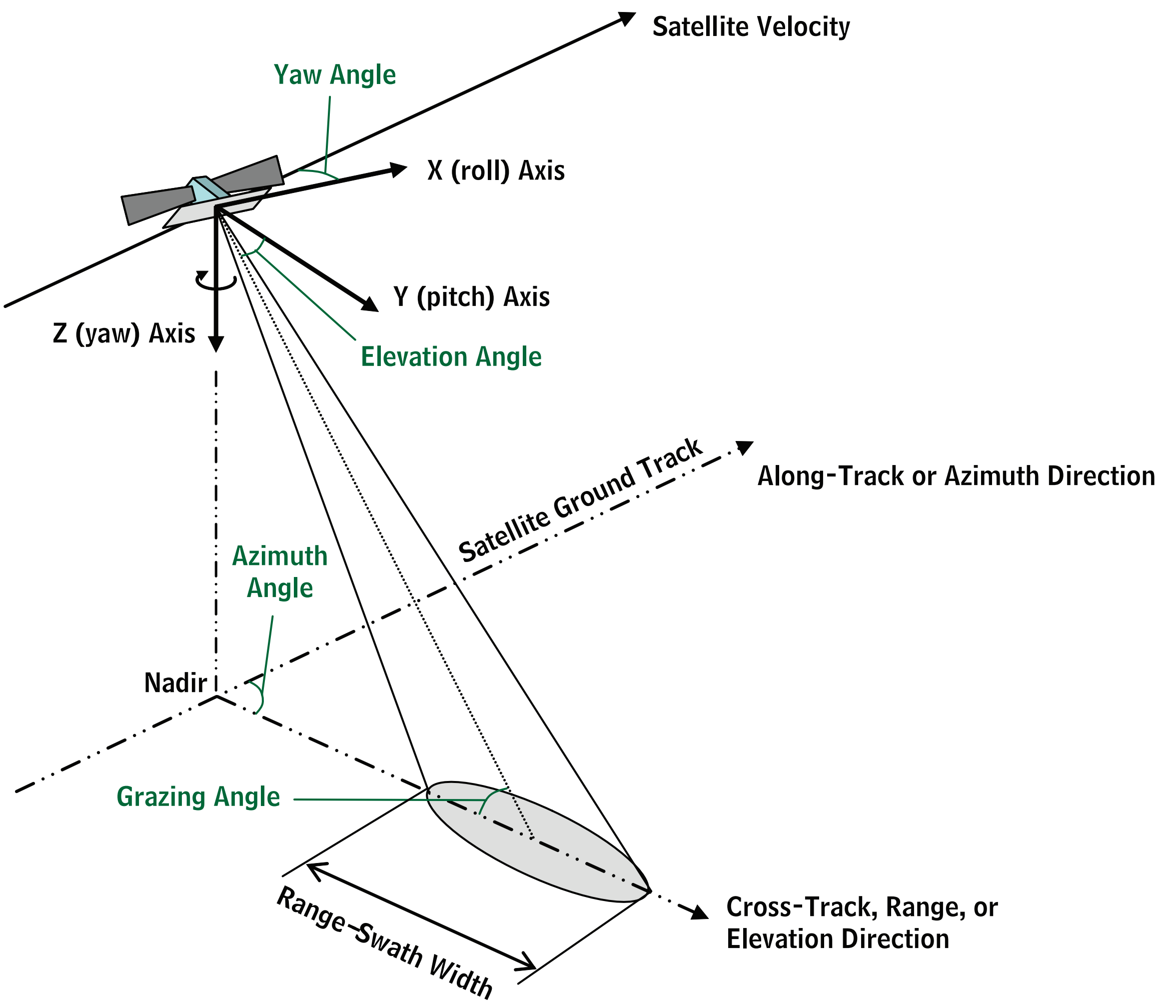
A CBO STUDY

JANUARY 2007

Alternatives for Military Space Radar



Satellite and Radar Geometries



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Alternatives for Military Space Radar

January 2007

The Congress of the United States ■ Congressional Budget Office

Notes

Numbers in the text and tables of this report may not add up to totals because of rounding.

The cover shows two images taken with airborne synthetic aperture radars. The top image, which is at 4-inch (or 0.1-meter) resolution, shows vehicles parked next to a display of historical Air Force helicopters and planes in New Mexico. The bottom image, which is at 1-meter resolution, shows an area of Washington, D.C., between the U.S. Capitol and the Washington Monument. (Images courtesy of Sandia National Laboratories.)

Preface

The Department of Defense (DoD) and the intelligence community rely on various systems to provide imagery to tactical commanders and intelligence analysts. In addition, DoD uses manned and unmanned aircraft equipped with ground moving-target indication (GMTI) radars to detect military units, vehicles, and other moving targets on the ground and inform commanders of their disposition. DoD's 2006 Quadrennial Defense Review calls for investment in such systems to grow in order to provide "a highly persistent capability to identify and track moving ground targets in denied areas." To that end, DoD and the National Reconnaissance Office are proposing to develop a constellation of Earth-orbiting Space Radar satellites that would provide imagery, GMTI, and geospatial intelligence products to members of the military and the intelligence community.

This Congressional Budget Office (CBO) study—prepared at the request of Senators Wayne Allard and Bill Nelson in their respective capacities as the Chairman and Ranking Member of the Senate Committee on Armed Services' Subcommittee on Strategic Forces—examines the costs and potential performance of four possible designs for a Space Radar system. Those four notional alternatives (which CBO developed on the basis of unclassified published sources) include three constellations of various sizes with 40-square-meter radar arrays and one constellation with 100-square-meter radar arrays, all in low earth orbit. The study also highlights some of the technological challenges associated with developing and operating Space Radar satellites. In keeping with CBO's mandate to provide objective, impartial analysis, this report makes no recommendations.

Joseph Post and Michael Bennett of CBO's National Security Division wrote the study, under the supervision of J. Michael Gilmore. (Joseph Post has since left CBO.) Adrienne Ramsay, also formerly of CBO, conducted preliminary analysis supporting the study. Raymond Hall of CBO's Budget Analysis Division prepared the cost estimates and wrote Appendix A, under the supervision of Sarah Jennings. Heidi Golding and Noah Meyerson of CBO provided thoughtful comments, as did S.W. McCandless of User Systems Inc. (The assistance of an external participant implies no responsibility for the final product, which rests solely with CBO.)

Christian Howlett edited the study, and Loretta Lettner proofread it. Maureen Costantino prepared the report for publication, with assistance from Allan Keaton, and designed the cover. Lenny Skutnik printed the initial copies, Linda Schimmel handled the print distribution, and Simone Thomas prepared the electronic version for CBO's Web site (www.cbo.gov).

Donald B. Marron

Donald B. Marron
Acting Director

January 2007

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Summary

The U.S. Air Force, National Reconnaissance Office, and National Geospatial-Intelligence Agency are developing a new radar reconnaissance satellite—known as Space Radar—to produce images of the Earth's surface using synthetic aperture radar (SAR) techniques and to detect moving targets on the ground, among other missions. The first launch of what would eventually be a constellation of Space Radar satellites is now planned for about 2015.

Since the late 1970s, various nations have operated SAR imaging satellites for national security or scientific purposes. However, as currently envisioned, Space Radar would be more capable than existing systems or those likely to be launched in the next few years. In particular, the ability to identify moving targets from space would constitute a major improvement in capability. Fully realizing that and other advances, however, would require designers to meet numerous technical challenges.

Arguably, the most critical technical challenge facing the Space Radar program is the development of data-processing algorithms that can distinguish between moving targets and the background clutter around them. Identifying such targets from space is especially hard: from the point of view of an orbiting satellite, the ground is moving at about 15,000 miles per hour, so distinguishing a vehicle that is moving only a few miles per hour faster than that is a difficult task.

Production of the Space Radar satellites would also require that various hardware challenges be met. Those challenges would include developing a large phased-array radar antenna that could survive launch and deployment in space; improving the efficiency of batteries that operate in space; and developing signal-processing systems, satellite-to-ground communications, and intelligence-exploitation systems that could handle the large flow of raw data and resulting intelligence products that a Space Radar satellite would generate.

This study examines the performance characteristics and life-cycle costs of possible design choices for the Space Radar system. The Air Force and its partners have not yet decided on the final design of the satellites or the final architecture of the constellation. For the purposes of this analysis, the Congressional Budget Office (CBO) developed four alternative Space Radar architectures that could meet the system's principal mission objectives. Those architectures were based on unclassified published studies and were designed to be technologically feasible (albeit challenging) in 2015, the anticipated year of the first launch. The alternatives incorporate two notional radar designs and various constellation sizes. The primary—or reference—architecture consists of nine satellites, each with a 40-square-meter radar array. The other options differ from that architecture by having either more (21) or fewer (5) satellites or larger radars (100-square-meter arrays on nine satellites).

Analysis of those architectures suggests that the Space Radar system should be able to produce large amounts of high-resolution SAR imagery with only modest advances in technology, even in the case of the smallest (five-satellite) constellation. The constellations that CBO considered would not be able to provide continuous SAR coverage of a region. However, their response time—how soon they could produce images of an area after receiving an order to do so—should offer an improvement over existing capabilities. For imagery with a resolution of 1 meter, average response times would range from about 45 minutes for the five-satellite constellation to less than 7 minutes for the 21-satellite constellation.

Space Radar's other primary mission—ground moving-target indication (GMTI)—would prove more challenging. CBO concluded that for constellations with

40-square-meter radar arrays, signal-processing algorithms would need to perform near their theoretical optimum level for Space Radar to be able to detect targets moving more slowly than about 20 miles per hour. Using a larger radar array, such as the 100-square-meter design that CBO examined, would reduce the level of signal-processing performance needed to detect slow-moving targets.

Even with optimal signal-processing performance (or larger-aperture radars), substantial time gaps in covering a given area would probably occur for all of the constellations that CBO considered. Thus, those systems would be impractical for tracking (as opposed to simply detecting) individual ground targets. If other surveillance systems were not available to augment Space Radar—for example, because a lack of access to airspace prevented the use of surveillance aircraft—constellations larger than the ones that CBO examined would be necessary to track individual ground targets.

Total life-cycle costs for the alternatives in this analysis would range from about $25 billion (in 2007 dollars) to more than $90 billion, depending on the number and type of satellites deployed and the potential for cost growth.[1] Those total costs cover research and development, procurement of the satellites and associated ground systems, satellite launches, and operations over the expected 20-year lifetime of the Space Radar system. For the reference architecture (nine satellites with 40-square-meter radar arrays), total costs would range from about $35 billion to more than $50 billion. Reducing the number of satellites from nine to five would lower total costs by about 25 percent. Conversely, increasing capability by using either larger radar arrays or more satellites would add between 50 percent and 90 percent to the system's total costs.

Space Radar's Operations and Intended Missions

Radars—whether mounted on satellites, aircraft, the ground, or handheld devices—provide information about targets by transmitting electromagnetic waves and then collecting the returning waves that are reflected by the targets. The reflected waves can be analyzed to reveal the distance to the target (through the elapsed time between transmission and collection of the reflected wave), the target's motion (through changes in the frequency of the wave), and even information about what the target is (through changes in the spatial orientation, or polarization, of the wave). Radar systems are used for a wide variety of purposes—from detecting speeding motorists to tracking weather patterns, mapping the Earth's surface for scientific study, controlling air traffic, and providing intelligence about enemies' activities on or off the battlefield.

The Air Force and its partner agencies are developing Space Radar satellites to complement the military's existing reconnaissance and surveillance systems, which include radars deployed on manned and unmanned aircraft. Because those satellites will orbit hundreds of kilometers above the Earth, their operations will not be affected by enemy air defenses or lack of access to certain airspace, as aircraft are. However, their great distance from the surface and very high speed while in orbit present a number of technical challenges that could affect their performance.

The Space Radar system is intended to carry out four missions for members of the military and the intelligence community:

- **Synthetic aperture radar imaging—**using transmitted microwaves to produce images of the Earth's surface (somewhat akin to photographs produced by optical imaging).[2] By providing their own illumination, radars can produce images day or night, and microwaves have the advantage of being able to penetrate obscuring layers of clouds (although heavy rain or snow can reduce the quality of the images). However, radar images can be more difficult to interpret than pictures produced with visible light.

- **Ground moving-target indication—**detecting moving targets on the surface of the Earth using special radar techniques. Radar signals that reflect off objects in

1. The methods and assumptions that CBO used to estimate the costs of the alternatives, including potential cost growth, are described in Appendix A.

2. The term "synthetic aperture radar" derives from the fact that the motion of a moving radar platform, such as an aircraft or satellite, can be used to create a "synthetic" aperture that is much larger than the radar's physical aperture. (Larger radar antennae generally outperform smaller ones because the bigger the aperture, the better the radar's energy can be focused and the more returning energy can be collected.)

motion have a different Doppler shift (the change in the frequency of a signal caused by the relative motion of the source and receiver) than do signals that reflect off the surface around them. Through careful signal processing, that Doppler shift can be detected and used to highlight the locations of moving targets. GMTI is used to conduct surveillance of large areas. It typically provides the operator with an indication of moving targets, which can be superimposed on a map or image.

- **Provision of high-resolution terrain information—** making precise measurements of surface elevation. If two observations of the same piece of terrain are collected from slightly different angles, small differences in timing between the returning radar signals used to form the two images can be used to estimate the terrain's height (through a technique known as interferometric SAR).

- **Open-ocean surveillance—**observing wide areas of the oceans to monitor the movement of ships.

In comparing alternative designs for the Space Radar system, this study focuses on the first two missions—SAR and GMTI—because they are considered the highest priorities for the new system and because detecting and tracking targets on the ground should be more difficult than detecting and tracking targets at sea.

Although the final design of the satellites and their orbital configuration have yet to be determined, the Space Radar Integrated Program Office is considering a constellation of about nine satellites in low earth orbit (LEO).[3] Such a constellation would not be large enough to provide continuous coverage of the globe from that height, but it should be able to revisit most of the populated areas at fairly frequent intervals.

Issues in Designing a Space Radar System

Designing a constellation of radar satellites—as CBO did in conceptual terms for the alternatives in this study—requires making a host of trade-offs about important characteristics of the constellation, such as the altitude and inclination of the satellites' orbits, the design of the radar antenna, and the frequencies at which it transmits. Because the Space Radar constellation is not due to be launched for at least eight years, CBO also had to make assumptions about the likely state of technical development at that time in such key areas as power sources for spacecraft, electronic components that could limit the radars' bandwidth, methods for processing GMTI signals, and high-capacity communication systems to downlink large amounts of radar data.

Design Trade-Offs

A key design consideration for any satellite is the orbital altitude. On one hand, higher orbits provide better coverage of the Earth's surface; they also have lower velocities, which helps with ground moving-target indication. On the other hand, the wide-area surveillance rate for GMTI is proportional to the radar's transmit power multiplied by its aperture size (the "power-aperture product") and is inversely proportional to the *square* of the distance to the target. Thus, a radar in medium earth orbit at 10,000 kilometers would require 100 times the power or 100 times the antenna area of an equivalent radar in low earth orbit at 1,000 kilometers.

Orbital inclination (the angle between the plane of the orbit and the equator) affects the areas of the globe that a satellite can observe. By choosing a particular inclination, a constellation designer can focus on particular latitudes of interest. For example, an orbital inclination of 60 degrees will provide better access to polar regions than will a lower inclination but less access to equatorial areas.

In designing radar antennae for Earth-imaging satellites, two major options exist: active electronically steered arrays (AESAs) or reflector antennae. Most recent or planned civilian SAR satellites employ AESA designs. Those arrays consist of a matrix of transmit/receive modules; differences in timing between the signals at each module are used to form and steer the radar beam. However, some satellites, such as the German Defense Ministry's SAR-Lupe constellation (which had its first launch in December 2006), use a conventional reflector antenna. The biggest advantage of an AESA design is the ability to steer the radar beam electronically. AESA antennae are also helpful for canceling clutter and countering electronic jamming. Conversely, a reflector antenna is generally lighter and less expensive than an AESA.

3. House Committee on Appropriations, *Department of Defense Appropriations Bill 2005,* report to accompany H.R. 4613, Report 108-553 (June 18, 2004). A low earth orbit is typically one at an altitude of 500 to 1,000 kilometers.

Modern radars transmit a complicated waveform that consists of a carrier frequency modulated by waves of varying frequencies. In general, higher carrier frequencies (or shorter wavelengths) allow for better image resolution. However, at the frequency range commonly used for radar, signals are attenuated (reduced in strength) in the atmosphere, and the amount of attenuation increases significantly as the frequency rises. Consequently, higher frequencies require greater transmit power to obtain measurable returning radar signals.

Key Technological Challenges

Satellites are typically powered by solar cells and backup batteries (for use when the Earth's shadow blocks out direct sunlight). The notional Space Radar designs that CBO examined would require a similar amount of solar power as other advanced LEO satellites. However, their solar arrays would be smaller and lighter than those of current-generation satellites with similar power requirements, necessitating the development of more-efficient solar cells.

Spacecraft batteries also present a technical challenge. Most current LEO satellites use nickel-based batteries, but some planned LEO satellites may incorporate lithium ion batteries, which can store at least twice as much energy per kilogram of battery mass. Concerns exist, however, about how long those batteries would last given the many cycles of use (and subsequent recharging from the solar arrays) that are required at LEO altitudes. The notional satellite designs that CBO examined would use lithium ion batteries with enough capacity to operate the radar at full power for 30 minutes of each 105-minute orbit. If heavier nickel-based batteries had to be used instead, less power would be available (given constraints on total satellite mass), so the radar's operating time per orbit would be shorter.

In SAR imagery, the resolution of an image is directly related to the bandwidth of the radar signal, which in turn is limited by the system's analog-to-digital converters (ADCs). Those converters are electronic circuits that change returning radar signals from analog into digital form for processing. The Space Radar designs in this analysis would require ADCs capable of sampling an incoming signal at a rate of 1 gigahertz, with 8 to 10 bits of precision. ADCs of that type are just beginning to become available for use in space.

To detect moving targets, a GMTI radar must be able to distinguish the Doppler shift of a target from that of the surrounding terrain. That task is more difficult when the radar is mounted on a satellite that is moving extremely fast relative to the ground. To overcome that problem, engineers propose using a technique known as space-time adaptive processing (STAP), in which the statistical properties of the radar returns from the surface terrain (referred to as ground clutter) are first estimated and then mathematically removed from the incoming signal, leaving only the targets. Development of effective STAP algorithms is crucial if relatively small spaceborne radars are to be used for GMTI. However, a number of technical and operational factors will affect how well those algorithms perform in the Space Radar system.

Space Radar satellites will generate large amounts of raw data, particularly in GMTI mode. Because the algorithms needed to turn those data into usable intelligence are complex, much of the data processing will have to be performed on the ground rather than on the satellites. Thus, the Space Radar system will need a substantial communications downlink capability. The Air Force's planned Transformational Satellite Communications System (TSAT) is one system that could provide enough capacity to ensure that Space Radar intelligence reached users without significant delays in data processing.

Alternative Space Radar Architectures

To evaluate the potential effectiveness and costs of different ways to deploy radars in space, CBO developed four alternative architectures for the Space Radar system (see Summary Table 1). Since no detailed, unclassified "design of record" currently exists for the system, CBO based its alternatives on a variety of other unclassified sources. In particular, the notional radar design for three of the alternatives is based in part on the design of the Discoverer II system, a 1990s effort by the Air Force and other agencies to demonstrate GMTI technologies in space. The Discoverer II program was canceled in 2001 (because of cost and management concerns) before a prototype satellite could be launched, but the characteristics and expected performance of its planned radar are well documented.

This study's reference architecture—dubbed Alternative 2—consists of AESA radars with apertures of 40 square meters on a nine-satellite constellation. To evenly distribute the satellites' access to regions between 60 degrees north and south latitude (home to more than 99 percent

Summary Table 1.

Alternative Space Radar Architectures Examined by CBO

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Number of Satellites	5	9	9	21
Aperture Dimensions	16 x 2.5 m	16 x 2.5 m	25 x 4 m	16 x 2.5 m
Aperture Area	40 m^2	40 m^2	100 m^2	40 m^2
Orbital Configuration[a]	Walker 5/5/1	Walker 9/3/2	Walker 9/3/2	Walker 21/7/3

Source: Congressional Budget Office.

Note: m = meter.

a. In the Walker notation system for constellations of satellites, the first number refers to the number of satellites in the constellation, the second to the number of different planes in which those satellites orbit, and the third to the angular separation (phasing) between satellites in successive orbital planes.

of the world's population), CBO chose a Walker 9/3/2 configuration for the constellation.[4]

For comparison, CBO also examined smaller and larger constellations of satellites with the same 40-square-meter AESA radars. Alternative 1 consists of five such satellites (in a Walker 5/5/1 constellation), and Alternative 4 comprises 21 satellites (in a Walker 21/7/3 constellation).

A radar aperture of 40 square meters may not be adequate for the GMTI mission, however, so CBO also included a larger radar design among its options. Alternative 3 features a nine-satellite constellation with 100-square-meter AESA radars. That radar has the same transmit power as the one in Alternative 2 but requires somewhat more solar-array power because of the greater mass of the satellite and the additional power needed by the radar electronics and processor.

In all of the alternatives, the satellites are assumed to be in circular orbits at an altitude of 1,000 kilometers and an inclination of 53 degrees. Apart from aperture size, the design characteristics of the radars are the same in all four alternatives. CBO chose an AESA design because most recent spaceborne SARs use such antennae and because the steering agility of such a radar greatly increases its utility. The radars in these alternatives operate at a carrier frequency of 10 gigahertz, which offers a compromise between SAR resolution in the along-track direction (see the figure on the inside front cover) and atmospheric attenuation. The radars' transmit power averages 1,500 watts, corresponding to a peak transmit power of 10,000 watts and a radar duty cycle of 15 percent (the fraction of its operating time that the radar antenna is transmitting rather than receiving).

CBO assumed that each Space Radar satellite would have a lifetime of 10 years and that the constellation would operate for 20 years. Thus, each spacecraft would need to be replaced once during the operational lifetime of the system.

Costs of the Alternative Space Radar Systems

Estimates of costs for systems, such as Space Radar, that are defined only conceptually or that depend on the development of new technologies are more uncertain than cost estimates for well-defined programs that use proven technologies. To account for such uncertainty, CBO estimated a range of costs for the Space Radar alternatives in this study. For each alternative, the low estimate represents what the system might cost if few technical difficulties arose in making it fully operational. The high estimate takes into account the cost growth that has

4. The Walker notation system is typically used to describe symmetrical constellations of satellites in circular orbits. The first number of the Walker designation refers to the number of satellites in the constellation, the second to the number of different planes in which those satellites orbit, and the third to the phasing, or the angle separating the satellites in adjacent orbital planes. In a symmetrical constellation, the satellites are divided equally among the orbital planes (which all have the same inclination and are evenly spaced around the globe), and the satellites within a given plane are also evenly spaced.

Summary Table 2.

Estimated Life-Cycle Costs of the Space Radar Alternatives Examined by CBO

(Billions of 2007 dollars)

	Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Low	High	Low	High	Low	High	Low	High
Research and Development	11	19	11	19	14	24	11	19
Procurement[a]	5	6	9	11	17	20	22	27
Operations (Over 20 years)[b]	9	15	15	23	23	33	33	49
Total	**26**	**40**	**35**	**52**	**53**	**77**	**66**	**94**

Source: Congressional Budget Office.

Note: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

a. Includes launch of initial satellites in a constellation.

b. Includes launch of replacement satellites.

commonly occurred for other space-based systems of the Department of Defense.

Including the costs of research and development, procurement, and 20 years of operations, CBO estimated that the cost of the nine-satellite, 40-square-meter radar constellation (Alternative 2) would range from about $35 billion (in 2007 dollars) to $52 billion (see Summary Table 2). Of the other three alternatives that CBO considered, the 21-satellite constellation in Alternative 4 would be the most expensive. Its total life-cycle costs would range from $66 billion to $94 billion, CBO estimated.

In those estimates, procurement costs include the costs involved in launching the initial satellites into low earth orbit (such as purchasing Delta IV or Atlas V launch vehicles). The costs of producing and launching replacement satellites after 10 years are included in the routine costs of operating the constellation. Operations costs also include the costs of collecting and prioritizing requests for use of the radar; generating control commands for the satellites; and then processing, exploiting, and disseminating the data that the satellites provide.

Performance Comparison of the Alternative Architectures

In addition to their costs, CBO compared how well the alternative Space Radar constellations would perform the SAR and GMTI missions according to a variety of measures. Those measures include how big an area the constellations could observe; how much of the time they could observe a specific location; how soon, after receiving a request, a satellite could be in position to view a given location; and how long a single ground target could be tracked. The comparison looked at the different constellations' performance globally (within the latitude band between 60 degrees north and south) and in a particular region (North Korea). Although the Space Radar system is intended to complement other reconnaissance and surveillance systems, for simplicity, this analysis treated Space Radar in isolation.

To keep the analysis unclassified and as widely applicable as possible, CBO focused the comparison on the general capabilities of the different constellations rather than on their performance in specific mission scenarios. However, CBO did use a generalized scenario to examine Space Radar's ability to help the military engage transitory targets—in this case, mobile launchers for tactical ballistic missiles. Besides comparing capabilities, CBO also analyzed the maximum communications bandwidth that each alternative constellation could require.

In regard to the SAR mission, the performance analysis points to several general conclusions about the potential utility of a Space Radar system:

- With only modest advances in technology, Space Radar could provide large amounts of high-resolution SAR imagery. The amount of imagery that could be produced would be proportional to the number of satellites being operated, assuming that sufficient ground-based processing and communications capabilities were available.

- Image resolution as fine as 0.1 meter would be achievable, but less area could be covered at that resolution than at coarser resolutions, such as 1 meter (the current state of the art for civilian spaceborne SARs).[5]

- Although continuous SAR coverage of a region would not be feasible with the constellations that CBO examined, the response times of those constellations should be better than current systems can achieve.

In regard to the GMTI mission:

- Special signal-processing technologies or large radar apertures (like the 100-square-meter aperture that CBO considered) would be necessary to detect ground targets moving slower than about 20 miles per hour.

- Even with better signal processing or large apertures, substantial temporal gaps in coverage can be expected with satellite constellations in low earth orbit.

- Those coverage gaps would make it impractical to track individual ground targets with Space Radar. However, the constellations examined in this analysis could provide indications of the movement of large military units (as long as those units were moving sufficiently fast).

- In the absence of other surveillance systems, much larger constellations than the ones in these alternatives would be necessary to provide targeting information for ground targets, such as individual vehicles, that can change their locations relatively quickly.

Those conclusions depend on the specific assumptions that CBO made about constellation and radar design; different design assumptions would yield different conclusions about performance. In addition, for the results of CBO's performance analysis to be realized, the government and its contractors would have to further develop some of the key technologies described above.

SAR Performance

CBO used three metrics to characterize the SAR imaging capabilities of the alternative constellations. *Access* is the percentage of time that a given geographic location (treated in isolation) can be observed by at least one satellite. *Response time* is the interval between when the Space Radar system receives an order (tasking) to observe a particular location and when a satellite will be in position to view that location.[6] *Coverage,* for the SAR mission, is the total area that can be imaged by a constellation per unit of time, such as a day. (Coverage has a slightly different meaning for moving-target indication.)

All of those performance metrics vary not only with the latitude of the target area but also with the image quality and resolution desired. Higher-quality images and finer resolution require a larger minimum grazing angle (the angle at which the radar beam strikes the ground), which reduces the area that the radar can observe within its normal range of motion. Good quality and fine resolution also require that the radar remain pointed at a given location for a longer period and may limit the width of the range swath that can be used (see the figure on the inside front cover). For all of those reasons, SAR performance—according to the metrics that CBO used—is worse when the desired image quality is high and the resolution is finer.

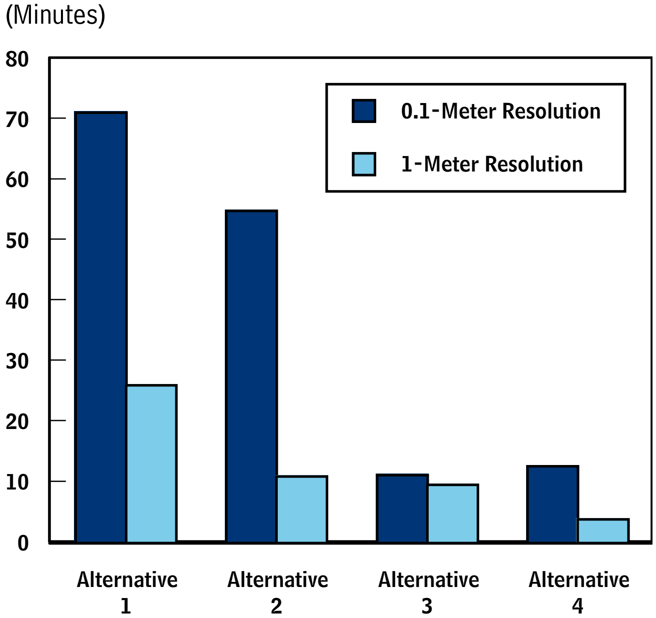
Access. For imagery of a quality that CBO associates with 1-meter resolution, the reference constellation in Alternative 2 would be able to observe a given location below 70 degrees latitude between 10 percent and 20 percent of the time. Access would be greater for the larger radars in Alternative 3 and the larger constellation in Alternative 4 but smaller for the smaller constellation in Alternative 1. For imagery of a quality associated with 0.1-meter resolution, access would be only about 2.5 percent to 5 percent for the reference constellation. At that resolution, the 100-square-meter radars in Alternative 3 would perform

5. CBO assumed that to ensure good image quality, the radar power reflected from the Earth's surface and received at the radar's antenna must be at least four times the level of noise in the system. That constraint imposes a limit on the area that can be imaged at a given resolution.

6. The tasking is assumed to occur at a random time. Because continuous coverage of any target is not possible with the architectures that CBO examined, average response time is always greater than zero. In this analysis, response time does not include any delays in forwarding the tasking to the satellites' controllers or any delays associated with prioritizing multiple requests and transmitting instructions to the satellites.

Summary Figure 1.

Average Response Time to Produce a SAR Image Within North Korea, by Resolution



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

Response time does not include time required for data communications and image processing.

SAR = synthetic aperture radar.

best because they could operate at much smaller grazing angles.

Response Time. If Space Radar was tasked with producing images of a target in North Korea at 1-meter resolution, average response times would range from about four minutes for the 21-satellite constellation in Alternative 4 to about 26 minutes for the five-satellite constellation in Alternative 1 (see Summary Figure 1).[7] In the case of the 40-square-meter radars in Alternatives 1, 2, and 4, average response times would be much longer for images with 0.1-meter resolution: between 13 minutes and 71 minutes. By contrast, the 100-square-meter radars in Alternative 3 would be able to operate at smaller grazing angles even at the finer resolution, so their response time would not be much longer for 0.1-meter imagery than for 1-meter imagery.

Coverage. SAR coverage also varies considerably with resolution (for a fixed image quality). For example, the reference architecture in Alternative 2 could image more than 600,000 square kilometers per day at 1-meter resolution—enough to cover the entire Korean Peninsula—but only about 5,500 square kilometers at 0.1-meter resolution (see Summary Figure 2).[8] For a given radar aperture, coverage increases approximately linearly with the number of satellites in a constellation.

GMTI Performance

To assess how well the alternative Space Radar systems could detect moving targets on the ground, CBO used various metrics, including *access*, *coverage* (in this case, the average area that a constellation can observe continually, rather than per day), and *mean track life* (the average length of time that a single ground target can be tracked).

GMTI performance is directly affected by the relative velocity of the target and the radar. The faster the radar is moving relative to a target, and the smaller the radar's aperture, the more difficult it is to distinguish the motion of the target from that of the surrounding terrain. A spaceborne GMTI radar will be moving thousands of miles per hour faster than its targets on the ground.

CBO assumed that space-time adaptive processing techniques would be used on Space Radar to remove ground clutter from the incoming signal. Since STAP is a relatively new technology, the improvement that it will provide to GMTI performance is uncertain. To reflect that uncertainty, CBO used two different assumptions about STAP performance in its GMTI analysis: an "aggressive" assumption, in which STAP techniques achieve their theoretical level of performance, and a "conservative" assumption, which attempts to account for various practical limitations that STAP might face in the field. For

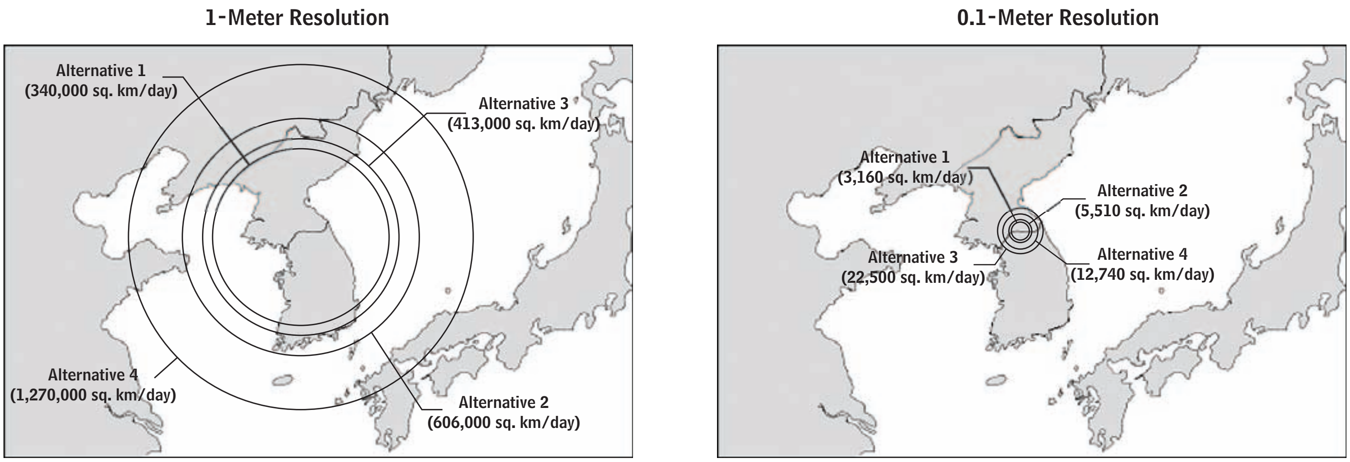
7. Performance at other latitudes is described in the main text of this report.

8. In these alternatives, the average access period for North Korea would last about 5 minutes, whereas the satellites would have enough power to perform full-power SAR for 30 minutes each orbit. Thus, in a given day, the Space Radar system would be able to provide SAR coverage of as many as five other areas of interest at a level similar to that shown here for North Korea.

Summary Figure 2.

SAR Coverage of North Korea, by Resolution

(Area covered per day)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

In all cases, CBO assumed that the entire radar aperture would be used. Alternative 3 could image larger areas at coarse resolutions if only part of the aperture was used.

SAR = synthetic aperture radar; sq. km = square kilometer.

environments where the clutter is very uniform, STAP performance could come near the theoretical limit. For other locations, where the clutter is heterogeneous or otherwise not ideal, performance could be closer to CBO's conservative assumption. (However, CBO lacks data to quantify what degree of conservatism is reflected in the "conservative" assumption.)

Access. Assumptions about signal processing significantly affect the estimated GMTI performance of the Space Radar system. Under the conservative assumption, the 40-square-meter radars in Alternatives 1, 2, and 4 would be able to detect a relatively slow target—such as one moving at 5 meters per second (or about 11 miles per hour)—in only the most favorable viewing geometries. CBO has defined access for GMTI as the fraction of time that at least one satellite can observe and detect a target with a given velocity. The 40-square-meter radars would have access to a 5-meter-per-second target only 1 percent to 7 percent of the time (see the top panel of Summary Figure 3). The 100-square-meter radars in Alternative 3 would perform substantially better because their larger aperture would allow them to use less favorable viewing geometries.

Thus, Alternative 3's constellation would have access to a target moving at 5 meters per second for about 19 percent of the time. Access would be much greater for a target moving at twice that speed: from 12 percent in Alternative 1 to 43 percent in Alternative 4.

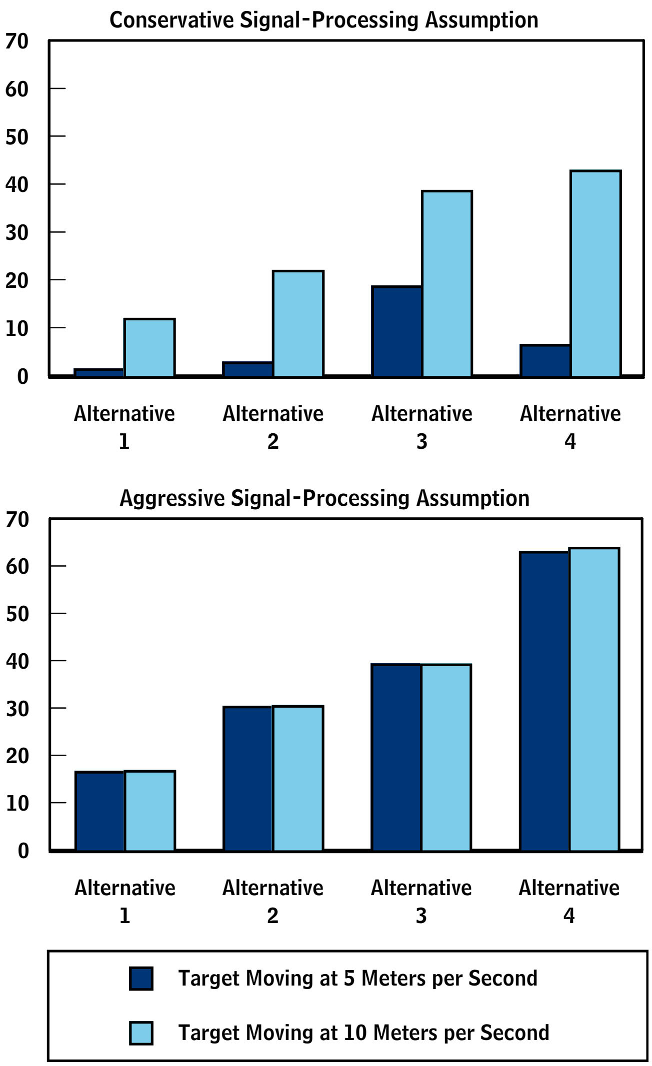
If STAP techniques performed as well as theoretically possible (the aggressive assumption), GMTI access would be nearly identical whether the target was moving at 5 or 10 meters per second. Even so, because of the gaps in coverage between satellite passes, those targets could be observed only between 17 percent and 64 percent of the time.

Coverage. CBO found that once a Space Radar satellite had access to a region, it could provide surveillance of a great deal of terrain. Unlike SAR imagery, which spends just enough time observing an area to produce a static picture, GMTI surveillance regularly revisits the same area to monitor how targets have moved. Thus, GMTI coverage depends on the revisit interval specified by the operator. To observe individual vehicles, an operator may choose to revisit the area as often as every 10 seconds (when the satellites are within range). To observe a large

Summary Figure 3.

Average GMTI Access in North Korea, by Velocity of Target

(Percentage of time)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

These numbers reflect the assumption that Space Radar satellites would be capable of maneuvering while their radars were operating.

GMTI = ground moving-target indication.

military unit, such as a division or corps, a revisit interval of 600 seconds (10 minutes) or longer may be adequate.

At all but the shortest revisit intervals, the alternative radars in this analysis could provide surveillance of fairly large areas. For example, with the sort of revisit intervals appropriate for large-unit surveillance, both the 40- and 100-square-meter radars could observe the entire land area of North Korea. With intermediate revisit intervals, they could observe over 20,000 square kilometers, equivalent to an area spanning the entire width of the Korean demilitarized zone and extending 80 kilometers into North Korea (see Summary Figure 4). With a revisit interval of just 10 seconds and conservative signal-processing performance, the 40-square-meter radars could observe about 8,000 square kilometers (roughly the area of Delaware and Rhode Island combined).

Mean Track Life. CBO used a simple statistical model to simulate the Space Radar system's ability to track an individual target under a range of conditions. The model assumes that the target moves at random and is in the vicinity of other, similar-looking targets that may be confused with the target of interest. Uncertainty exists about both the position and velocity of the target. The amount of uncertainty depends on the performance of the satellite and its radar as well as on the unpredictability of the target's random movement. As the simulation progresses, the uncertainty can build, making it increasingly difficult for a tracking algorithm to differentiate between the real target and the "confusers."

Even under the aggressive signal-processing assumption, Alternatives 1, 2, and 4 would be able to track a single target for less than 4 minutes, on average (see Summary Figure 5). The 100-square-meter radar in Alternative 3 would increase that time to about 5 to 6 minutes, on average. In the absence of other surveillance systems, those track lives are generally too short for a target to be attacked because they are unlikely to provide enough time for strike aircraft to locate the target.

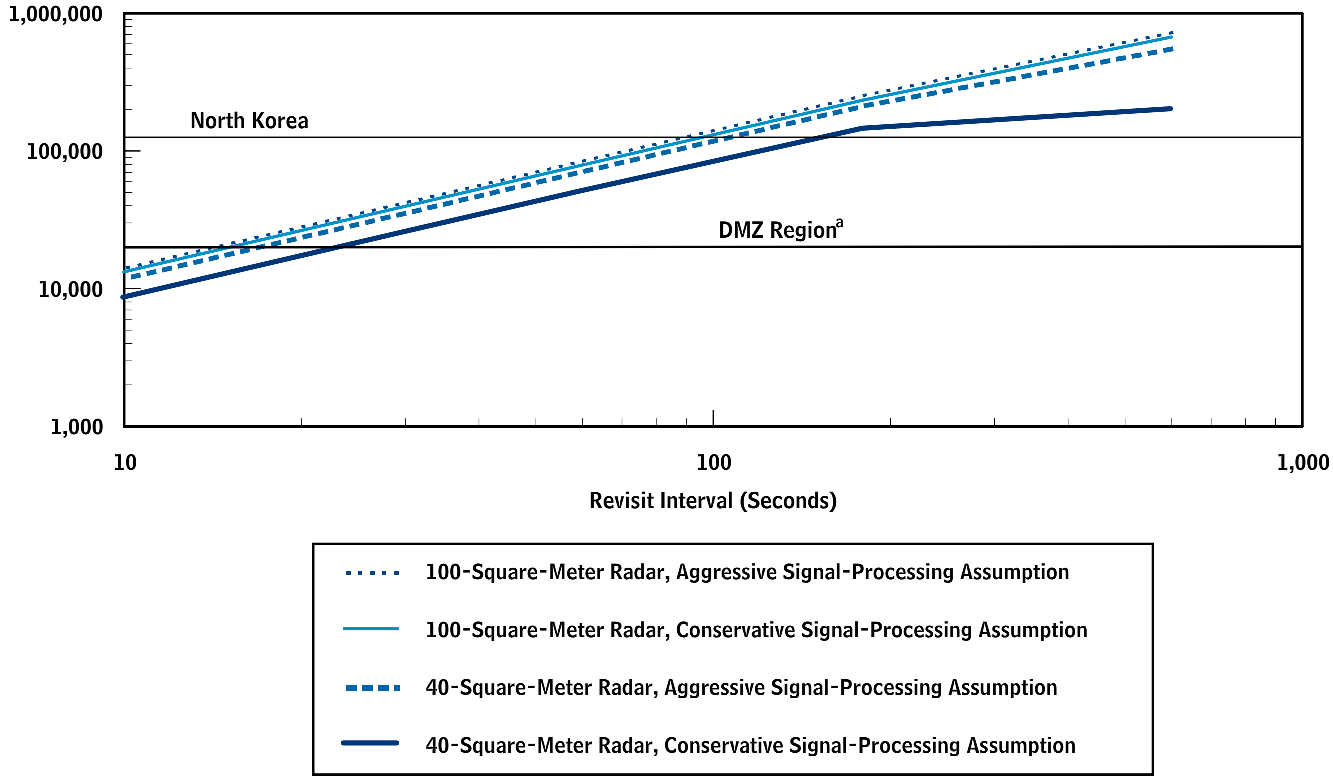
Performance Against Mobile Missile Launchers

To estimate how many satellites would be needed to engage targets that do not stay in place for very long, CBO used a generalized scenario involving mobile launchers for tactical ballistic missiles (such as the ones that launched Scud missiles during the Persian Gulf

Summary Figure 4.

Average GMTI Coverage of North Korea for Targets Moving at 10 Meters per Second

(Square kilometers per access period)



Source: Congressional Budget Office.

Notes: These numbers reflect the assumption that Space Radar satellites would be capable of maneuvering while their radars were operating.

GMTI = ground moving-target indication; DMZ = demilitarized zone.

a. An area spanning the full width of the DMZ and extending 80 kilometers into North Korea.

War). In this scenario, the launch of a tactical ballistic missile is first detected by a satellite of the Air Force's Space-Based Infrared System or the Defense Support Program. Space Radar is then used to track the truck-mounted launcher until a strike aircraft can fly to the area, detect the launcher, and fire at it. CBO assumed that the mobile launcher would start to move within 5 minutes after launching a missile and that, once it had left its known location, the launcher would be impossible to distinguish unambiguously from other vehicles that might be in the area. CBO further assumed that because of command-and-control delays, only 3 to 4 minutes would be available to locate the launcher before it moved.

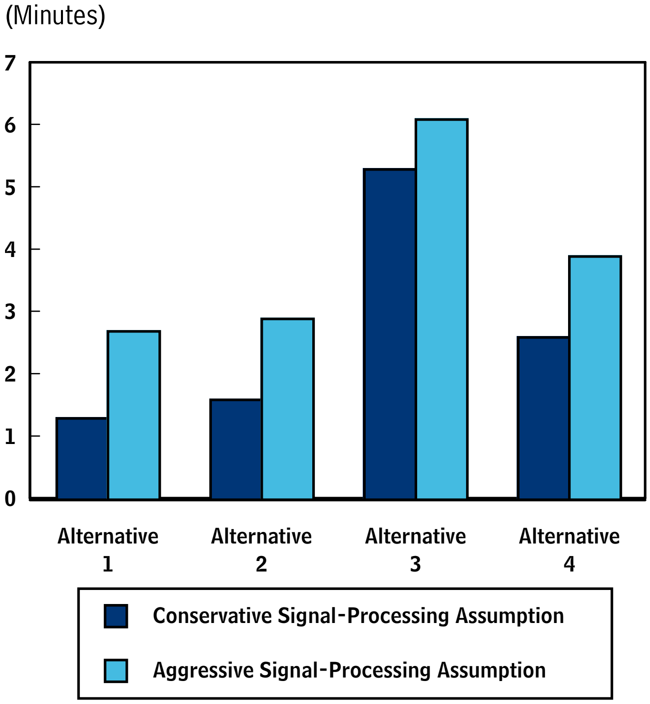
Given the relationship between GMTI response time and the number of satellites in a constellation, CBO concluded that to have a 95 percent probability of locating the mobile launcher before it moved, the Space Radar constellation would require:

- Approximately 35 satellites with 40-square-meter radars under the aggressive signal-processing assumption or with 100-square-meter radars under either signal-processing assumption; or

- Approximately 45 satellites with 40-square-meter radars under the conservative STAP assumption.

Summary Figure 5.

Mean Track Life for a Single Target in North Korea Moving at 10 Meters per Second



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

These numbers reflect the assumption that Space Radar satellites would not maneuver while their radars were operating.

Those results assume that the satellites can maneuver (that is, physically change the direction in which the radar aperture is pointing) while the radar is operating. If that is not possible, about five more satellites will be necessary in either case, CBO estimates.

Data Processing and Communications Bandwidth

Any Space Radar constellation will generate a large amount of data that must be transmitted to the surface (downlinked). CBO assumed that to ensure continuous communications with command, control, and processing facilities, Space Radar satellites would transmit their data to a satellite communications "backbone" system, which would then relay the data to the ground.

Currently, one means of providing high downlink rates is through the National Aeronautics and Space Administration's Tracking and Data Relay Satellite System (TDRSS).[9] In addition, the Air Force is planning the TSAT communications system, which is intended to use laser communications links between satellites and be capable of downlinking as much as 10 gigabits of data per second.

If SAR imagery was fully processed on board the Space Radar satellites, the bandwidth available through a system such as TDRSS would be sufficient for downlinking SAR data. TDRSS has a maximum single-channel downlink capacity of 800 million bits per second (Mbps). By comparison, a 21-satellite constellation producing SAR images of North Korea at 1-meter resolution would need an average downlink rate of about 200 Mbps. That constellation's required downlink rate could peak at more than 800 Mbps for brief periods, in which case, using TDRSS could involve transmission delays of less than a minute. Even higher data rates (and longer potential delays) would occur if that constellation used its full SAR coverage capability to produce images at 0.1-meter resolution. However, such high-resolution imagery is likely to be restricted to the immediate area of interest to facilitate analysis of the images, which would decrease the required downlink rate. Thus, the communications bandwidth of the TDRSS system (assuming that one of TDRSS's six 800 Mbps channels was available)—or of any system providing at least as much capacity as TDRSS—should be sufficient for SAR imagery.

Fully processing SAR data on board the satellites, however, could prove difficult. To CBO's knowledge, no current spaceborne SAR uses full onboard data processing. If some processing was done on the ground, the peak communications bandwidth required would probably exceed the capacity of TDRSS, resulting in delays in processing. Those delays could be avoided if TSAT or some other high-capacity communications system was available.

9. The Department of Defense has not indicated that it would employ TDRSS to downlink Space Radar data. CBO used the system as a benchmark for comparison in this analysis because TDRSS is a widely used, currently available communications system whose performance parameters are well known.

Summary Table 3.

Potential Delays in Transmitting GMTI Data from Space Radar Satellites to the Ground

GMTI Operating Mode	Average Pre-STAP Data Rate (Gbps)	Potential Delay (Minutes): Using TDRSS Ka-Band Channel at 800 Mbps	Potential Delay (Minutes): Using TSAT System at 10 Gbps
Low Range Resolution, Wide Area Scan	1.2	0–4	Negligible
High Range Resolution, Wide Area Scan	18.1	40–180	2–7
High Range Resolution, 10 x 10 km Area, with a 10 Second Revisit Interval	0.2	Negligible	Negligible

Source: Congressional Budget Office based on R.A. Coury and others, *Discoverer II Performance Analysis Tool Modeling Report* (prepared by M.I.T. Lincoln Laboratory for the Defense Advanced Research Projects Agency, July 28, 1999), and Gérard Maral and Michel Bousquet, *Satellite Communications Systems: Systems, Techniques, and Technology,* 4th ed. (Chichester, England: John Wiley and Sons, 2002).

Note: GMTI = ground moving-target indication; STAP = space-time adaptive processing; Gbps = gigabits per second; TDRSS = Tracking and Data Relay Satellite System; TSAT = Transformational Satellite Communications System; Mbps = megabits per second; km = kilometer.

Communications would be even more challenging when Space Radar satellites were operating in GMTI mode. Intelligence on moving targets is particularly time sensitive. Moreover, given the current level of development of STAP techniques, GMTI data are likely to be processed on the ground, requiring a high communications bandwidth.

CBO estimated pre-STAP data rates—the rates at which data would need to be transmitted to the surface—for three potential GMTI operating modes:

- Low resolution in the range direction (15 meters), with a wide area search;
- High range resolution (1 meter), with a wide area search; and
- High range resolution, with the search limited to a single 10-kilometer by 10-kilometer area and a revisit interval of 10 seconds (such as might be used for tracking a single vehicle).

In the first two cases, GMTI data rates would exceed the capacity of TDRSS (see Summary Table 3). In the second case (high range resolution and wide area search), data rates would substantially exceed even the anticipated capacity of TSAT, causing delays of two to seven minutes, CBO estimates. (Those times would be in addition to any delays involved in turning the partially processed data into a usable intelligence product and distributing that product to its end users.) Downlink delays could be reduced or eliminated, however, by reducing the area subject to high-resolution scanning.

CHAPTER

1

Introduction

The Air Force, the National Reconnaissance Office, and the National Geospatial-Intelligence Agency are developing a new radar satellite—known as Space Radar—to complement the military's existing reconnaissance systems. The Integrated Program Office (IPO) for the Space Radar program proposes to begin fielding a constellation of those satellites in about 2015 to perform reconnaissance and surveillance missions and to gather geospatial data for members of the military and the intelligence community.[1] Because the satellites will use radar technology—which relies on reflected electromagnetic waves to reveal information about objects below—they will be able to perform their missions day and night, in almost all weather conditions. Moreover, Space Radar satellites will not face some of the constraints that hinder reconnaissance and surveillance aircraft, such as enemy air defenses or denial of access to airspace. However, the satellites' great distance from the ground and very high speed present challenges that will have to be overcome for the system to perform its missions.

The final design of the Space Radar satellite and the configuration of the constellation have yet to be decided, and a prime contractor has not yet been selected for the program. Reportedly, the IPO is considering a total of about nine satellites in low earth orbit.[2] Such a constellation should provide a relatively quick response time for discovering, monitoring, and analyzing intelligence targets and should be able to revisit a target frequently as the satellites pass by. However, nine satellites would not be enough to provide continuous coverage of a given target from low earth orbit.[3]

1. Geospatial data identify the geographic location and characteristics of natural or man-made features on the Earth.

2. House Committee on Appropriations, *Department of Defense Appropriations Bill 2005,* report to accompany H.R. 4613, Report 108-553 (June 18, 2004).

The Space Radar system will be capable of producing large amounts of radar data. Thus, it will need to be supported by an extensive space and terrestrial communications network. Automated systems for tasking the radar and for processing, exploiting, and disseminating the data will also be necessary.[4] (Much of the processing is likely to take place at ground stations rather than on board the satellites.) The Space Radar system may be able to downlink radar data directly to users in a theater of operations.

Space Radar's Intended Missions

Radars transmit electromagnetic waves and then collect the waves' reflections from objects in their path, including the surface of the Earth. The reflected waves can be analyzed to reveal how far away a given object is (through the elapsed time between transmission and collection of the reflected wave); the object's motion (through changes in the frequency of the wave); and information about the nature of the object (through changes in the spatial orientation, or polarization, of the wave).

Space Radar is being designed to carry out four primary missions for the military and the intelligence community:

- Producing images of various locations using synthetic aperture radar (SAR),

3. The Department of Defense now refers to its goal as being "persistent" coverage rather than "continuous" coverage. For example, the department's 2006 *Quadrennial Defense Review Report* includes among its objectives that "investments in moving target indicator and synthetic aperture radar capabilities, including Space Radar, will grow to provide a highly persistent capability to identify and track moving ground targets in denied areas."

4. In this context, "tasking" refers to directing the radar at a particular target and specifying the mode of operation, and "exploiting" means interpreting the processed data (a task that is partly automated and partly done by hand, as opposed to the fully automated task of processing the data).

- Detecting moving targets on the ground and the surface of the sea,
- Providing high-resolution information about terrain, and
- Performing surveillance of the open ocean.

This study focuses on the first two missions, which the Congressional Budget Office (CBO) considers to be the most critical.

Synthetic Aperture Radar Imaging

Each Space Radar satellite will use its SAR to image areas of interest on the Earth's surface, using transmitted microwaves for illumination (rather than sunlight, as in an optical imaging system). By providing their own illumination, radars can produce images day or night, and microwaves have the advantage of being able to penetrate obscuring layers of clouds (although heavy rain or snow can spoil the images). Because of the nature of the imaging process, however, radar images are somewhat more difficult for imagery analysts to interpret than are images formed by visible light.

In general, the larger the aperture of a radar, the better the radar's energy can be focused and the more returning energy can be collected. Thus, larger radar antennae generally outperform smaller ones. SAR reduces the need for a large physical antenna, however, by taking advantage of the movement of a radar platform—in this case a satellite—to form a "synthetic" aperture. The radar emits a series of pulses as it travels, and the amplitude and timing of the returning energy are recorded. Since the radar beam is fairly wide where it hits the ground, many pulses will be returned for a given area of terrain (or terrain cell). All of the radar returns from that cell that are observable by the radar as it travels are mathematically combined to form an image. The distance traveled by the radar forms a synthetic aperture that is much larger than the radar's physical aperture, which can be quite small.

SAR systems rely on the time delay between transmission and receipt of a radar pulse to determine the distance (range) to a terrain cell; they use the frequency shift of the pulses to distinguish between terrain cells at the same range. Because the radar platform is moving relative to the Earth's surface, the reflected radar signal undergoes a Doppler shift, coming back at a different frequency than the one at which it was transmitted. Signals from different azimuth angles undergo different shifts in frequency, with the amount of the Doppler shift proportional to the azimuth angle.[5] Thus, by measuring the energy of a reflected pulse as a function of time delay (for range identification) and Doppler shift (for azimuth-angle identification), it is possible to determine the radar reflectivity for each range-azimuth terrain cell. Values from the different cells are combined to form a two-dimensional image.

Two main factors determine the resolution of a SAR image: the length of the synthetic aperture and the duration (width) of the radar pulse.

- The synthetic aperture length determines the image's resolution in the azimuth (or along-track) dimension. The longer the aperture, the finer the possible resolution. Aperture length is itself determined by the range to the target, the velocity of the platform, and the radar's wavelength.
- The pulse width of the signal determines the image's resolution in the range (or cross-track) dimension. The shorter the pulse width, the finer the range resolution. The ability to shorten pulses is limited, however, by a radar's peak power capability (longer pulses spread the power out) and by the need to ensure that echoes from consecutive pulses do not overlap at the receiver.[6] To improve resolution without shortening the pulse, modern systems use a method called pulse compression, which modulates the frequency of the pulse so that it contains a range of different frequencies. In those systems, range resolution is expressed in terms of the signal's bandwidth (the frequency range over which the signal is varied in a given pulse), with greater bandwidth providing finer resolution.

Although it is not necessary for producing an image, modern SAR systems typically use phased-array technology, and CBO expects that Space Radar will use that approach.[7] An active phased-array radar consists of a

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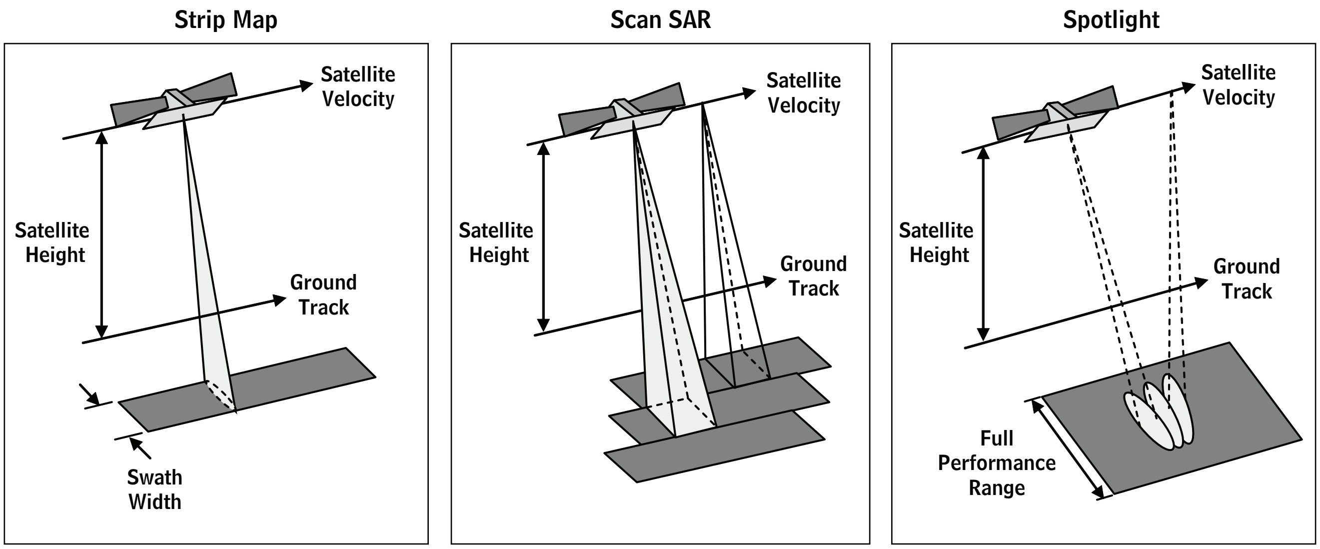
5. For an illustration of azimuth angle and other geometric terms used in this report, see the diagram on the inside front cover. Definitions of those terms can be found in the glossary.

6. Such so-called ambiguity relationships are discussed in Appendix B.

7. Rebecca Christie, "Case for Space Radar May Rest on Fate of Similar System," *Dow Jones Newswires*, March 27, 2006 (available at http://aimpoints.hq.af.mil/display.cfm?id=10228&printer=yes).

Figure 1-1.

Typical SAR Operating Modes



Source: Congressional Budget Office based on information from Infoterra GmbH.

Note: SAR = synthetic aperture radar.

large number of individual transmitting and receiving elements. Varying the phase of the transmitted signals across the array allows the beam to be steered without physically moving the aperture. That agility greatly increases the usefulness of the radar, allowing it to produce images of multiple sites in rapid succession and facilitating advanced operating modes.

Synthetic aperture radars typically use three operating modes: strip map, scan SAR, and spotlight. In strip-map mode, the radar beam is pointed in a fixed direction perpendicular to the velocity vector of the radar platform (see Figure 1-1). The beam sweeps a long strip of terrain, and the processor creates a corresponding long image, or strip map. In scan SAR mode, the beam is slewed to produce images of adjacent strips of terrain. Images from scan SAR generally have coarser resolution than strip-map images because less time is spent imaging each strip. (That need not always be the case, however; the outcome depends on the details of how the satellite is operated.) The third mode, spotlight, is capable of creating the highest-resolution images. In that mode, the radar is continuously steered to keep the beam on one spot, thereby maximizing dwell time (the time during which signals are collected from a given target). Spotlight is a complex mode for radar control and signal processing because the beam must constantly be repositioned during imaging.[8]

Current civilian SARs that are used to provide images of the Earth's surface for scientific or commercial purposes can generate imagery with resolutions as fine as about 8 meters, although designs on the drawing boards claim to be capable of 1-meter or finer resolution. (Selected past, present, and planned SARs are described in the next chapter.) For this analysis, CBO assumed that the bandwidth of the Space Radar system would allow it to produce SAR images with resolutions of much less than 1 meter.

Ground Moving-Target Indication

The Space Radar system is also intended to be able to use its radars to detect moving targets on the ground. The radar energy reflecting off moving targets has a different Doppler shift than that of the radar pulses reflecting off the surface around them. Through careful signal processing, that difference in Doppler shift can be detected and used to highlight the locations of moving targets. Ground moving-target indication (GMTI) is used to continuously monitor large areas. Unlike synthetic aperture radar, which produces an image (akin to a photograph), GMTI shows the operator an indication of the location

8. See J.C. Toomay and Paul J. Hannen, *Radar Principles for the Non-Specialist* (Raleigh, N.C.: SciTech, 2004), pp. 188–196.

of moving targets, typically represented as dots, which can be superimposed on a map or image of the terrain.

The U.S. military operates a number of GMTI systems on aircraft. One example is the Air Force's E-8 Joint Surveillance Target Attack Radar System, or JSTARS, a modified Boeing 707 that carries a side-looking, phased-array radar for detecting targets in motion.

GMTI will be more difficult to perform from space than from aircraft. The radar energy returning from a target competes with strong returns from the "ground clutter" around it (other objects near the target, including the ground itself, vegetation, or buildings). As in SAR imaging, the Doppler shift of that clutter's return will vary across the radar beam. The Doppler shift of the target must be large enough that the target can be distinguished from the clutter. That requirement means that either the target must be moving relatively fast or the radar antenna must be large, which yields a narrow Doppler spread for the clutter. Engineers have developed a signal-processing technique known as space-time adaptive processing (STAP), which uses knowledge about the statistical composition of clutter to filter it out of an incoming signal. Although that technology is still in the development phase, it holds the potential to greatly improve the performance of GMTI systems. (The challenges of STAP technology are discussed in more detail in Chapter 3.)

High-Resolution Terrain Information and Open-Ocean Surveillance

Another mission of Space Radar will be to precisely measure the elevation of terrain. If SAR images of the same area are collected from two slightly different angles, small timing differences between the radar returns used to form the two images can be analyzed to estimate the terrain height (through a technique known as interferometric SAR). In addition, the Space Radar system will be able to observe wide areas of the oceans to monitor the traffic of large ships. In this analysis, CBO did not examine Space Radar's ability to perform either of those missions, which it considered to be of lower priority than SAR imaging and GMTI.

CBO's Analytic Approach

The Space Radar Integrated Program Office has not yet decided on an architecture for the Space Radar system. Therefore, to evaluate the system's possible costs and effectiveness, CBO used unclassified published studies to create four alternative architectures that would meet the principal mission objectives for Space Radar. In doing so, CBO developed two different notional designs for the Space Radar satellites and then grouped those satellites into hypothetical constellations of various sizes. (The different alternatives are described in Chapter 3.)

To compare the alternative architectures, CBO estimated the total cost of each option, including costs for research and development, production, launching of the satellites, and 20 years of operations. (Those cost estimates are also discussed in Chapter 3.) CBO then analyzed the ability of the different radar designs to perform the SAR and GMTI functions and evaluated the capabilities of the full constellations according to fairly simple, common measures—such as the fraction of time they could observe a given target, how soon after receiving a tasking order they could move into position and detect the target, and how large an area the radars could cover. (That performance comparison is the subject of Chapter 4.) In conducting its analysis, CBO opted for that general approach—rather than using detailed mission scenarios or focusing on specific threats—in order to keep the study unclassified and as widely applicable as possible.

Space Radar is intended to operate as part of a larger network of reconnaissance and surveillance systems. Analyzing the entire network would require having a concept of operations for Space Radar as well as for the other systems, a detailed mission scenario, and an extensive simulation model. To keep the analysis unclassified and relevant to a wide range of scenarios, CBO examined the capabilities of Space Radar in isolation from other systems.

None of the notional architectures in this study are likely to represent the final design for Space Radar, in part because the number of possible combinations of design parameters is nearly infinite. Two teams of contractors are currently performing trade-off studies for the IPO; a prime contractor is not scheduled to be chosen until 2009. Furthermore, CBO did not consider the requirements imposed by the need to provide high-resolution terrain information or perform open-ocean surveillance. Thus, rather than describing the capabilities of the specific Space Radar system that may eventually be fielded, the results presented in this study are meant to suggest the operational capabilities that could be achieved for different levels of investment, given the anticipated state of technology.

CHAPTER

2

Past and Present SAR and GMTI Platforms

The Space Radar system would by no means be the first synthetic aperture radar to orbit the Earth. The United States and other nations have flown a number of spacecraft with imaging SARs, beginning in the late 1970s. Several SARs have also been successfully sent into space to produce images of other planets. Interest has been growing worldwide in using SAR imagery to observe the Earth for such purposes as managing natural resources, monitoring vegetation, studying geology and climate, and responding to disasters, as well as for national security purposes. Several SAR satellites are now operating, and several more are planned for launch in the near future. However, none of those spacecraft will have the capabilities expected of the Space Radar system. Moreover, to the Congressional Budget Office's knowledge, no systems exist that routinely perform Space Radar's other primary mission—ground moving-target indication—from space.

The U.S. military operates a number of airborne platforms equipped with SAR and GMTI radar. Those aircraft (some manned, others unmanned) conduct intelligence, surveillance, and reconnaissance missions for theater commanders and joint-task-force commanders.

Previous SAR Spacecraft

The first spacecraft to carry a synthetic aperture radar was SEASAT, which was built by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration (NASA) and launched in 1978. SEASAT was used mainly to measure the height and motion of ocean waves and to produce images of sea and freshwater ice and snow cover. It flew in a nearly circular polar orbit at an altitude of about 780 kilometers and used a single-polarization L-band radar.[1] (For a description of different radar bands, see Box 2-1.) SEASAT produced images with 25-meter resolution for 105 days before an electrical failure ended its mission.

NASA twice flew a radar similar to SEASAT's on the space shuttle in the 1980s. Those SARs were known as the Spaceborne Imaging Radar (SIR) A and B. Slight changes in bandwidth allowed those instruments to create images with resolutions of 40 meters and 25 meters, respectively. Other SAR experiments on the space shuttle were conducted in 1994 and involved the second-generation SIR-C/X-SAR radar. That radar combined L-, C-, and X-band antennae at multiple polarizations to produce images with 30-meter resolution for use by environmental scientists.

In a February 2000 space shuttle mission, the primary SIR-C/X-SAR radar antenna was augmented by the addition of C-band and X-band antennae at the end of the 60-meter mast. Those additional antennae enabled the shuttle to perform a radar topography mission, in which operators used a technique called interferometry to combine the signals from the two sets of antennae to measure the height of terrain on all of the Earth's land surface between 60 degrees north and 56 degrees south latitude.

The Soviet Union, Europe, and Japan also flew a number of Earth-observing SAR spacecraft in the 1980s and 1990s. One of the early Soviet examples was the massive (18,550-kilogram) Cosmos 1870, which used components from the Salyut space stations. Cosmos 1870, also called Almaz-T, was launched in 1987 and provided radar imagery for two years. In 1991, the Soviets launched an improved version of Almaz, designated Almaz 1, into an orbit with an altitude of 270 kilometers and an inclina-

1. Polarization refers to the angular alignment of the wave transmitted by the radar. Early SARs could transmit in only one alignment and receive the same component of the reflected wave. Modern systems can transmit and receive waves aligned in multiple directions. In such systems, different polarizations can be combined to provide additional information about the area being imaged.

Box 2-1.

Radar Bands

Radars provide information about targets by transmitting electromagnetic waves and then collecting the reflected waves (or radar echo) that come from the targets. Analysis of the reflected waves can reveal details of the target's distance, movement, and other characteristics.

Modern radars transmit very complicated waveforms, which allow several types of information about a target to be collected at once. The radars considered in this study transmit waves in a series of pulses, which repeat at some pulse repetition frequency. Each pulse consists of waves of a central (or carrier) frequency, which are added to waves that change frequency over the duration of the pulse. The range over which those frequencies change in a given pulse is referred to as the radar bandwidth. Each of the characteristics of the waveforms—pulse repetition frequency, carrier frequency, and bandwidth—affects the performance of the radar.

Radars are usually categorized in terms of their carrier frequency. The interaction between electromagnetic waves of that frequency and the atmosphere determines, for a given transmit power, the maximum range of a radar. The carrier wavelength (expressed as the speed of light divided by the carrier frequency) is roughly equivalent to the potential resolution of the radar.

For purposes of categorization, the part of the electromagnetic spectrum commonly used by radars (and some other devices that use electromagnetic waves) is separated into frequency bands. The earliest radars operated in the high frequency (HF) or very high frequency (VHF) bands, with frequencies between 3 and 300 megahertz (see the figure at right). Modern radars generally operate at microwave frequencies, between 1 and 40 gigahertz (GHz). Frequency bands in the microwave region are often referred to by letter designations (which were introduced for security purposes during World War II but are still in use today):

- L Band—frequency of 1.0 to 2.0 GHz, wavelength of 15 to 30 centimeters;
- S Band—frequency of 2.0 to 4.0 GHz, wavelength of 7.5 to 15 centimeters;
- C Band—frequency of 4.0 to 8.0 GHz, wavelength of 3.75 to 7.5 centimeters;
- X Band—frequency of 8.0 to 12.5 GHz, wavelength of 2.4 to 3.75 centimeters; and
- Ku, K, and Ka Bands—frequency of 12.5 to 40 GHz, wavelength of 0.75 to 2.4 centimeters.

Each of those microwave bands is particularly suited to specific applications.[1] (The S band, for example, is well suited to accurate measurement of rainfall rates.) All of the current and planned synthetic aperture radars that are mounted on satellites operate in the L, C, or X band.

1. For a full discussion of the advantages of various frequency bands, see Merrill I. Skolnik, ed., *Radar Handbook* (New York: McGraw-Hill, 1990), pp. 1.14–1.20.

tion of 72.7 degrees.[2] Almaz 1 returned imagery with 10-meter to 15-meter resolution for 18 months.

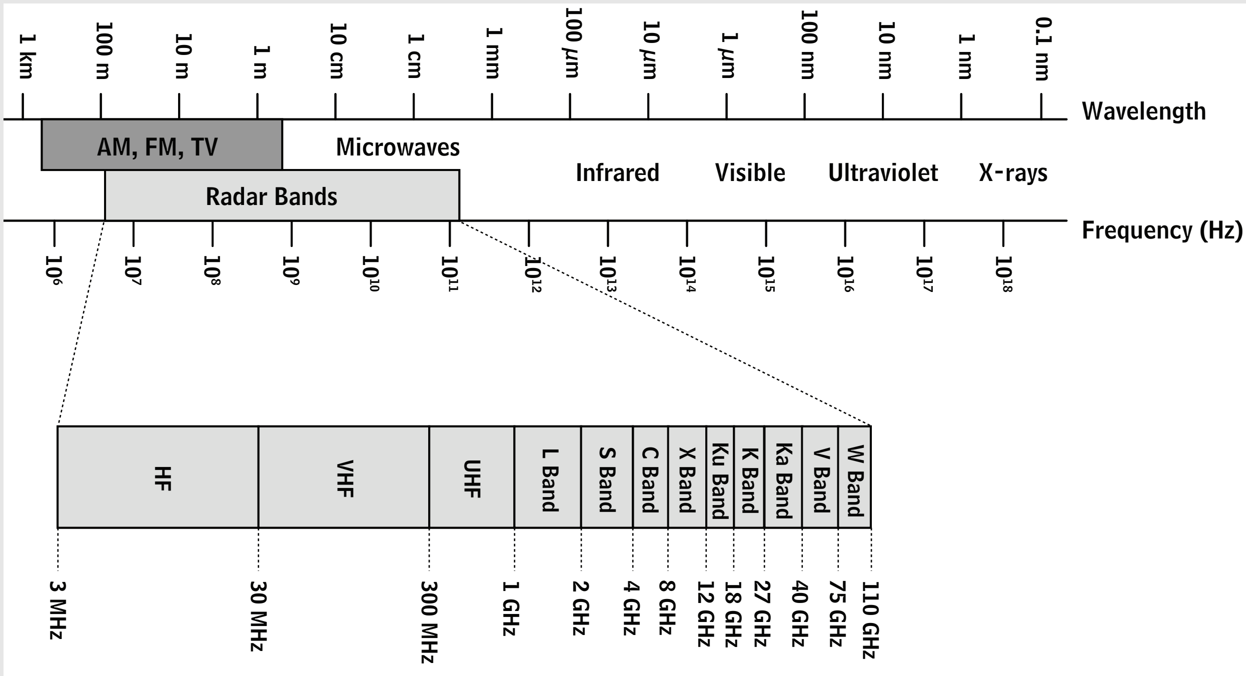
2. Inclination is the angle between the plane of a spacecraft's orbit and the equator. An inclination of zero degrees means that the craft orbits the equator, and an inclination of 90 degrees means that it passes over the poles.

Also in 1991, the European Space Agency launched the European Remote Sensing Satellite 1 (ERS-1), which contained a suite of instruments including a single-polarization C-band SAR. Orbiting at an altitude of 775 kilometers and an inclination of 98.5 degrees, ERS-1 provided images with 10-meter to 30-meter resolution for about nine years.

Box 2-1.

Continued

The Electromagnetic Spectrum and Radar Bands



Source: Congressional Budget Office.

Note: km = kilometer; m = meter; cm = centimeter; mm = millimeter; µm = micrometer; nm = nanometer; Hz = hertz; MHz = megahertz; GHz = gigahertz; HF = high frequency; VHF = very high frequency; UHF = ultrahigh frequency.

The Japanese National Space Development Agency launched its first SAR spacecraft, JERS-1, in 1992. That satellite orbited at a height of 568 kilometers and an inclination of 98 degrees. JERS-1, which featured an L-band SAR with single polarization, returned imagery with 18-meter resolution for about six years, until the spacecraft failed.

Current SAR Spacecraft

As of mid-2006, at least four civilian Earth-observing SAR satellites were in orbit: the European Space Agency's ERS-2 and Envisat/ASAR, the Canadian Space Agency's RADARSAT-1, and the Japanese Aerospace Exploration Agency's ALOS/PALSAR. All of those satellites have nearly circular, sun-synchronous orbits (in which the orbit precesses so as to maintain approximately constant orientation to the sun). That type of orbit is very common for satellites designed to monitor natural resources because observations can be made under the same sunlight conditions on each orbital pass and because the high inclination provides worldwide coverage.

The European ERS-2 was launched in 1995. Its orbit and design are identical to those of ERS-1, although it includes an additional instrument for measuring atmospheric ozone levels. A series of gyroscope failures resulted in the degradation of some data, and the spacecraft's data-storage tape drive failed in 2003. As a result, ERS-2's instruments can now be operated only when the satellite is in view of a ground station.

Envisat was launched in 2002 to ensure continuity of Earth-observation data after the anticipated failure of

Table 2-1.

Design Characteristics of SAR Spacecraft Now in Development

	RADARSAT-2	TerraSAR-X	SAR-Lupe	COSMO-Skymed
Sponsor	Canadian Space Agency	German Aerospace Center	German Defense Ministry	Italian Space Agency, Defense and Research Ministries
Prime Contractor	MacDonald Dettwiler and Associates	EADS Astrium	OHB-System	Alenia Spazio
Number of Satellites	1	2	5	4
Antenna Size	15 x 1.37 m	4.8 x 0.7 m	3.3 x 2.7 m	5.7 x 1.4 m
Mass	2,300 kg	~ 1,000 kg	770 kg	1,700 kg
Altitude	798 km	514 km	500 km	620 km
Orbital Inclination	98.6°	97.4°	~ 90°	97.9°
Center Frequency	5.4 GHz (C band)	9.65 GHz (X band)	X Band	9.6 GHz (X band)
Radar Bandwidth	100 MHz	295 MHz	Unknown	Unknown
Data Downlink	X Band, 2 x 105 Mbps	X Band, 2 x 150 Mbps	X Band	X Band, 300 Mbps
Solar-Cell Power	3,156 watts[a]	1,800 watts[a]	Unknown	3,600 watts[b]
Peak Transmit Power	2,280 watts	2,260 watts	Unknown	Unknown
Image Resolution	3 m	~ 1 m	< 1 m	< 1 m
Design Life	7 years	5 years	10 years	5 years

Source: Congressional Budget Office.

Note: SAR = synthetic aperture radar; m = meter; kg = kilogram; km = kilometer; GHz = gigahertz; MHz = megahertz; Mbps = million bits per second.

a. Power at beginning of life.

b. Power at end of life.

ERS-2. Envisat carries 10 instruments, the largest of which is the Advanced Synthetic Aperture Radar, or ASAR. That radar operates in the C band with multiple polarizations and produces 28-meter imagery.

Canada's RADARSAT-1 was launched in 1995 by NASA (in exchange for access to its data) into a circular orbit about 800 kilometers high at 98.6 degrees inclination. Early the following year, the satellite's C-band SAR began providing imagery with up to 8-meter resolution to government and commercial users.

The Japanese launched their Advanced Land Observation Satellite (ALOS) in January 2006 into a 692-kilometer circular orbit. ALOS has multiple instruments for Earth observation, one of which is the Phased Array L-Band Synthetic Aperture Radar, or PALSAR. That radar should provide imagery with 10-meter resolution.

Designs for Planned SAR Spacecraft

Canada, Germany, and Italy are currently completing new Earth-observing SAR spacecraft for launch in the near future (see Table 2-1). The German and Italian efforts involve constellations of satellites. Those spacecraft are intended to serve both military and civilian users and offer finer-resolution images than have previously been available.

The Canadian Space Agency is developing RADARSAT-2 as a successor to the current RADARSAT-1, which is nearing the end of its service life. Like its predecessor, RADARSAT-2 will operate in the C band, but the radar will have greater bandwidth, allowing for images with 3-meter resolution. RADARSAT-2 will also offer multiple polarizations, and the satellite will be able to roll (rotate around its direction of motion) so that it can capture images on either side of the ground track, greatly reducing response times. RADARSAT-2 is scheduled to be launched in March 2007 on a Russian Soyuz booster.

The German Aerospace Center is developing the TerraSAR-X satellite for launch in late 2006 or early 2007 on a Russian-Ukrainian Dnepr rocket. TerraSAR-X features an X-band SAR that will be capable of producing imagery with 1-meter resolution. TerraSAR-X also carries a laser terminal that will be used to test high-bandwidth satellite-to-satellite communications. The German Aerospace Center plans to launch a nearly identical second satellite, dubbed TanDem-X, in 2009.

In addition, the German Defense Ministry is developing a constellation, called SAR-Lupe, of five X-band radar satellites. The first satellite was launched in December 2006. Whereas most other SAR satellites in operation or development rely on electronically scanned array antennae, SAR-Lupe features a parabolic reflector antenna. Consequently, pointing the radar beam will require maneuvering the satellite. The satellite's developer, OHB-System of Bremen, asserts that SAR-Lupe will produce images with better than 1-meter resolution. According to a published report, OHB-System is offering a satellite based on the SAR-Lupe design to other governments for 40 million euros (about $50 million).[3]

The Italian Space Agency is planning to orbit four COSMO-Skymed spacecraft beginning in 2007. The synthetic aperture radars on those satellites will operate in the X band and reportedly produce imagery with resolutions of less than 1 meter. The COSMO-Skymed system is intended to serve both civilian and military users and is being partly funded by the Italian Ministry of Defense. According to an industry analyst, the contract for the first three spacecraft totaled 775 million euros (about $1 billion), with a later contract for the fourth satellite expected to cost 116 million euros (about $150 million).[4]

Airborne SAR and GMTI Systems

The U.S. military currently operates several manned and unmanned reconnaissance aircraft that perform SAR imaging and GMTI collection. Manned aircraft include the U-2, the RC-7 Airborne Reconnaissance Low (ARL), and the E-8C Joint Surveillance Target Attack Radar System (JSTARS). Unmanned aircraft include the MQ-1 Predator and the RQ-4 Global Hawk.

First flown in 1955, the U-2 is used by the Air Force for theater-level high-altitude reconnaissance and surveillance. The latest version, the Lockheed Martin U-2S, can carry a variety of payloads, including electro-optical, infrared, and SAR imagers; a film camera; and signals-intelligence equipment. The aircraft's latest Advanced Synthetic Aperture Radar System (ASARS-2A) payload has both imaging and GMTI capabilities.[5] The Air Force currently has about 30 U-2s in its inventory.

The Army operates a small number of RC-7 ARL aircraft (modified versions of the DeHavilland Dash-7 turboprop) to collect theater-level and tactical intelligence. The ARL can be equipped with communications-, signals-, and imagery-intelligence payloads, including a SAR with GMTI capability. The RC-7's SAR is capable of producing images with 1.8-meter resolution.

The E-8C JSTARS is a modified Boeing 707-300 aircraft that carries a side-looking, 24-foot-long, phased-array radar. Its primary mission is to provide theater commanders with ground surveillance (including moving-target indication). The JSTARS antenna can be tilted to either side of the aircraft to provide a 120-degree field of view covering nearly 50,000 square kilometers. JSTARS can detect ground targets at ranges of more than 250 kilometers. The Air Force's 116th Air Control Wing operates the 17 E-8C aircraft.

The Air Force's MQ-1 Predator is a fixed-wing, propeller-driven unmanned aerial vehicle designed to perform surveillance and reconnaissance missions for long periods at altitudes as high as 25,000 feet. The Predator has been in operation since 1995, when it was used to observe targets

3. With launch into low earth orbit included, the price tag is less than 60 million euros (about $75 million). See "OHB-System Shopping Radar Satellite Design," *Space News On-Line*, July 7, 2003 (available at www.space.com/spacenews/archive03/parisbriefsarch_070703.html).

4. Deagel.com, "COSMO-SkyMed," available at www.deagel.com/pandora/cosmo-skymed_pm00353001.aspx.

5. The performance characteristics of ASARS-2A are classified.

in Bosnia. The Predator can be equipped with a SAR capable of 1-foot resolution. The Air Force currently operates 57 Predators in three squadrons.

The Air Force's RQ-4A Global Hawk is a turbofan-powered, high-altitude unmanned aerial vehicle that is also designed to perform for long periods (reportedly, up to 35 hours). It provides imagery intelligence using electro-optical, infrared, and SAR imagers. Global Hawk's SAR can produce spotlight-mode imagery with 1-foot resolution and also perform moving-target indication. Global Hawk can operate more than twice as high as Predator: at altitudes of up to 65,000 feet.

Discoverer II GMTI Program

In the late 1990s, the Air Force, the Defense Advanced Research Projects Agency, and the National Reconnaissance Office began a program to demonstrate GMTI technologies in space. The program, called Discoverer II, planned to launch two prototype satellites equipped with active electronically scanned array (AESA) radars into low earth orbit. The program was motivated by a desire to improve the reconnaissance and surveillance support available to theater and joint-task-force commanders. A significant amount of that support is now provided by aircraft, which are less able than orbiting satellites to cover widely dispersed areas persistently over long periods of time.

The Congress and the President eliminated funding for the Discoverer II program in 2000 because of concerns about its high costs; lack of stated requirements, operational concepts, or trade-off analyses; and potential impact on "overtaxed" existing systems for processing, exploiting, and disseminating imagery.[6] Following the cancellation of Discoverer II, the Air Force initiated the Space-Based Radar (now Space Radar) program.

Discoverer II was intended to feature an AESA radar of 40 square meters that would operate in the X band at 10 gigahertz. The program planned to place the two prototype satellites in circular orbits at altitudes of 770 kilometers and inclinations of 53 degrees. After a successful demonstration, the Defense Department hoped to deploy a constellation of about 24 satellites to provide "near-continuous" surveillance of selected targets as well as rapid acquisition and tracking of mobile time-critical targets. The cost goals for the program were a unit production cost of less than $100 million for the satellites and a total program cost of less than $10 billion over 20 years.[7] Because the characteristics and performance of Discoverer II's radar are well documented, CBO based the design of its notional Space Radar on that of Discoverer II (with some modifications).

6. House Committee on Appropriations, *Department of Defense Appropriations Bill 2001*, report to accompany H.R. 4576, Report 106-644 (May 25, 2000).

7. U.S. Air Force Space and Missile Systems Center, "Fact Sheet: Discoverer II Joint Program" (available at www.losangeles.af.mil/SMC/PA/Fact_Sheets/discoverer_2.pdf).

CHAPTER

3

Design Trades, Key Technologies, and Alternative Architectures for Space Radar

The operational effectiveness of a Space Radar system depends on both the physical locations of the orbiting satellites and their individual capabilities. Satellite capability in turn depends on many factors, such as the size and type of radar antenna used, its transmission power, the type of waveform it sends, and the data-processing power and communications capacity of the system, to name a few. Each of those factors requires a host of design decisions, some of which may be constrained by the limitations of available technologies. This chapter discusses the pros and cons of some of those design trade-offs and examines various technologies that could limit the performance of the Space Radar system. It also describes the alternative notional architectures for Space Radar that the Congressional Budget Office analyzed and the potential costs of the alternatives.

Trade-Offs in Designing a Space Radar System

Systems engineers must consider a wide range of issues when designing a radar satellite. In particular, at what altitude should the satellite orbit? What kind of antenna should the radar use? At what frequencies should it transmit signals? In each case, the various options that are available have different strengths and weaknesses that affect the performance of the system.

Orbital Altitude and Inclination

The first concern when choosing an orbit is the nature of the space environment in which a satellite will operate. That environment depends primarily on altitude. Below about 500 kilometers, the atmosphere is still sufficiently dense that the drag from traveling through it will degrade a satellite's orbit and shorten the satellite's operational life. At higher altitudes, radiation can pose a problem. The Earth's magnetic field captures charged particles from cosmic and solar radiation and traps them in bands, called Van Allen belts, at certain altitudes. High radiation levels can destroy unhardened electronics and will reduce the performance of even hardened electronics over time.

To minimize exposure to radiation, satellites are typically deployed in one of three altitude ranges:

- 500 to 1,000 kilometers, referred to as low earth orbit (LEO);
- 5,000 to 15,000 kilometers, referred to as medium earth orbit (MEO); or
- 20,000 kilometers and higher, with the most common altitude being about 36,000 kilometers (a geosynchronous orbit in which a satellite will complete one full pass around the Earth in 24 hours).[1]

Benefits and Drawbacks of Various Altitudes. Choosing between a low earth, medium earth, or geosynchronous orbit generally represents a trade-off between having more-numerous, less-capable satellites at lower altitudes and having fewer, more-capable satellites at higher altitudes. With radar satellites, the transmitted signal must travel to the Earth, be reflected at the surface, and then travel back to the satellite for detection. As the range to the surface increases, the strength of the radar echo received at the satellite diminishes rapidly, decreasing by a factor that is equivalent to dividing by that range to the fourth power. (For example, if the range doubles, the strength of the received radar echo will be one-sixteenth of what it was at the original range.) Thus, a satellite at a higher altitude must transmit its signals with much

1. When a geosynchronous orbit is above the equator, it is referred to as geostationary, because the satellite appears fixed over a spot on the Earth.

greater power to receive a detectable echo. That requirement generally necessitates a larger, more expensive satellite, with a bigger solar array for power and a larger radar antenna. However, since a satellite at a higher altitude can view more of the Earth's surface at any one time than a lower satellite can, high-altitude constellations require fewer satellites to achieve a given level of global coverage.

Altitude can also affect the potential operational lifetime of a satellite by limiting how long its batteries will last. As satellites orbit, they can pass through the shadow of the Earth, undergoing a brief solar eclipse. Satellites at lower altitudes, being closer to the Earth, spend more time in those eclipses. For example:

- A satellite at 10,000 kilometers (medium earth orbit) spends an average of 12 minutes of each 348-minute orbit in shadow and undergoes an average of about 500 eclipses per year, whereas

- A satellite at 1,000 kilometers (low earth orbit) spends an average of 27 minutes of each 105-minute orbit in shadow and experiences an average of about 4,400 eclipses per year.[2]

During those eclipses, the satellite operates from batteries, which are then recharged by the solar arrays when sunlight is available. The power-storage capacity of the batteries typically declines over the course of many such discharge/recharge cycles. Thus, the lifetime of a satellite can be limited by the number of discharge/recharge cycles that its batteries undergo, and the extent of the allowable discharge can constrain the satellite's operations during eclipses.

Altitude can also affect the ability of the Space Radar system to detect moving targets. As altitude increases, the orbital velocity of a satellite decreases, and that lower velocity makes it easier for signal-processing algorithms to differentiate slow-moving ground targets from background clutter.

On the whole, higher altitudes offer some significant advantages: more viewing area per satellite, longer satellite lifetimes, and (potentially) better GMTI. However, the power and antenna-size requirements for operating at higher altitudes present design challenges. For those reasons, all current Earth-observing synthetic aperture radar satellites operate in low earth orbit.

Potential Problems with Medium Earth Orbits. Deploying a very large radar antenna in space—such as would be required at medium earth orbit—would be technically challenging. For an active electronically steered array radar (the kind that CBO anticipates for Space Radar) to operate properly, all of the transmitting components of the antenna need to be aligned precisely into a single plane. Any deviations from precise planarity degrade the system's performance. A design rule of thumb is that arrays need to be planar to within 5 percent of the radar's wavelength over the entire array (or to less than 2 millimeters for a 10 gigahertz signal). The larger the array, the more difficult it becomes to achieve that precision. The "brute force" answer to that design problem is to use a very rigid structure to hold the array, but that may not be feasible in space, where constraints on mass necessitate a light support structure. Moreover, to fit into a launch vehicle, the AESA will need to be folded into a small volume (and then unfolded for deployment once the satellite is in orbit), so a single rigid structure is not possible.

Further challenges to maintaining alignment over a large array include thermal expansion as the array passes into and out of the Earth's shadow, mechanical stresses as the satellite rotates into viewing position, and impacts to the surface of the array from tiny meteorites. If the system could not adequately correct for such effects electronically (by inserting small delays into the signals), it might require actively controlled structures, in which sensors embedded in the structure sensed tiny deflections, and tens or hundreds of electromechanical actuators constantly applied forces to compensate for those deflections.

Despite the potential difficulty of deploying a large array, some concepts for a Space Radar system at MEO altitudes have been developed. For example, the Defense Advanced Research Projects Agency is working on the Innovative Space Based Radar Antenna Technology (ISAT) project, which is planning to launch a test satellite with a 100-meter-long AESA radar into low earth orbit. The project's eventual goal is to field a 300-meter-long array in medium earth orbit to perform both SAR imaging and GMTI.[3] That large an array—roughly 10 times

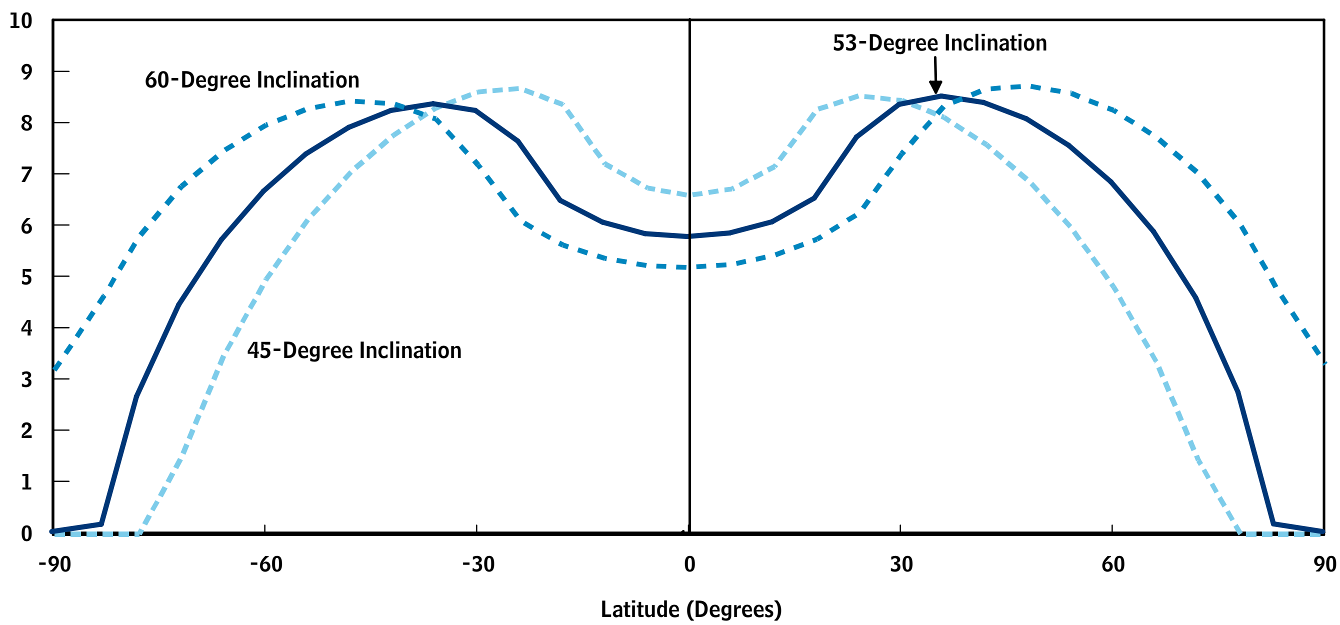
2. Those numbers apply to satellites with an orbital inclination of 53 degrees (the inclination assumed for the alternative Space Radar constellations examined in this report).

3. "DARPA Funds Further ISAT Development," *Defense Industry Daily* (May 26, 2005), available at www.defenseindustrydaily.com/2005/05/darpa-funds-further-isat-development/index.php.

Figure 3-1.

SAR Satellite Access at Different Orbital Inclinations

(Percentage of time)



Source: Congressional Budget Office.

Note: SAR = synthetic aperture radar.

the size of the ones considered in this report—would be required at MEO altitudes to obtain manageable power density in the array and a sufficiently small beam spot on the Earth's surface. (The larger the antenna, whether an electronically steered array or a dish, the narrower the beam.) A structure of such large size is unprecedented in space and presents many engineering challenges, to say nothing of its potential cost. Consequently, CBO did not consider medium earth orbits in this analysis.

The Role of Inclination. In addition to altitude, systems engineers must consider the inclination of a satellite's orbit (the angle between the plane of the orbit and the plane of the equator). Orbital inclination primarily affects the area that the satellite can observe. By choosing a particular inclination, engineers can cause the satellite to spend more time over particular areas of interest. Most regions of current military interest to the United States lie between 20 degrees and 60 degrees north latitude; an inclination of 20 to 60 degrees will maximize viewing times in those latitudes. An orbital inclination of 60 degrees, for example, will provide better access to polar regions at the expense of coverage in the lower latitudes (see Figure 3-1).

Specialized orbits are also possible. All existing civilian SARs, because they are designed for scientific or commercial observations rather than military intelligence, are in "sun-synchronous" orbits, at between 90 and 100 degrees inclination (slightly offset from the poles). Such an orbit allows a satellite to cover regions at the same time of day on each orbital pass—which is important for detecting changes in vegetation, for example, but less important for military purposes. By choosing appropriate values for inclination, altitude, and spacing between satellites, it is also possible to construct a constellation with repeating ground tracks, so that a satellite (or a successive satellite in the same constellation) views a region from the same angle each time it passes over. That feature could be especially useful for imagery analysis that relies on automated processes to detect changes between images.

Radar Antenna: Electronically Steered Array or Reflector?

Most existing or planned SAR satellites incorporate active electronically steered arrays. Modern versions of those arrays consist of a matrix of transmit/receive modules; timing differences between the signals at each module are used to form and steer the radar beam. However, some satellites—such as the German Defense Ministry's planned SAR-Lupe X-band radar satellites—use reflector antennae. In such satellites, the radar signal originates in a horn, or possibly a small AESA, and is reflected toward the target from a larger, usually parabolic, surface. The main potential advantages of a reflector are lighter weight and lower cost.

The biggest advantage of an AESA antenna is the ability to steer the radar beam electronically. The range over which the beam can be steered electronically depends on the spacing between adjacent transmit/receive modules. Electronic steering is essentially instantaneous, allowing the satellite to switch quickly from viewing one area to another even when the areas are far apart geographically. To observe areas outside the electronic steering range, the beam must be steered mechanically by rotating the satellite. Mechanical steering is much slower than electronic steering, and the radar may not be able to operate while the satellite is being rotated (see Chapter 4 for details).

Steering the radar beam would be more difficult with a reflector antenna. In the case of a reflector fed by a horn, the beam could be steered minimally (over a few degrees) by mechanically moving the horn. Most steering, however, would require rotating the satellite. To aim the beam accurately, the feed antenna and the reflector would need to be precisely aligned, which means that operating the radar while rotating the satellite might not be feasible. Since mechanical steering is relatively slow, using a reflector would reduce a satellite's ability to observe widely separated areas on a given orbital pass.

An AESA antenna would also have advantages over a reflector in defeating electronic jamming and in canceling ground clutter. The geometry of such an array lends itself to segmenting the radar beam into multiple subbeams. When added together (with the proper weighting factors), those subbeams allow for the construction of a "blind spot" to nullify a source of electronic jamming. The geometry of an AESA antenna also facilitates the use of advanced signal-processing techniques, such as space-time adaptive processing, for filtering out clutter. Those techniques would be more difficult or not possible with a reflector antenna.

Radar Frequency

Modern radars transmit a very complicated waveform, which generally consists of a carrier frequency that is modulated by waves of varying frequencies to improve the radar's performance. The choice of carrier frequency plays a role in performance by affecting how the radar signal propagates through the atmosphere. (The performance implications of the frequency-varying portion of the waveform are discussed below in the section on radar bandwidth.)

At carrier frequencies above 15 gigahertz (GHz), a radar signal undergoes significant attenuation (decrease in strength) in the atmosphere. At frequencies below 1 GHz, the signal can undergo refraction (change in direction) and phase distortions (changes in the relative timing of different frequency components of the waveform). All existing and planned SAR satellites operate in the region between 1 GHz and 12 GHz (see Box 2-1 on page 6).

In general, higher frequencies—and thus shorter wavelengths—allow for better image resolution and a greater ratio of signal to noise (a measure of the quality of the signal). Over the frequency range commonly used for radar, however, attenuation in the atmosphere also increases with frequency, so higher frequencies require greater power to obtain measurable radar echoes. Since high resolution is of primary importance to the Space Radar system, the notional radar designs included in this analysis use an X-band frequency of 10 GHz.

Challenges Posed by Key Technologies

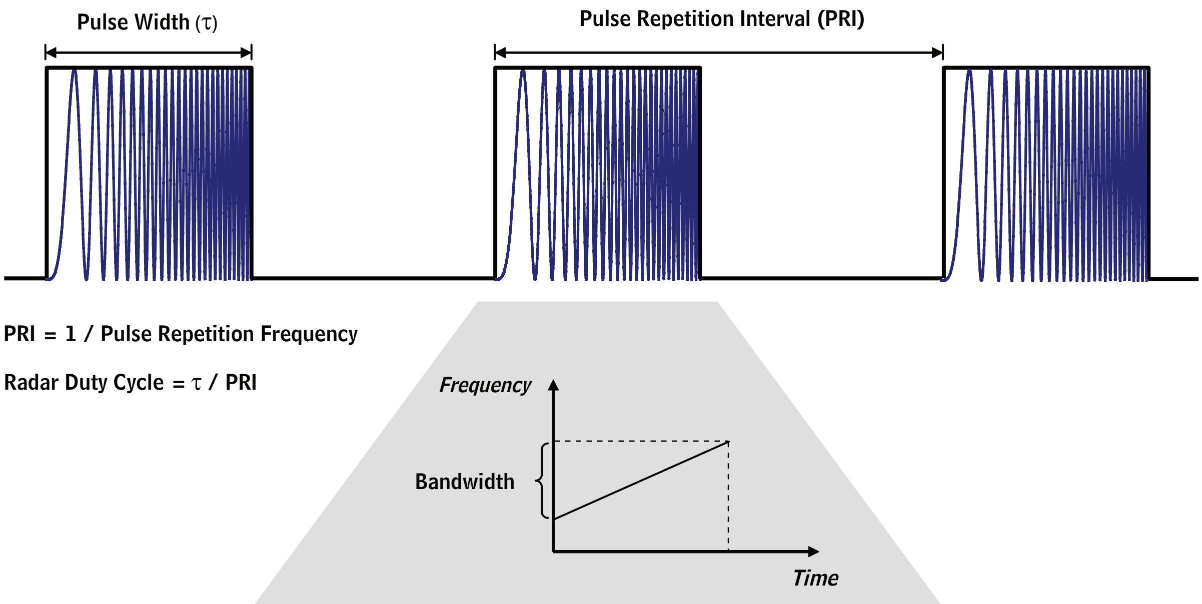
In modeling the performance of different designs for Space Radar, CBO made assumptions about how mature various key technologies would be when the satellite design process began in earnest. The ability of an actual Space Radar system to achieve the performance described in this analysis would depend on progress in the development of several technologies, including solar and battery power, electronics components that could limit the radar bandwidth, methods for processing GMTI signals, and high-capacity communication systems to downlink large amounts of radar data.

Satellite Power

Recent progress in solar-cell technology has improved the efficiency and reduced the mass of solar-power arrays. The total power required for the solar arrays in CBO's notional satellite designs should not present a technical challenge. However, those arrays are smaller and lighter than arrays with similar power output on current-generation satellites.

Figure 3-2.

A Linear Frequency Modulated Waveform



Source: Congressional Budget Office.

Spacecraft batteries could pose technical difficulties. Most current LEO satellites use nickel-based (Ni-Cd or NiH_2) batteries. But efforts are under way to move to lithium ion (Li-ion) batteries, which are capable of storing at least twice as much energy per kilogram of battery mass. Li-ion batteries are now being used in satellites in geosynchronous orbits and are slated for use in future LEO satellites (such as the four Italian COSMO-Skymed satellites to be launched starting in 2007). However, some concern exists about the lifetime of Li-ion batteries over the many discharge/recharge cycles required at LEO altitudes. The notional satellites that CBO considers in this analysis carry enough capacity in their Li-ion batteries to operate their radars at full power for 30 minutes of each 105-minute orbit. If those lighter Li-ion batteries were not available and nickel-based batteries had to be used instead, less power would be available (given constraints on total satellite mass), so the operating time per orbit would be shorter.

Radar Bandwidth

The use of pulse-Doppler technology allows radars to simultaneously measure the range and velocity of a target. When the radar transmits a pulse of energy, the time that elapses before the reflected pulse returns indicates the range to the target, and the frequency (or Doppler) shift of the returning pulse indicates the component of the target's total velocity that is in the direction of the radar. In modern radars, the pulse typically consists of a signal that increases linearly in frequency over the duration of the pulse, a pattern known as linear frequency modulation, or "chirp" (see Figure 3-2). Compressing the pulse in that way improves the spatial resolution of the radar. The range over which the pulse varies—the radar bandwidth—is directly related to the radar's resolution in the range (or cross-track) direction, with higher bandwidth corresponding to finer resolution. The notional radar designs analyzed in this study use a bandwidth of 1 GHz.

Resolution cannot be improved indefinitely by simply increasing the bandwidth. To be processed, the returning radar signal must be converted from analog to digital at a rate at least equal to the radar bandwidth.[4] Thus, the availability of high-resolution, high-rate analog-to-digital converters (ADCs) limits how high the radar bandwidth can be. CBO's choice of 1 GHz bandwidth would require

4. According to standard practice (the so-called Nyquist criterion), the incoming radar signal must be digitized at a rate at least twice the bandwidth. However, that rate can be reduced to the original bandwidth through the use of quadrature mixing, which splits the task of digitization between an in-phase channel and a channel delayed by a quarter-cycle.

an ADC capable of sampling the returning signal at a rate of at least 1 GHz, with 8 or 10 bits of precision. ADCs of that description are just beginning to become available for space applications.[5]

Signal-processing techniques that rely on hardware to shift the frequency of the incoming signal can be used to increase the effective bandwidth of the system. Techniques such as “stretch” processing or “stepped chirp” waveforms can provide finer-resolution imagery without the need for faster ADCs. For the performance comparison described in Chapter 4, CBO assumed that stretch processing and 1-GHz ADCs would be used. If techniques more advanced than stretch processing proved feasible, ADCs slower than 1 GHz might be sufficient.

GMTI Signal Processing

Radars used for GMTI—such as the one on the Air Force’s JSTARS aircraft—must be able to differentiate between returns from moving targets on the ground and returns from the surrounding terrain (ground clutter). As discussed earlier in this chapter, the radar beam has an angular width that depends on the size of the radar antenna, so the beam’s footprint on the Earth covers a range of azimuth angles. The component of the ground’s velocity that is in the direction of the satellite differs for each of those angles, resulting in a range of Doppler shifts from the ground clutter. Radar engineers refer to that range of Doppler shifts as the clutter-Doppler spread. The faster the radar platform is moving relative to the target and the smaller its antenna, the wider the clutter-Doppler spread and the harder it is to detect a slow-moving target. Any spaceborne radar will necessarily be moving extremely fast relative to a ground target (on the order of 15,000 miles per hour faster). So unless the radar is very large, detecting slow-moving targets will be challenging.

To overcome that problem, engineers propose to use a signal-processing technique known as space-time adaptive processing. That procedure involves estimating the statistical properties of the radar returns from ground clutter as well as any jamming that might be present (clutter and jamming are together referred to as interference). Once the interference has been characterized, a software filter can be constructed that, in theory, perfectly cancels it. The filter is considered adaptive because it varies with the characteristics of the signal being filtered.

Numerous technical and operational impediments stand in the way of achieving the theoretical perfect-cancellation STAP performance. To conduct space-time adaptive processing, a radar must be divided into a number of subapertures. The signal processor mathematically compares data from the separate subapertures to characterize the signal interference. In “fully adaptive” STAP, each transmit/receive module (or a small group of modules) of an electronically steered radar array is treated as an individual aperture, which yields as many as tens of thousands of data sources and an intractable computational problem. Alternatively, in “partially adaptive” (or “reduced rank”) STAP, the number of data sources the algorithm uses is reduced by dividing the radar aperture into a relatively small number of subapertures or by combining signals from multiple pulses. That simplification facilitates computation but reduces performance.

Theoretical perfect-cancellation STAP performance also relies on the assumption that clutter is both homogeneous and stationary. If, instead, the statistical properties of clutter vary in range or angle, the clutter is said to be heterogeneous; if those properties vary in time, the clutter is said to be nonstationary. Either of those situations will degrade the performance of the software filter. Clutter is likely to be heterogeneous in urban areas, along coastlines, or anywhere that terrain or vegetation varies in a nonrandom manner. Nonstationary clutter could result from leaves blowing in the wind, waves on the ocean, or any number of common sources.

Another problem with space-time adaptive processing is the potential for traffic-induced distortions. The STAP algorithm, like other adaptive algorithms, uses radar return data collected from previous target observations (called training data) to estimate the coefficients of the filter. The presence of background traffic in those training data can lead to cancellation of the targets: in effect, the filter could try to filter out the targets as well as the clutter.[6]

5. See, for example, National Aeronautics and Space Administration, Jet Propulsion Laboratory, *NASA/JPL A/D Converter Selection Guide* (January 14, 2005), available at http://parts.jpl.nasa.gov/docs/adguide011405.pdf.

6. North Atlantic Treaty Organization, Research and Technology Organization, *Military Applications of Space-Time Adaptive Processing*, Lecture Series 228 (Ottawa: St. Joseph Print Group, 2003).

The various problems inherent in space-time adaptive processing can be lessened through careful algorithm development and system design.[7] Even so, those problems will reduce the performance of the system and make it more difficult to detect slow-moving targets than theoretical STAP results suggest.

Communications Bandwidth

When performing radar observations, Space Radar satellites will generate a huge amount of raw data. Given the complexity of the processing algorithms needed to turn those data into usable intelligence and the current level of development of those algorithms, much of the data processing is likely to be performed on the ground. For that processing to occur in a timely fashion, the rate at which data are downlinked to Earth—that is, the communications bandwidth—will need to be very high. CBO estimates that downlink rates of at least 1 billion bits per second (1 Gbps) may be necessary to avoid substantial delays in data processing.

Data can be downlinked in one of two ways: directly from the Space Radar satellite to a ground antenna, or indirectly via a satellite communications "backbone" system, which then relays the data to the ground. Direct transmission requires that a Space Radar satellite have a line of sight to the ground antenna, which could introduce a delay in transmission. A backbone system, because it involves satellite-to-satellite communications prior to downlink, has the advantage of being available regardless of the position of the Space Radar satellite (provided other users are not taking all of the backbone's capacity). Thus, the preferred primary mode for downlink will most likely be a backbone system.

The Tracking and Data Relay Satellite System (TDRSS) operated by NASA offers an example of high downlink rates that are currently available.[8] That 10-satellite constellation includes 20 Ku-band communications channels, each of which is capable of transmitting data at 300 million bits per second, and six Ka-band channels, each capable of 800 million bits per second. Those rates, however, may not be sufficient to avoid delays in downlinking Space Radar data for processing (see Chapter 4 for more details).

One way in which higher downlink capacities could be available in the future is through the use of laser communication links. The Air Force is in the planning stages for the Transformational Satellite Communications System, or TSAT, which would use laser communications links between satellites and could be capable of downlink rates of 5 Gbps to 10 Gbps.[9] Other systems are in the initial testing stages. The U.S. Missile Defense Agency's Near Field Infrared Experiment satellite will attempt to establish laser communications at 5.5 Gbps with the German TerraSAR-X satellite.[10] The Japan Aerospace Exploration Agency and Japan's National Institute of Information and Communication Technology recently successfully established satellite-to-ground laser communications with their Kirari test satellite. Such a link is difficult to establish "because the satellite has to keep sending laser beams accurately to the ground station while moving at a very high speed although the optical reception level fluctuates remarkably due to atmospheric attenuation and flickers."[11]

The Alternative Architectures Analyzed in This Report

Taking into account the design trade-offs and technological challenges discussed above, CBO chose four notional Space Radar architectures for evaluation. Those alternatives differ by the number of satellites in the constellation and the size of the radar apertures (see Table 3-1). All of the constellations would be launched into low earth orbits.

7. Government contractors are using aircraft to collect radar data in order to develop STAP algorithms. The radars on those aircraft are designed to have very broad main beams, thereby placing slow-moving targets inside the main beam's clutter, as would be the case for Space Radar.

8. The Department of Defense has not indicated that it would use TDRSS to downlink Space Radar data. CBO used TDRSS as a basis of comparison in this analysis because the system is currently available, is widely used, and has well-known performance parameters.

9. Mark Baird, "Transformational Satellite Communications System" (briefing by the Air Force to Congressional staff, February 2006).

10. Peter B. deSelding, "Space-to-Ground Laser Link Tests Set for 2007," *Space News*, vol. 17, no. 13 (April 3, 2006), p. 24.

11. Japan Aerospace Exploration Agency, "Successful Optical Communication Experiment Between the NICT Optical Ground Station and the Optical Inter-orbit Communications Engineering Test Satellite Kirari" (press release, April 7, 2006), available at www.jaxa.jp/press/2006/04/20060407_kirari_e.html#at02.

Table 3-1.

Alternative Space Radar Architectures Examined by CBO

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Number of Satellites	5	9	9	21
Aperture Dimensions	16 x 2.5 m	16 x 2.5 m	25 x 4 m	16 x 2.5 m
Aperture Area	40 m^2	40 m^2	100 m^2	40 m^2
Orbital Configuration[a]	Walker 5/5/1	Walker 9/3/2	Walker 9/3/2	Walker 21/7/3
Satellite Power (Beginning of life)	5,000 watts	5,000 watts	7,000 watts	5,000 watts

Source: Congressional Budget Office.

Note: m = meter.

a. In the Walker notation system for constellations of satellites, the first number refers to the number of satellites in the constellation, the second to the number of different planes in which those satellites orbit, and the third to the angular separation (phasing) between satellites in successive orbital planes.

CBO's starting point, or reference architecture (called Alternative 2 in this analysis), incorporates nine satellites, each with a radar aperture of 40 square meters. The number of satellites is consistent with a report by the House Appropriations Committee, which stated that the Space Radar system being considered by the Air Force at that time consisted of a nine-satellite constellation in low earth orbit.[12] The aperture size is consistent with plans by the former Discoverer II program to use a 40-square-meter radar design.[13] To evenly distribute the satellites' access to regions between 60 degrees north and south latitude, CBO chose a Walker 9/3/2 constellation for Alternative 2. (See Box 3-1 on page 20 for a description of the Walker notation system for satellite constellations.)

Alternatives 1 and 4 employ the same size radar but on different numbers of satellites. Alternative 1 consists of five satellites (placed in a Walker 5/5/1 constellation), the same number of satellites as in the German Defense Ministry's planned SAR-Lupe constellation. CBO included that smaller constellation as a lower-cost option. Alternative 4 features 21 satellites (in a Walker 21/7/3 configuration), a constellation size also mentioned in the House Appropriations Committee's report. CBO included that alternative to explore the performance of a denser constellation.

Radars with an aperture of 40 square meters may not be adequate for the GMTI mission, however, so CBO also examined a design with a larger aperture. Alternative 3 features the same nine-satellite constellation as the reference architecture but uses radars with an aperture of 100 square meters. Although that design has the same transmit power as the 40-square-meter radars in the other alternatives, it requires more power from its solar arrays to operate because of its greater mass and the additional power needed by its electronics and processor.

In all four alternatives, the Space Radar satellites operate in circular orbits with an altitude of 1,000 kilometers and an inclination of 53 degrees. Previous spaceborne SARs have orbited at slightly lower altitudes, and Discoverer II was to have operated at 770 kilometers, but a higher altitude should improve GMTI performance (given adequate power). A 2001 study recommended a 1,100-kilometer altitude for the Space Radar constellation.[14] CBO chose 1,000 kilometers as a round number between those altitudes. The 53-degree orbital inclination is the

12. House Committee on Appropriations, *Department of Defense Appropriations Bill 2005,* report to accompany H.R. 4613, Report 108-553 (June 18, 2004).

13. Air Force Space and Missile Systems Center, "Fact Sheet: Discoverer II Joint Program" (available at www.losangeles.af.mil/SMC/PA/Fact_Sheets/discoverer_2.pdf).

14. Yolanda J. King, John Garnham, and Bruce Preiss, "Innovative Space-Based Surveillance Concepts" (paper presented at the American Institute of Aeronautics and Astronautics Space 2001 Conference, Albuquerque, New Mexico, August 28-30, 2001).

Table 3-2.

Notional Satellite Designs Examined by CBO

	Alternatives 1, 2, and 4	Alternative 3
Antenna Type	Active electronically steered array	Active electronically steered array
Aperture Size	16 x 2.5 m (40 m^2)	25 x 4 m (100 m^2)
Operating Altitude	1,000 km	1,000 km
Orbital Inclination	53°	53°
Frequency	10 GHz (X band)	10 GHz (X band)
Average Transmit Power	1,500 watts	1,500 watts
Bandwidth		
SAR	1 GHz	1 GHz
GMTI	15 MHz	15 MHz
Radar Duty Cycle	15 percent	15 percent
Grazing-Angle Range		
SAR	15°–70°	8°–70°
GMTI	6°–70°	6°–70°
Azimuth Steering		
SAR	±45° electronic steering	±45° electronic steering
GMTI	360° mechanical steering	360° mechanical steering
Elevation Steering	±21° electronic steering	±21° electronic steering
Spacecraft Power (Beginning of life)	5,000 watts	7,000 watts
Power Duty Cycle	Enough battery capacity to operate radar for 30 minutes per 105-minute orbit	Enough battery capacity to operate radar for 30 minutes per 105-minute orbit
Design Life of Satellites[a]	10 years	10 years

Source: Congressional Budget Office.

Note: m = meter; km = kilometer; GHz = gigahertz; SAR = synthetic aperture radar; GMTI = ground moving-target indication; MHz = megahertz.

a. The total life of the Space Radar constellation is assumed to be 20 years, meaning that each satellite would need to be replaced once.

same as that planned for Discoverer II; as shown in Figure 3-1 (for a single satellite), that inclination provides good access through 60 degrees of latitude.[15] (However, the Integrated Program Office may elect to place one of the Space Radar satellites in a more highly inclined orbit to provide some access to polar regions.)

Other than the size of the aperture, the design characteristics of the radar itself are the same in all of the alternatives (see Table 3-2). For the radar antenna, CBO chose an active electronically steered array rather than a reflector because most past and current civilian spaceborne SARs use that design, and the agility of such a radar should greatly increase its usefulness. The radar is assumed to operate at a carrier frequency of 10 GHz—the frequency planned for Discoverer II—which offers a compromise between SAR along-track resolution and atmospheric attenuation.[16] CBO assumed that the radar would transmit for 15 percent of its operating time (a

15. See Air Force Space and Missile Systems Center, "Fact Sheet: Discoverer II Joint Program."

16. Ibid.

Box 3-1.

The Walker Notation System for Satellite Constellations

In 1970, J.G. Walker of Britain's Royal Aircraft Establishment, a defense research agency, proposed a method for describing symmetrical constellations of satellites in circular orbits.[1] That notation, which is in common use today, consists of three numbers:

- The first, *T*, refers to the number of satellites in the constellation;
- The second, *P*, refers to the number of orbital planes; and
- The third, *F*, refers to the phasing of the satellites in adjacent planes (how far behind a given satellite the next one is).

In a symmetrical constellation, *T* satellites are divided equally among *P* orbital planes, which all have the same orbital inclination. The planes are evenly spaced around the globe, and within a plane, the satellites are also evenly spaced. The notional Space Radar constellations examined in this study are in Walker 5/5/1, 9/3/2, and 21/7/3 configurations. In other words, the constellation in Alternative 1 consists of five satellites, each in its own orbital plane. The constellations in Alternatives 2 and 3 comprise nine satellites, three per orbital plane. And the constellation in Alternative 4 features 21 satellites divided among seven orbital planes (again, three per plane).

The phasing of satellites in adjacent planes is measured in terms of the fraction of a full 360-degree orbit that one satellite has gone through when another (the reference satellite) passes over the equator into the Northern Hemisphere—or as (360 x *F*)/*T* (see the figure at right). For example, a phasing parameter *(F)* of zero indicates that the satellites in adjacent planes cross the equator simultaneously. A phasing parameter of 2 for a nine-satellite constellation (as in Alternatives 2 and 3) means that the satellites in adjacent planes are separated by 80 degrees.

Even with the relative simplicity that comes from requiring symmetrical constellations, determining the optimal number of satellites for a given task is arduous because of the large number of different constellations that can be formed—and hence must be evaluated—for each quantity of satellites considered. For *T* satellites, the number of possible Walker constellations is equal to the sum of all of the factors of *T*. Thus, for a five-satellite constellation, there are 6 (1 + 5) possible Walker configurations; with nine satellites, there are 13 (1 + 3 + 9) possible configurations; and with 24 satellites (the desired size of the Discoverer II constellation), there are 60 (1 + 2 + 3 + 4 + 6 + 8 + 12 + 24) possible configurations.

1. J.G. Walker, *Circular Orbit Patterns Providing Continuous Whole-Earth Coverage,* Technical Report 70211 (Farnborough, England: Royal Aircraft Establishment, November 1970).

measure known as its radar duty cycle) and would receive for the rest of the time. That duty cycle is a compromise between the 10 percent value used in an analysis of Discoverer II and the 18 percent to 20 percent cycle planned for the German TerraSAR-X satellite.[17]

The Space Radar system needs to have as much power as possible to maximize its performance. CBO chose a peak transmit power of 10,000 watts. With a 15 percent duty cycle, that figure yields an average transmit power of 1,500 watts. CBO's analysis indicates that about 5,000 to 7,000 watts of solar power would be needed to support such a radar and the satellite that carried it—a level consistent with those of current LEO Earth-imaging satellites such as the Japanese ALOS.[18]

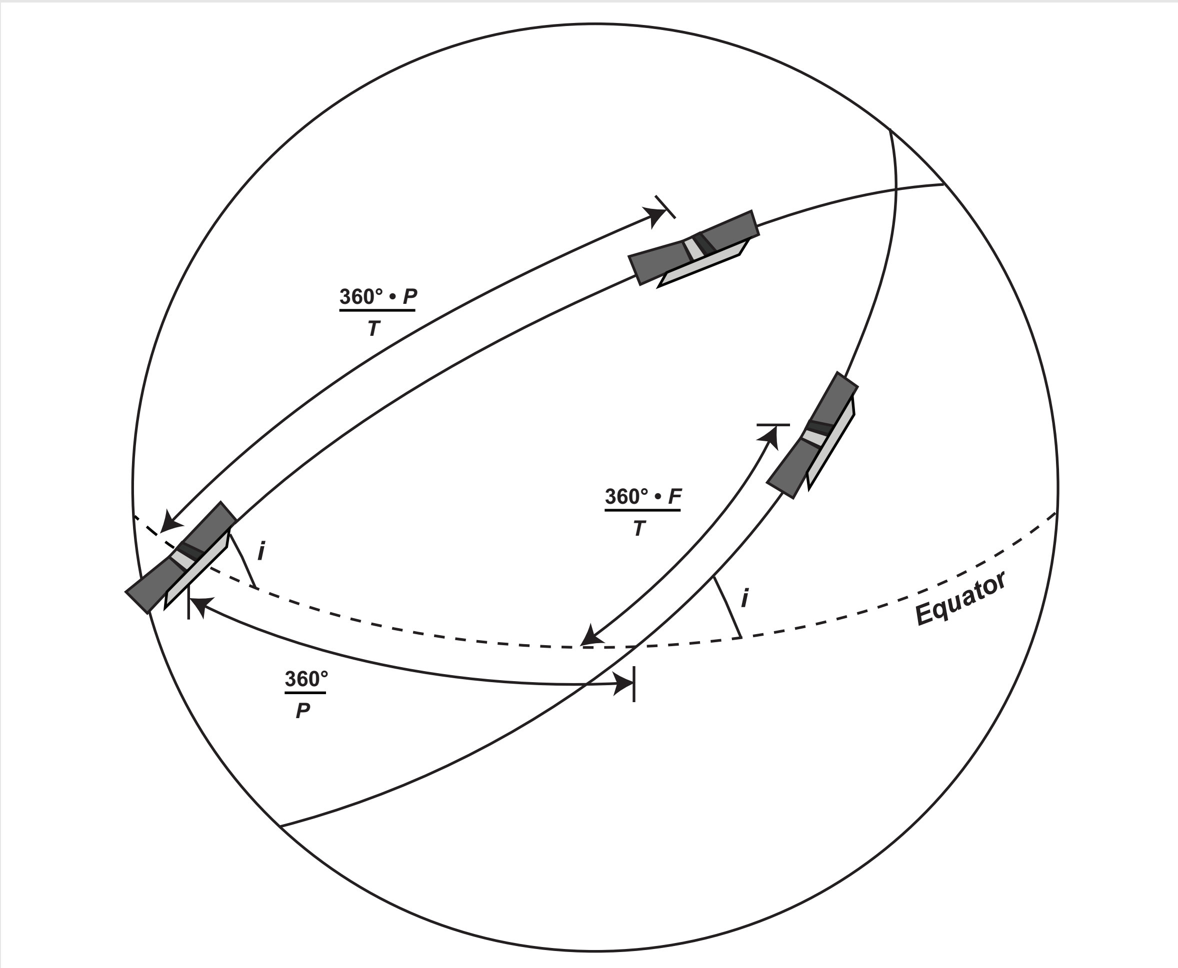
17. R.A. Coury and others, *Discoverer II Performance Analysis Tool Modeling Report* (prepared by M.I.T. Lincoln Laboratory for the Defense Advanced Research Projects Agency, July 28, 1999), p. 47; and M. Suess and others, "TerraSAR-X—Design and Performance," in *Proceedings of the 4th European Conference on Synthetic Aperture Radar* (Cologne, Germany: June 2002).

18. Kazuki Shiibashi and Michael Mecham, "Looking Down: JAXA Returns to Earth Observation Missions with ALOS Mapping," *Aviation Week and Space Technology* (January 30, 2006), p. 37.

Box 3-1.

Continued

Walker Notation Parameters for the Positions of Satellites in Two Orbital Planes



Source: Congressional Budget Office.

Note: *T* = number of satellites in a constellation; *P* = number of orbital planes in a constellation; *F* = phasing parameter (fraction of a 360-degree orbit) between satellites in adjacent planes; *i* = orbital inclination.

In terms of radar bandwidth, CBO assumed that 1 GHz would probably be the maximum bandwidth that could be achieved by space-qualified hardware in 2015 (using two ADCs of 1 GHz each and a quadrature mixer).[19] That bandwidth should provide very good cross-track resolution for SAR imagery. Both the 40- and 100-square-meter radars are assumed to operate to a maximum grazing angle of 70 degrees, which is consistent with current designs and was the limit considered in analyses of Discoverer II.[20] Minimum grazing angles, under CBO's assumptions about the radars' performance, are

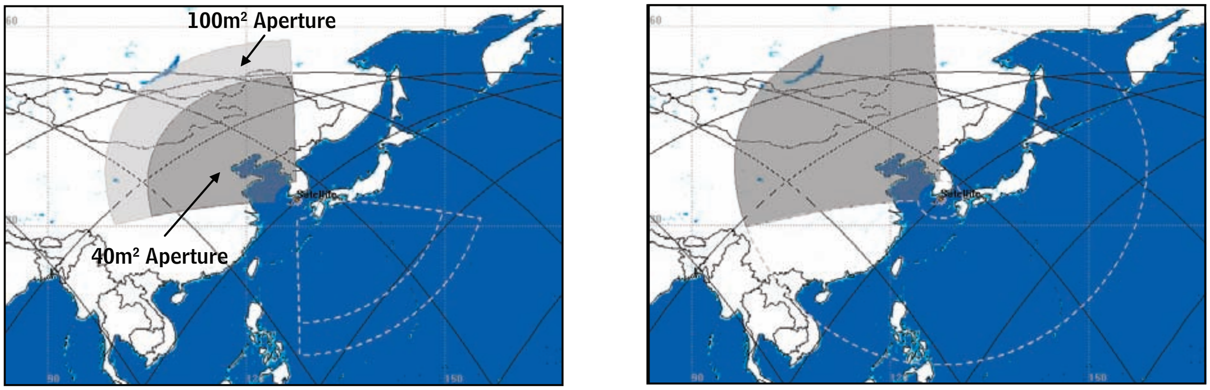
19. National Aeronautics and Space Administration, *NASA/JPL A/D Converter Selection Guide.*

20. Coury and others, *Discoverer II Performance Analysis Tool Modeling Report*, pp. 50–60. The grazing angle is the angle between the radar beam and the surface of the Earth. (For example, a beam pointing straight down beneath a satellite would have a grazing angle of 90 degrees.) For information about grazing-angle limits, see Appendix B.

Figure 3-3.

Field of Regard for a Space Radar Satellite

Synthetic Aperture Radar Imaging[a] **Ground Moving-Target Indication**



Sources: Congressional Budget Office and Analytical Graphics Inc.

Notes: The field of regard is the angular area of Earth that a satellite-based radar can image within its normal range of motion. Shading denotes areas that can be imaged by electronically steering the radar beam. Dashed lines denote additional areas that can be imaged by spinning (yawing) the satellite.

m^2 = square meter.

a. The field of regard shown here is for imagery with 1-meter resolution.

15 degrees for the smaller radar and 8 degrees for the larger radar in SAR mode. In GMTI mode, the minimum grazing angle is 6 degrees for both radars (the limit considered in the Discoverer II analysis). However, at small grazing angles, the 40-square-meter radar would not detect moving targets as readily as the larger radar could.

In CBO's notional design, the radar beam can be steered electronically 45 degrees to either side of the perpendicular to the antenna (azimuth steering) and 21 degrees up or down (elevation steering). The latter allows the beam to operate at all of its possible grazing angles without mechanical steering. CBO also assumed that the satellite could spin around a vertical axis (yaw) for a full 360 degrees to allow detection of moving targets on the ground in any direction.[21] Unlike GMTI, SAR images can be made only to the side of the satellite's ground track, not fore and aft (see Figure 3-3). CBO assumed that the satellite could be either yawed or rolled to allow SAR coverage on either side of the ground track, as is planned for Canada's RADARSAT-2 spacecraft.

21. The Discoverer II design could reportedly scan ±45 degrees in SAR mode and had 360-degree coverage in GMTI mode. See Federation of American Scientists, Space Policy Project, "Discoverer II STARLITE" (January 24, 2000), available at www.fas.org/spp/military/program/imint/starlight.htm.

Costs of the Alternatives

Total life-cycle costs for the four illustrative Space Radar systems that CBO examined would range from about \$26 billion to \$94 billion (in 2007 dollars), depending on the number and type of satellites deployed and the possibility that the program might experience typical rates of cost growth (see Table 3-3). Those estimates include costs for research and development, procurement of the satellites and their associated equipment, launches, and satellite operations and data processing for 20 years (the assumed lifetime of the system).

For the reference architecture in Alternative 2, total costs would range from about \$35 billion to \$52 billion, CBO estimates. Costs for Alternatives 3 and 4—which would offer more performance capability through either larger-aperture radars or more satellites—would be roughly \$20 billion to \$40 billion higher than for the reference architecture. Alternative 1, with half as many satellites as Alternative 2, would cost about \$9 billion to \$12 billion less than the reference architecture.

Table 3-3.

Estimated Life-Cycle Costs of the Space Radar Alternatives Examined by CBO

(Billions of 2007 dollars)

	Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Low	High	Low	High	Low	High	Low	High
Research and Development	11	19	11	19	14	24	11	19
Procurement[a]	5	6	9	11	17	20	22	27
Operations (Over 20 years)[b]	9	15	15	23	23	33	33	49
Total	**26**	**40**	**35**	**52**	**53**	**77**	**66**	**94**

Source: Congressional Budget Office.

Note: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

a. Includes launch of initial satellites in a constellation.

b. Includes launch of replacement satellites.

Cost estimates for systems that, like Space Radar, are defined only conceptually or that depend on the development of new technologies involve more uncertainty than do estimates for well-defined programs that are based on proven technologies. To account for the potential effects of such uncertainty, CBO estimated a range of costs for each Space Radar system. The low end of the range represents what a system might cost if few technical difficulties arose in making it fully operational. The high end of the range incorporates the cost growth that has been common among other space-based systems of the Department of Defense. (For more details, see Appendix A.)

Estimates of research and development costs were based on the Air Force's current funding plans for Space Radar, its analysis of alternatives for GMTI, and analogies with other Air Force satellite programs. Because of the additional technical challenges associated with a 100-square-meter radar aperture, CBO assumed that research and development costs would be 25 percent higher for Alternative 3 than for the other options, which all use a 40-square-meter aperture.

To estimate procurement costs for the satellites and their radar payloads, CBO used cost-estimating relationships from the Unmanned Space Vehicle Cost Model (a cost model developed by Tecolote Research for the Air Force's Space and Missile Systems Center), industry studies, and analogies with existing radar systems. Costs for ground equipment include the establishment of command-and-control centers that would collect and prioritize tasking requests, generate satellite control commands, receive and process data from the satellites, translate the processed data into usable intelligence products, and disseminate those products to their end users. The extent of such a ground system would depend on the concept of operations used for Space Radar. CBO's cost estimates were adapted from ground-system costs in the Air Force's analysis of alternatives for GMTI.

Estimates of launch costs assume that, in each alternative, the satellites would be placed into orbit using Delta IV or Atlas V launch vehicles. The number of launches required would be determined by the number of orbital planes in a constellation and the number of satellites that a single launch vehicle could carry. CBO estimates that one vehicle could launch up to three satellites with smaller (40-square-meter) radars or up to two satellites with larger (100-square-meter) radars.

Operations costs include the costs of controlling the satellites, conducting intelligence operations through the command-and-control centers, and providing continual engineering support over the 20-year life of the Space Radar system. Operations costs would begin with the system's initial operating capability, in about 2015. CBO assumed that the individual satellites would last for 10 years (consistent with the expected lifetime of current satellites). Thus, each satellite would need to be replaced once during the nominal 20-year lifetime of the system. Production and launch costs are assumed to be the same for the replacement satellites as for the initial set.

CHAPTER

4

Performance Comparison of Alternative Architectures for Space Radar

In addition to estimating the costs of its notional designs for a Space Radar system, the Congressional Budget Office compared how well those designs would perform the system's primary missions: synthetic aperture radar imaging and ground moving-target indication. With reconnaissance satellites in inclined circular orbits, performance depends in part on the latitude at which the target is located. For each mission area—SAR or GMTI—CBO began its analysis by comparing the performance of the alternative architectures globally. CBO then analyzed how well each alternative would perform within the latitude band between 60 degrees north and 60 degrees south, which is home to more than 99 percent of the world's population. The orbital inclination assumed for all of the constellations (53 degrees) makes that range appropriate for summary statistics. Finally, for illustrative purposes, CBO examined each option's performance for one regional area of interest: the Korean Peninsula.

The ability to provide SAR imagery and to detect moving targets on the ground depends on a host of operational and design factors besides the latitude of likely targets. For example, SAR performance is affected by the clutter level of the area being imaged and the resolution desired. GMTI performance is affected by the radar cross section and velocity of the target, the clutter level, the system's signal-processing capability, and other factors. With so many possible variables, CBO by necessity had to restrict its performance analysis to fairly limited sets of parameter values. Although that analysis could not be exhaustive, it nonetheless offers insights into the overall SAR and GMTI capabilities of the alternative constellations.

The comparison focuses on the general capabilities of different architectures rather than their performance in particular mission scenarios, for two reasons. First, scenarios developed by the Department of Defense tend to be classified. Second, mission scenarios are often very specific and rely on myriad assumptions about targets, timelines, and, in some cases, the utility of intelligence products (which is highly subjective). It is not clear how widely applicable an analysis derived from such specifics would be. For example, a scenario could be constructed for the defense of South Korea, with a detailed order of battle, target list, location of air defenses, engagement timelines, and so on. Estimates of the effectiveness of a Space Radar system in that scenario would probably be highly sensitive to key assumptions made during the modeling, which could not be validated by comparing simulated results with actual outcomes. Furthermore, a change in the scenario could yield completely different results.

Although CBO avoided using specific, detailed scenarios for its analysis, it did employ a generalized scenario in one case: to examine Space Radar's ability to aid in engaging transitory targets. CBO used a simplified scenario that involved detecting mobile launchers for tactical ballistic missiles to illustrate that a very large number of satellites would be needed to successfully engage those targets.

Besides comparing the capabilities of the alternative architectures, CBO analyzed the maximum communications bandwidth that each constellation of satellites could require. The GMTI mission in particular will generate large amounts of data that may have to be processed on the ground (because of the complexity of the algorithms involved). Communications bandwidth comparable to that of the Air Force's planned Transformational Satellite Communications System (TSAT) or some other high-capacity communications system is likely to be necessary to relay that data to ground stations in a timely fashion.

SAR Imaging Performance

To characterize the SAR imaging capabilities of the alternative constellations, CBO focused on three metrics:

- How much of the time a particular location can be observed (access),
- How soon a satellite can be in position to observe that location (response time), and
- How big an area can be observed per unit of time (coverage).

The quality of the imagery produced by a synthetic aperture radar—that is, the ease with which an observer can identify features within the image—is directly related to the grazing angle at which the radar views the terrain. Sufficient radar energy must be reflected back from the terrain to form an image. At small grazing angles, less energy is reflected back, which degrades the quality of the image.[1] Thus, to achieve a given image quality, the range of possible grazing angles and resolutions is limited.[2] Since the radar's access to terrain is limited by the grazing-angle constraint, all three of the SAR performance metrics that CBO examined vary with the desired resolution.

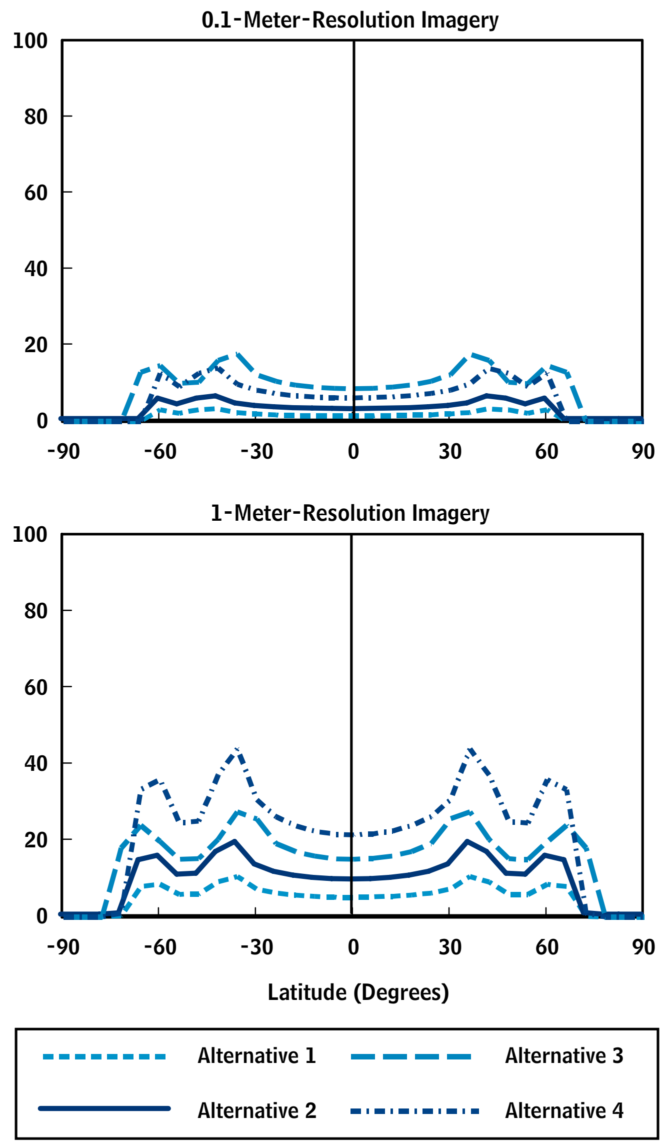
SAR Access

An important feature of any SAR constellation is the percentage of time that a given geographic location, treated in isolation, can be observed by at least one satellite. In estimating access, CBO treated a given target in isolation for two reasons. First, because of power limitations, a satellite typically does not continuously produce images throughout its orbit.[3] CBO's analysis did not explicitly consider that limitation. Instead, the analysis assumed that targets would be sufficiently separated, or few enough in number, that power constraints would not

Figure 4-1.

Global SAR Access with Alternative Space Radar Constellations

(Percentage of time)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

SAR = synthetic aperture radar.

1. The extent to which the grazing angle restricts resolution depends on the reflectivity of the terrain and other image-quality considerations. For further discussion of the methods that CBO used to analyze SAR performance, see Appendix B.

2. Resolution is only one component of image quality; the signal-to-noise ratio is another.

3. The notional satellite design that CBO analyzed would have enough battery capacity to operate a radar at full power for 30 minutes of each 105-minute orbit.

affect operations. Second, the notional satellite design that CBO examined has a field of regard that spans 90 degrees in azimuth angle for SAR operations (see Figure 3-3 on page 22). The satellite can be maneuvered so that targets can be imaged on either side of the ground track, but such maneuvering could take several minutes. Thus, viewing a target on one side of the ground track and then rolling the satellite to view a target on the opposite side of the ground track would not be possible if the targets were too near one another.

In CBO's Space Radar simulations, the value for access, averaged over a long time scale, varies with the latitude of the target but not with the longitude. A simulation starts with the satellites in certain positions at a given time; over a short time scale, access will depend on the initial proximity of the satellites to the target and hence on the target's longitude. But averaged over a long period, the satellites in CBO's simulations cover all longitudes with equal frequency, because their orbits have not been engineered to have repeating ground tracks.

For relatively coarse imagery (resolution of about 0.7 meters or more), grazing angle would not limit the operation of either the notional 40- or 100-square-meter radars. With 1-meter resolution images, the reference constellation in Alternative 2 would be able to observe a given location below 70 degrees latitude between about 10 percent and 20 percent of the time (see Figure 4-1). Access would be greater for the larger radar in Alternative 3 and the larger constellation in Alternative 4 but smaller for the smaller constellation in Alternative 1. In all of the options, access would be best at about 35 degrees latitude (performance is symmetrical in the Northern and Southern Hemispheres).

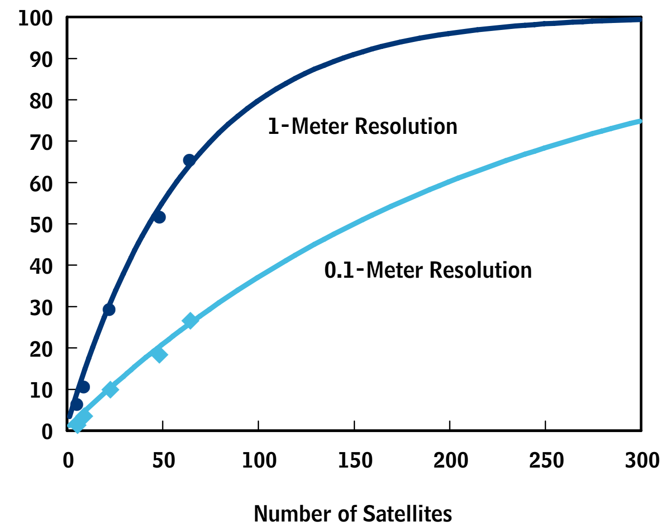
With imagery of 0.1-meter resolution, access would be greatly reduced, varying between about 2.5 percent and 6 percent for the reference constellation. At that resolution, the 100-square-meter radar in Alternative 3 would provide the best performance because it could operate at much smaller grazing angles.

CBO found that the relationship between access and number of satellites in a constellation is approximately exponential (see Figure 4-2). Because a satellite cannot image the area directly beneath it (the "nadir hole"), achieving 100 percent access is very difficult. To achieve 90 percent access between 60 degrees north and south at 1-meter resolution with 40-square-meter radars would require about 150 satellites. Even with that many satellites, however, at 0.1-meter resolution, average access would be less than 50 percent.

Figure 4-2.

Average SAR Access Between 60 Degrees North and South Latitude with 40-Square-Meter Radars

(Percentage of time)



Source: Congressional Budget Office.

Note: The curves in this figure represent parametric fits to the simulated data points. The curve for 1-meter resolution is defined by $y = 1 - e^{-0.0158x}$. The curve for 0.1-meter resolution is defined by $y = 1 - e^{-0.0046x}$.

SAR Response Time

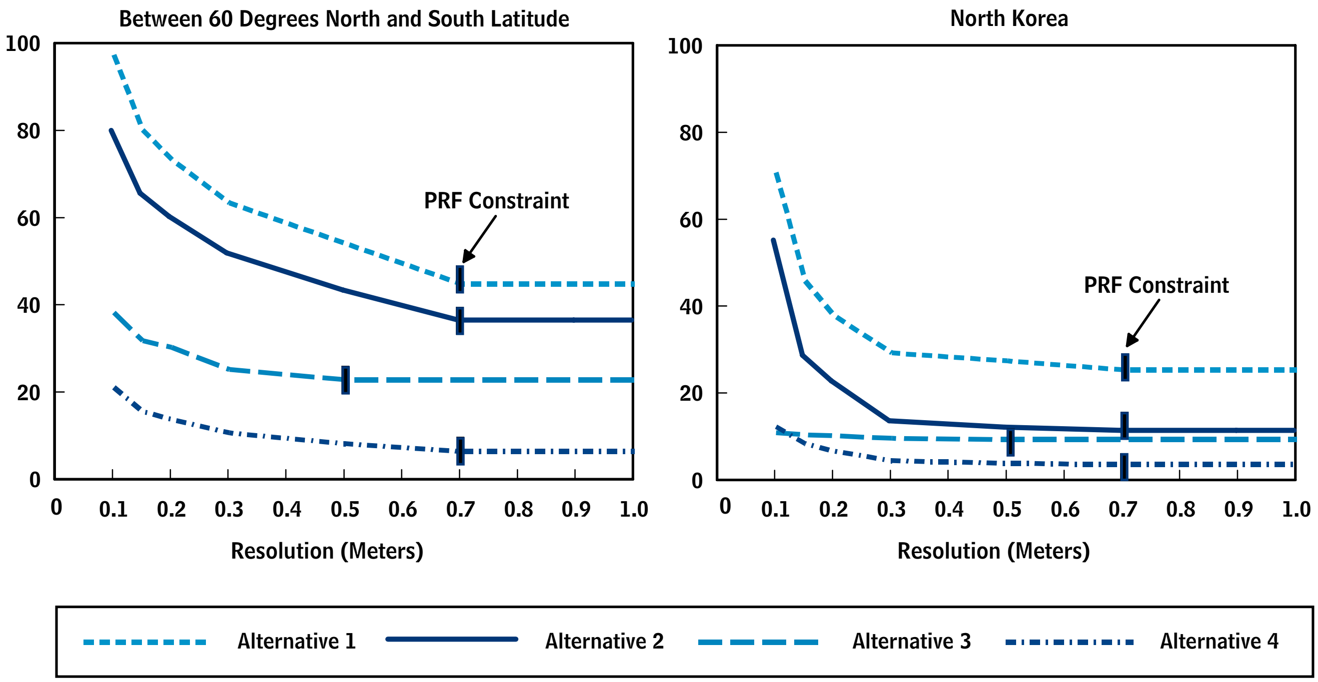
Another important metric for SAR imagery is the time that elapses between the receipt of a tasking to observe a given location and the actual viewing of that location. The tasking is assumed to occur at a random time, so the expected value for response time is independent of the target's longitude. If the target is within view of a satellite for a given observation, the response time is zero; if not, the response time is the time to the next access period.

CBO's estimates of response time are somewhat optimistic in that they include only the time required for a satellite's orbit to bring it into position to observe the target.

Figure 4-3.

Average SAR Response Times with Alternative Space Radar Constellations

(Minutes)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

SAR = synthetic aperture radar; PRF = pulse repetition frequency.

They do not include the time that might be necessary to maneuver the satellite (in other words, the satellite is assumed to be ideally aligned for imaging the target at the next opportunity). Furthermore, in this analysis, response time does not include any delays in prioritizing multiple requests, forwarding a tasking to the satellite controllers, translating the tasking into a series of operational instructions to the satellites, or transmitting those instructions to the satellites. (If command, control, and communications delays could be quantified, they could be added to that measure to obtain a total response time.)

Response time varies with the desired image resolution, because a satellite will need to reach a position where its radar can operate at or above the minimum grazing angle to produce images with a specific resolution. In the case of 0.1-meter-resolution imagery, the average response time under Alternative 2 for a location between 60 degrees north and south would be about 80 minutes (see the first panel of Figure 4-3). With 0.7-meter-resolution imagery, response time under Alternative 2 would improve to about 36 minutes, on average. At that point, however, response time would stop decreasing, because smaller grazing angles could not be used.[4] Response time stops improving at 0.7-meter resolution for the 40-square-meter radar (corresponding to a grazing angle of 15 degrees) and at 0.5-meter resolution for the 100-square-meter radar (a grazing angle of 8 degrees). With 21 satellites, the average response time would drop to 21 minutes and 7 minutes for 0.1-meter and 1-meter resolution, respectively.

4. Smaller grazing angles are not feasible once the maximum pulse repetition frequency (PRF) necessary to avoid range ambiguities, which decreases with the grazing angle, approaches the minimum PRF necessary to avoid Doppler ambiguities. (For more details, see Appendix B.) CBO has assumed that those PRF constraints cannot be violated.

Response time also varies considerably with the target's latitude. At some latitudes, in fact, the five-satellite constellation in Alternative 1, because of its larger number of orbital planes, would have shorter response times than the nine-satellite constellation in Alternative 2. In the case of a target in North Korea (which lies between roughly 38 and 43 degrees north latitude), response times would be appreciably better than the average over the entire 60-degrees-to-60-degrees range. For Alternative 2, the average response time in North Korea would be about 11 minutes with 1-meter-resolution imagery, increasing to 55 minutes with 0.1-meter-resolution imagery (see the second panel of Figure 4-3). For the 100-square-meter radars of Alternative 3, response times in North Korea would not vary much with resolution; in fact, at very fine resolution, those times would be shorter than for the much larger constellation of Alternative 4.

SAR Coverage

For the SAR mission, coverage is defined as the area that can be imaged by a constellation in a given unit of time, such as a day. In simulating the coverage possible with alternative architectures, CBO treated a given target area in isolation of other targets, as it did when estimating access. Coverage is also similar to access in that, averaged over a long time scale, it does not depend on the longitude of the target.

The area that can be covered per day varies with the resolution of the imagery. At 0.1-meter resolution, the reference constellation in Alternative 2 could image about 5,500 square kilometers per day in North Korea, CBO estimates (see Figure 4-4).[5] To put that area in perspective, CBO compared it with several benchmarks. For example, a single mechanized division in a defensive posture, using former Soviet tactics, could be expected to occupy an area of 500 to 1,000 square kilometers.[6] Thus, Alternative 2's constellation could image about 5 to 10 divisions in a day. As another example, during the 1991 Persian Gulf War, the Air Force divided Iraq into boxes that measured 30 arc minutes on a side for the purpose of detecting and targeting transporter erector launchers (TELs) for Scud missiles.[7] A box of those dimensions placed in North Korea would have an area of approximately 2,400 square kilometers. The constellation in Alternative 2 could image two such boxes per day at 0.1-meter resolution. The same size constellation with larger radars (Alternative 3) could image more than nine such boxes per day.

Area coverage increases rapidly as the required resolution becomes coarser. At 0.15-meter resolution, Alternative 2 could image slightly more than 20,000 square kilometers in one day, equivalent to an area spanning the entire width of the Korean demilitarized zone and extending about 80 kilometers into North Korea. At 1-meter resolution, Alternative 2 could image about 600,000 square kilometers per day, or nearly three times the entire 220,000-square-kilometer land area of the Korean Peninsula (see Figure 4-5). Even the five-satellite constellation in Alternative 1 would be capable of imaging the entire land area of the Korean Peninsula in one day at 0.7-meter resolution.

In its estimates of access, CBO assumed that a SAR signal-processing technique known as stretch processing would be used to generate fine-resolution imagery.[8] That technique involves expanding the time scale of the incoming signal so higher frequencies can be digitized (which allows finer resolution) using lower-speed hardware. With that approach, the usable range swath of the radar decreases; consequently, so does the coverage rate. More-complex signal-processing techniques that use composite waveforms (in which each pulse encompasses a different frequency range) have also been proposed. Such techniques do not suffer from the same limits on range-swath width that stretch processing does, but they are more difficult to implement. If, for example, a "stepped-chirp" waveform could be used, the estimates shown here for area coverage would increase. (See Appendix B for more discussion of SAR signal processing.)

5. The values for SAR coverage described here apply to a single area of interest—in this case, North Korea. The average access period for North Korea lasts around five minutes, out of 30 minutes of full-power SAR imaging per orbit (based on the power levels of the notional Space Radar designs that CBO examined). Thus, in a given day, the Space Radar system would be able to provide SAR coverage of as many as five other areas of interest at a level similar to that for North Korea.

6. Department of the Army, *Armor- and Mechanized-Based Opposing Force: Operational Art,* Field Manual 100-61 (January 26, 1998).

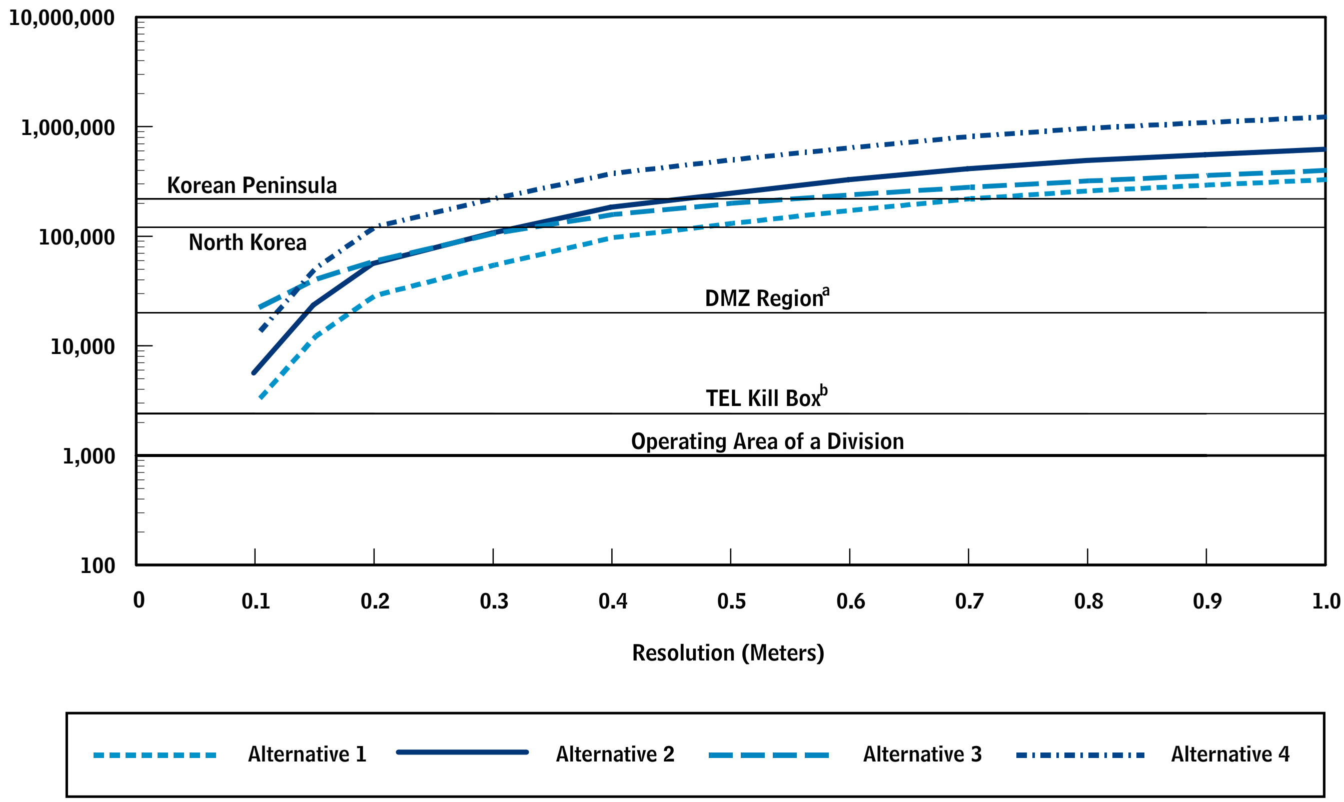
7. Lewis D. Hill and others, *Gulf War Air Power Survey,* vol. 5, *A Statistical Compendium and Chronology* (Washington, D.C.: Government Reprints Press, 1993), p. 462.

8. Stretch processing is also known as dechirping or deramping.

Figure 4-4.

SAR Coverage of North Korea with Alternative Space Radar Constellations

(Square kilometers per day)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

In all cases, CBO assumed that the entire radar aperture would be used. Alternative 3 could image larger areas at coarse resolutions if only part of the aperture was used.

SAR = synthetic aperture radar; DMZ = demilitarized zone; TEL = transporter erector launcher.

a. An area spanning the full width of the DMZ and extending 80 kilometers into North Korea.

b. An area that is 30 arc minutes per side (such as the areas that the Air Force divided Iraq into during the Persian Gulf War to detect and engage Scud missile launchers).

GMTI Performance

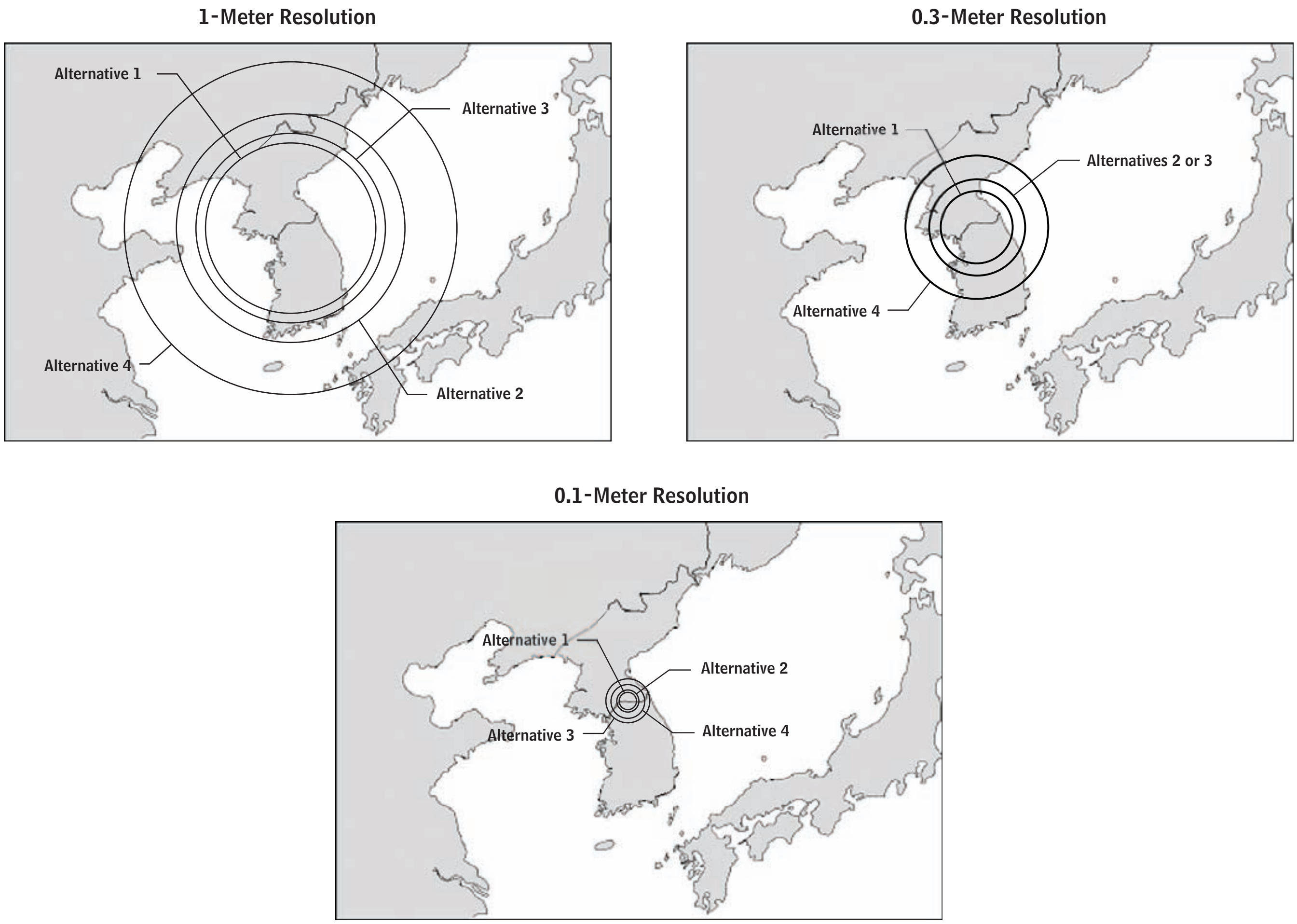
To characterize the GMTI capabilities of the alternatives, CBO used the same three metrics as in its SAR analysis (with some variations) as well as a fourth measure:

- Access—the percentage of time that a given geographic area, considered in isolation, can be observed by at least one satellite;
- Response time—the interval between receiving a tasking to observe a given location and beginning to observe that location, with no delays in tasking, control, or intelligence dissemination;
- Coverage—the average area that can be observed continually by a constellation (rather than the area that can be imaged per day, as with SAR imagery); and

Figure 4-5.

SAR Coverage of North Korea at Selected Resolutions

(Area covered per day)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

In all cases, CBO assumed that the entire radar aperture would be used. Alternative 3 could image larger areas at coarse resolutions if only part of the aperture was used.

SAR = synthetic aperture radar.

- Mean track life—the average length of time that a single ground target can be tracked.

CBO assumed that space-time adaptive processing techniques would be used on the Space Radar system. Since STAP is relatively new technology, the GMTI performance that could be achieved with it is not yet certain. CBO therefore used two alternative assumptions about STAP performance in its GMTI analysis. In the “aggressive” assumption, STAP techniques achieve their theoretical level of performance (with some adjustment for clutter motion and a reduced-rank implementation). In the “conservative” assumption, STAP performance is reduced by some additional practical limitations. Those two assumptions provide a range of performance for Space Radar that is likely to be realized operationally. In some environments, where the clutter is very consistent, the performance of the system may near the theoretical level. In other cases, where the clutter is heterogeneous or otherwise not ideal, the conservative assumption may be nearer the mark.

GMTI Access

As it does for SAR imaging, the radar has a 90-degree field of regard for GMTI. But unlike in SAR mode, where the radar cannot produce images of locations on the Earth directly in front of or behind its orbital path, in GMTI mode, the radar can function while looking in any direction on the ground.[9] Some other studies have calculated GMTI access using an effective field of regard of 360 degrees (that is, the field of regard looks like a doughnut, with a small nadir hole directly beneath the spacecraft). However, that approach assumes that the satellite will be able to maneuver fast enough to keep the target within the radar's actual field of regard—something that may not be possible. Rotating the spacecraft while the radar is operating will make it harder to keep the radar pointed at the target. That movement may also complicate the signal-processing computations and cause problematic flexing of the electronically steered radar array.

For those reasons, CBO considered two cases for GMTI access, one in which the satellite does not maneuver during radar operation, and the other in which it does. In the latter case, CBO made two assumptions about a satellite's maneuverability: first, that the yaw rate would be constant throughout the access period, and second, that it would not be possible to yaw fast enough to scan both fore and aft of the nadir hole (in cases where the satellite passed directly over the target). CBO also considered radar performance, using both "aggressive" and "conservative" performance assumptions (as described above), in computing access. Depending on the signal-processing performance assumed, in certain geometries, the radar might not be able to detect a ground target that had a given radar cross section and velocity. Even if the target was within the radar's field of regard, CBO judged there to be access only if the target could be detected with the specified probability.

9. A satellite-based synthetic aperture radar cannot image areas directly before or behind its orbital path because, in the along-track direction, the length of the synthetic aperture is zero.

As with SAR access, GMTI access is limited by grazing angle, but in a more complex fashion. Depending on the radar's capabilities (and, in particular, the STAP performance), certain combinations of grazing and azimuth angles may not yield sufficient probability of detection to be effective.

GMTI performance also depends critically on the velocity of the target. Slower targets are more difficult to separate from the background clutter. A Doppler radar can detect motion only in the direction of the radar's line of sight. The component of velocity in that direction is referred to as the radial velocity. The greater the target's radial velocity (either toward or away from the radar), the easier it is to detect. The radar cannot detect the motion of targets moving perpendicular to that direction. In the discussion below, all velocities refer to the total velocity of a target moving in a random direction.[10]

Under the most restrictive assumptions—fixed yaw angle, conservative signal-processing performance—the nine-satellite reference architecture in Alternative 2 would be able to observe a target moving at 10 meters per second, or about 22 miles per hour, for only 9 percent to 18 percent of the time (see Figure 4-6). If the target was at a latitude higher than about 70 degrees, however, access would drop sharply. With the aggressive STAP performance assumption, access would improve by about 4 to 10 percentage points, depending on latitude. If the radar could operate while the satellite was maneuvering, access would improve by another 1 to 7 percentage points. Thus, under the most optimistic performance assumptions, Alternative 2's constellation could observe a target between 17 percent to 30 percent of the time.[11]

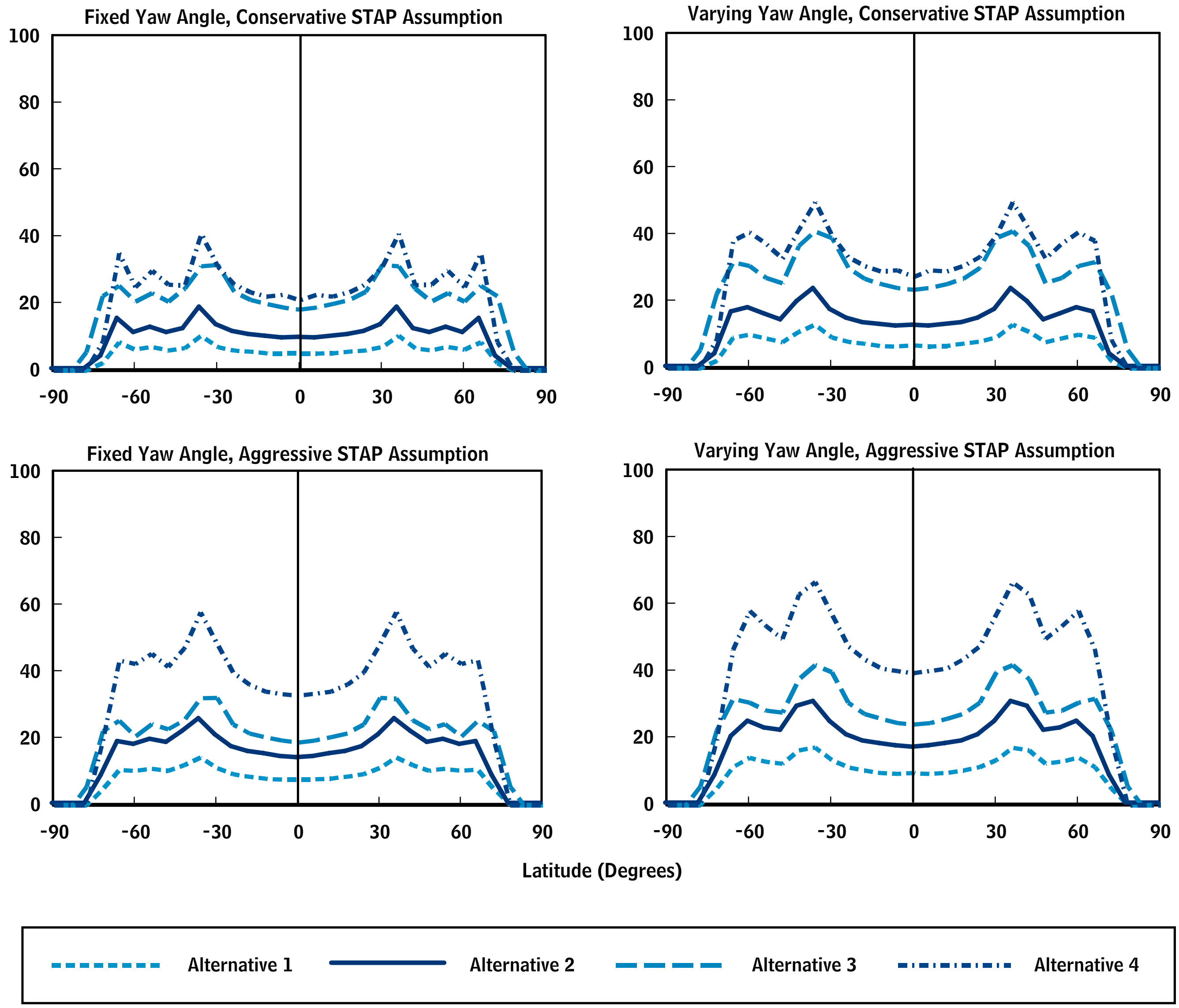
10. The expected value of the magnitude of the velocity of a target moving in a random direction, projected onto any fixed axis on the Earth's surface, is $2/\pi$ (or 0.64) times the magnitude of the target's total velocity. Since Space Radar is not on the Earth's surface, radial velocity also has a correction for grazing angle. Thus, the average radial component of the velocity of a target moving in a random direction is equal to 0.64 times the cosine of the grazing angle times the total velocity. In all of the results described here, velocity is given in terms of total velocity of the target (that is, what the driver of a moving vehicle would see on the speedometer), whereas the performance modeling is based on only the average radial component of that velocity.

11. The incremental performance improvements do not necessarily sum because they may have different impacts at different latitudes.

Figure 4-6.

Global GMTI Access for a Target Moving at 10 Meters per Second with Alternative Space Radar Constellations

(Percentage of time)



Source: Congressional Budget Office.

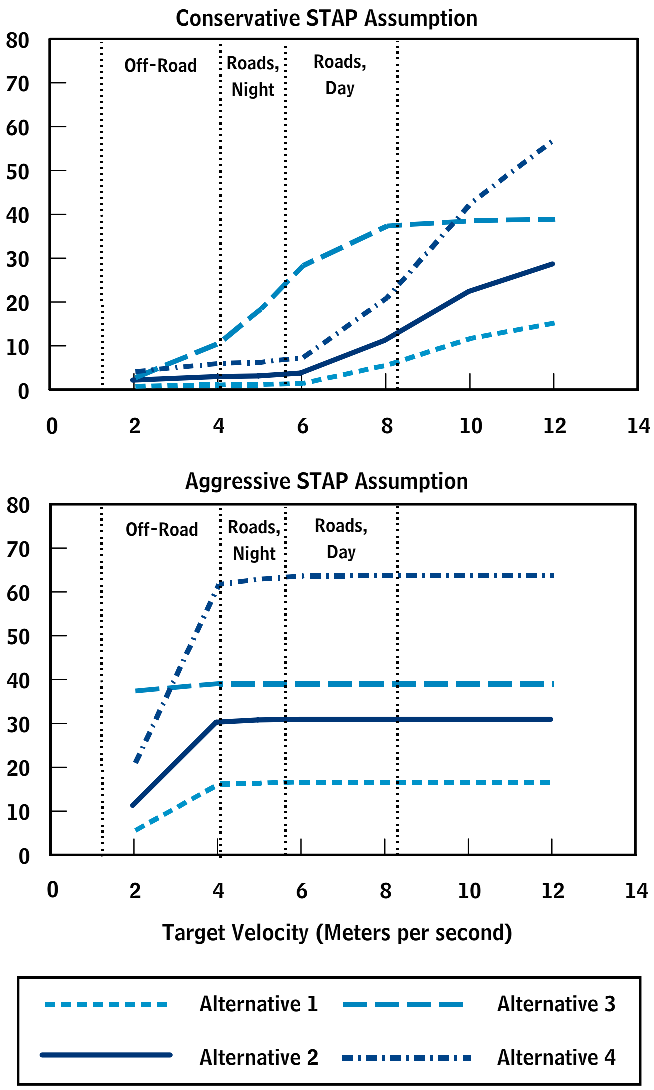
Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

GMTI = ground moving-target indication; STAP = space-time adaptive processing.

Figure 4-7.

GMTI Access in North Korea, by Velocity of Target, with Varying Yaw Angle

(Percentage of time)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

Areas between the dotted lines indicate the average march rate for mixed columns under the conditions indicated.

GMTI = ground moving-target indication; STAP = space-time adaptive processing.

The large-aperture constellation in Alternative 3 would have considerably better access: about 9 to 18 percentage points better than Alternative 2 under the most restrictive assumptions. In that case, Alternative 3 could observe an individual target area for 18 percent to 32 percent of the time. With targets moving at 10 meters per second, the performance of the 100-square-meter radar is fairly insensitive to assumptions about signal processing, since the large antenna by itself adequately reduces the clutter-Doppler spread. The ability to maneuver during scanning adds 4 to 12 percentage points to Alternative 3's access.

The 21-satellite constellation in Alternative 4 would perform slightly better than Alternative 3 at most latitudes under the conservative signal-processing assumption, but significantly better than Alternative 3 under the aggressive STAP assumption. In the most optimistic case—varying yaw angle and aggressive signal-processing performance—the 21-satellite constellation could observe a given target area between 40 percent and 67 percent of the time. (In the case of that constellation, performance would vary widely with the target's latitude.)

Although slow-moving targets are much harder to detect than fast ones, targets traveling as slowly as 4 meters per second could readily be detected under those optimistic assumptions. For a target in North Korea moving faster than 4 meters per second, access would vary from about 17 percent for Alternative 1 to 64 percent for Alternative 4 under those assumptions (see the bottom panel of Figure 4-7). As before, the large constellation (Alternative 4) would outperform the smaller constellation with a larger-aperture radar (Alternative 3) except at very low target velocities. Under the conservative signal-processing assumption, however, only relatively fast targets could be detected by the 40-square-meter radar; that radar would have difficulty detecting tracked vehicles moving at typical march speeds. Even the larger radar would have trouble detecting mixed columns of tanks and trucks moving off-road under the conservative assumption about STAP performance.

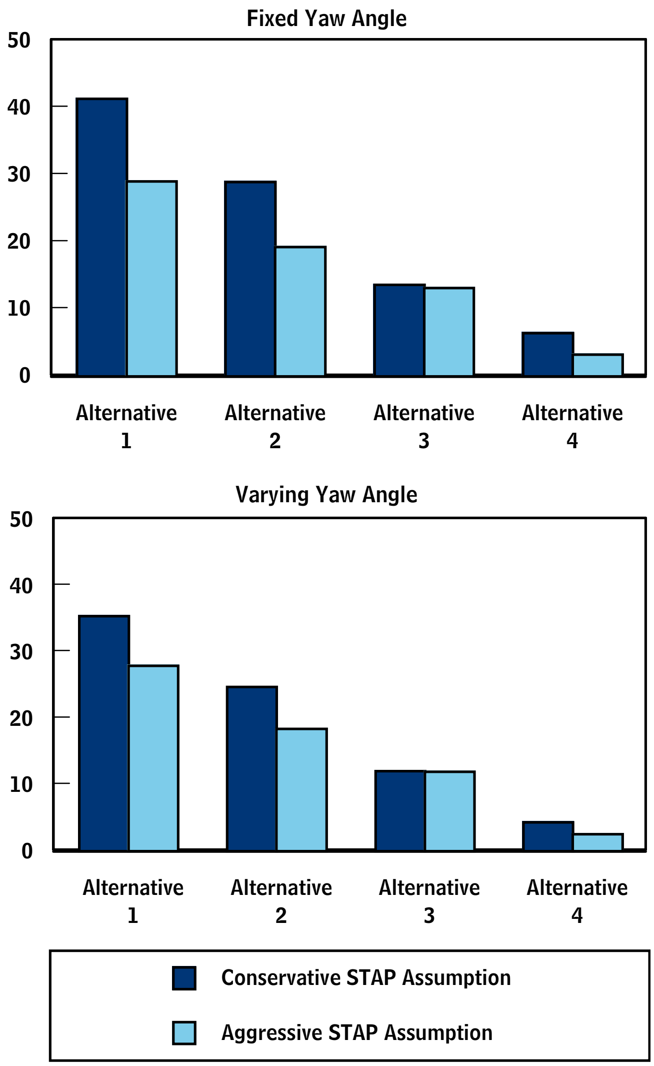
GMTI Response Time

As in the SAR analysis, response time is the period from receipt of a tasking to observe a particular geographic area until the area can be observed. That measure combines the fraction of time the system has access to the targeted area and the duration of the gaps between those access periods. CBO considered cases in which the satellite can and cannot yaw while the radar is operating.

Figure 4-8.

Average GMTI Response Time for a Target Moving at 10 Meters per Second Between 60 Degrees North and South Latitude

(Minutes)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

GMTI = ground moving-target indication; STAP = space-time adaptive processing.

Like access, response time varies with the probability of detection—and thus with the viewing geometry between the satellite and the target as well as with the target's velocity. For Alternative 2, under the most restrictive assumptions, the average response time to detect a target moving at 10 meters per second between 60 degrees north and south latitude would be about 29 minutes (not including delays in receiving and processing the tasking order or disseminating the intelligence product). Even with a varying yaw angle and the aggressive signal-processing assumption, that average response time would only drop to about 18 minutes for the nine-satellite reference architecture of Alternative 2 (see Figure 4-8). Attacking transitory targets would be difficult with those relatively long timelines. The larger antennae in Alternative 3 would cut the response time of a nine-satellite constellation by roughly half under the conservative STAP assumption or by about one-third under the aggressive assumption. With 21 satellites (Alternative 4), average response times would range from about 2.5 minutes to 6.5 minutes.

For targets moving more slowly than 10 meters per second, response times could be quite long. For example, on average, Alternative 1 would take 205 minutes and Alternative 2 would take 151 minutes to observe a 5-meter-per-second target in North Korea under the conservative signal-processing assumption (see Figure 4-9). Once again, however, assumed STAP performance has a major impact on estimated response times for slow-moving targets. Under the more optimistic STAP assumption, average response times for the 5-meter-per-second North Korean target drop to 17 minutes in Alternative 1 and to just 8 minutes in Alternative 2. With the 100-square-meter radar in Alternative 3, average response time is generally less than 10 minutes under the conservative STAP assumption, except in the case of vehicles moving at less than 5 meters per second (mixed columns traveling off-road). With aggressive signal-processing performance, response times would show little variation by target velocity (above about 4 meters per second) in any of the alternatives.

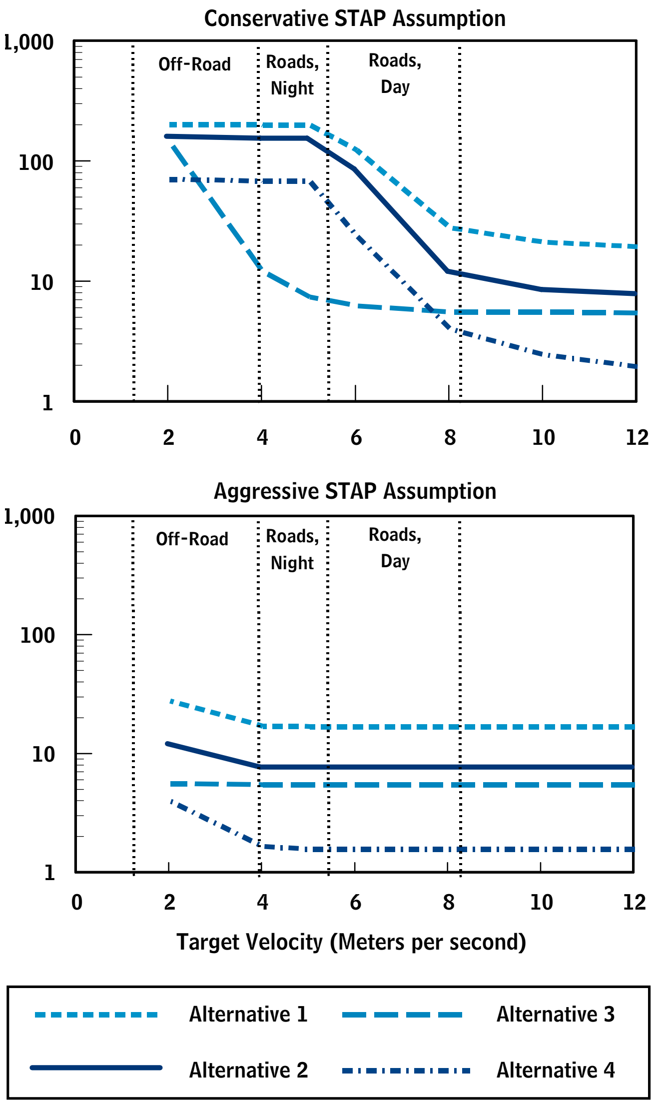
GMTI Coverage

The coverage metric is slightly different for ground moving-target indication than it is for synthetic aperture radar imaging. GMTI is generally used for surveillance of specific moving targets and produces a product similar to video, whereas SAR is used for reconnaissance of particular locations and provides individual, static images of

Figure 4-9.

GMTI Response Time in North Korea, by Velocity of Target, with Varying Yaw Angle

(Minutes)



Source: Congressional Budget Office.

Notes: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

Areas between the dotted lines indicate the average march rate for mixed columns under the conditions indicated.

GMTI = ground moving-target indication; STAP = space-time adaptive processing.

those locations. CBO defines GMTI coverage as the average area that can be continually watched by a constellation (as opposed to the area that can be imaged by the constellation in a day).

Obviously, no area can be observed during a gap in access—that is, when no satellite is within range of the target. Thus, for both SAR and GMTI, access indicates the percentage of time that a target area can be observed, and coverage indicates the area that can be observed (on average) during an access period.

Although GMTI provides a video-like product, the radar does not need to watch one piece of terrain without interruption. Rather, since the AESA radar can be steered almost instantaneously (within its field of regard), once the radar has observed a location long enough to collect sufficient data, it can be pointed at adjacent (or even non-adjacent) areas before returning to the initial location. The radar's controller can specify an update rate, which determines the time interval before a target is revisited. The area that can be observed is therefore directly dependent on the revisit interval specified. CBO analyzed GMTI coverage as a function of that revisit interval.

The revisit interval is likely to vary with the tactical situation. A radar does not need to scan as often when it is observing a large military unit, since the overall unit moves relatively slowly, changes direction infrequently, and contains a large number of targets. For example, a mechanized division might take 1.5 hours to execute a maneuver (see Table 4-1). Scanning the division 10 times during that period—or about once every 10 minutes—should provide an adequate indication of its composition and movement. Smaller units contain fewer vehicles (which may more easily be confused with extraneous radar returns), move somewhat faster, and can change direction more easily. A Soviet-style motorized rifle battalion should be able to assemble into a march column in 10 to 15 minutes.[12] When a radar is observing such a unit, the picture will need to be updated more often—say, once per minute. At the extreme of the continuum, an individual target can stop and start rapidly and easily be confused with other targets. Tracking such a target might require a revisit interval as short as 10 seconds.

12. Department of the Army, *Intelligence Preparation of the Battlefield*, Field Manual 34-130 (July 8, 1994), p. B-23.

Table 4-1.

GMTI Revisit Intervals Needed to Monitor Units of Various Sizes

Unit	Defensive Area Covered (Square kilometers)	Time to Execute a General Maneuver	Revisit Interval Needed for GMTI
Army	2,000–10,000	4 hours	30 minutes
Division	500–1,000	1.5 hours	10 minutes
Regiment	~100	30 minutes	3 minutes
Battalion	~20	10 minutes	1 minute
Company	~3	5 minutes	30 seconds
Individual Transporter Erector Launcher for Ballistic Missiles	n.a.	5 minutes	10 seconds

Source: Congressional Budget Office based on information from the Massachusetts Institute of Technology's Lincoln Laboratory.

Note: GMTI = ground moving-target indication; n.a. = not applicable.

CBO estimated the area that Space Radar would be able to observe as a function of each of the revisit intervals listed in Table 4-1. That area is largely independent of the number of satellites in a given constellation, since the satellites provide little overlapping access (even in the 21-satellite constellation). However, the 100-square-meter radar offers better performance at small grazing angles and disadvantageous azimuth angles than the smaller radar does, so it provides longer and more frequent access periods.

GMTI coverage initially increases linearly with the revisit interval (see Figure 4-10). Under the most conservative assumptions (a fixed yaw angle and conservative signal-processing performance), the 40-square-meter radar could observe between 7,000 and 140,000 square kilometers in North Korea, depending on the revisit interval specified. With a revisit interval of just 10 seconds (suitable for watching individual targets, such as transporter erector launchers), the 40-square-meter radar could observe fewer than three "TEL kill boxes" of about 2,400 square kilometers each under those conservative assumptions. With a 30-second revisit interval (suitable for units as small as a company), they could observe more than 20,000 square kilometers, equivalent to an area spanning the entire width of the Korean demilitarized zone and extending about 80 kilometers into North Korea. As the revisit interval approaches the length of the average access period, coverage area increases more slowly because there may not be enough time during the access period to complete the scan. Nevertheless, at a revisit interval of 10 minutes (appropriate for divisions and larger units), the smaller radar could cover all of North Korea.

Coverage for the 40-square-meter radar rises significantly (between 40 percent and 200 percent) under the aggressive signal-processing assumption. In that case, about five "TEL kill boxes" could be observed with a 10-second revisit interval.

The ability to yaw the spacecraft while scanning varies in its impact on the coverage of that smaller radar. Under the conservative STAP assumption, ability to maneuver during a scan increases the area covered by about 23 percent to 42 percent. Under the aggressive STAP assumption, ability to maneuver boosts coverage by only about 4 percent for most revisit intervals.

The 100-square-meter radar could observe a considerably greater area than the 40-square-meter radar under the conservative STAP assumption. For example, the larger radar would be capable of observing about 11,000 square kilometers at a 10-second revisit interval—over 50 percent more than the smaller radar. Under the aggressive signal-processing assumption, the smaller radar's performance nearly matches that of the larger radar if the yaw angle of the satellite is fixed, except at the longest revisit interval. If the satellite can maneuver, however, the larger radar can cover about 20 percent more area than the smaller radar at all but the longest revisit interval (at which the difference is somewhat greater).

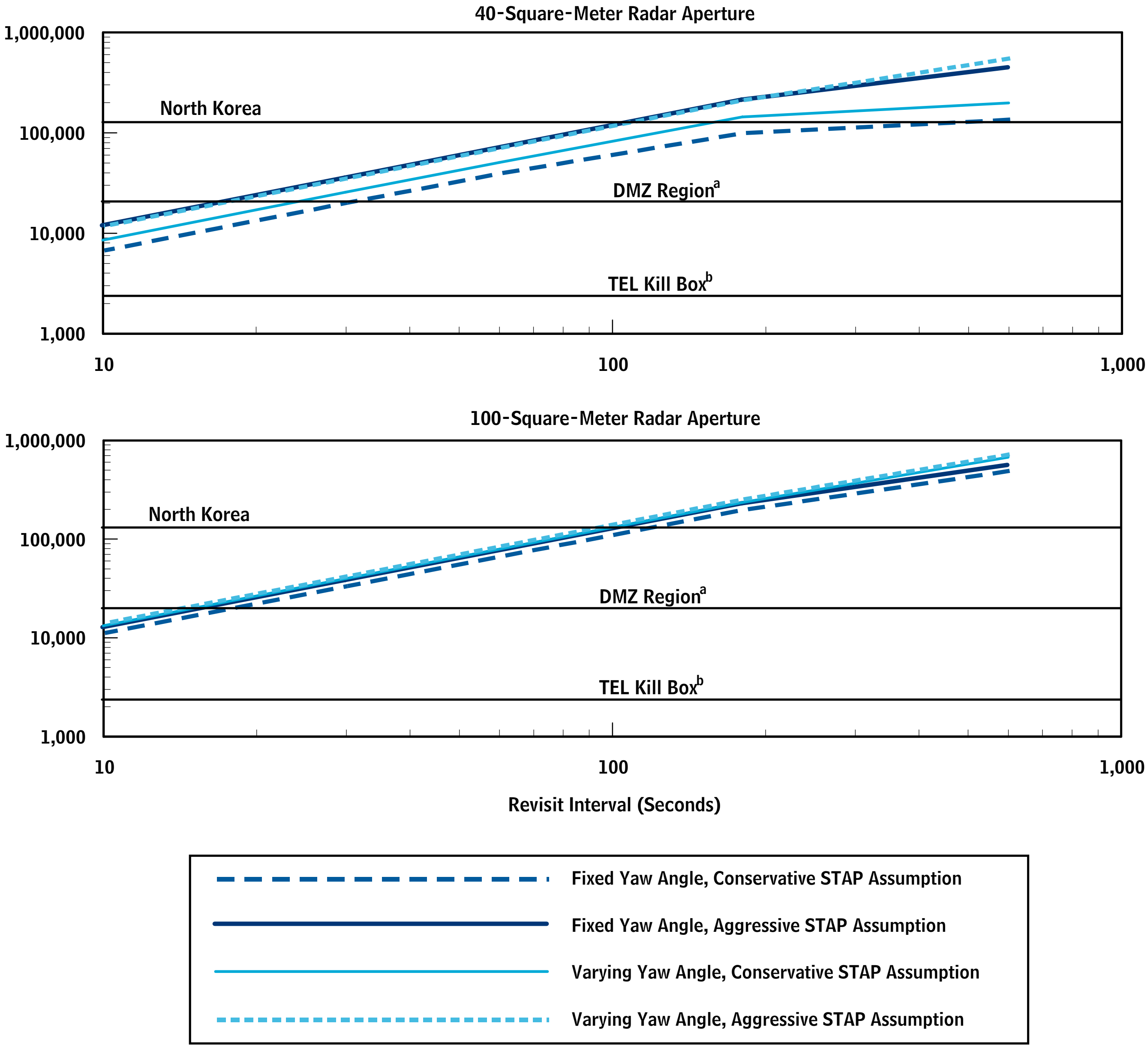
Mean Track Life for Individual Targets

Some early descriptions of the Space Radar system suggested that it would be able to track—not just detect—moving targets without assistance from other surveillance systems. Because the notional constellations in this analysis will not afford continuous access to any geographic

Figure 4-10.

Average GMTI Coverage of North Korea for Targets Moving at 10 Meters per Second

(Square kilometers per access period)



Source: Congressional Budget Office.

Note: GMTI = ground moving-target indication; DMZ = demilitarized zone; TEL = transporter erector launcher.

a. An area spanning the full width of the DMZ and extending 80 kilometers into North Korea.

b. An area that is 30 arc minutes per side (such as the areas that the Air Force divided Iraq into during the Persian Gulf War to detect and engage Scud missile launchers).

location, and because the radar's ability to detect and locate targets is imperfect, tracking a ground target indefinitely would not be possible. CBO estimated the average length of time that a single ground target could be tracked—the mean track life—under a range of conditions using a simple statistical tracking model developed by consulting firm Booz Allen Hamilton (BAH).

The BAH model assumes that a target moves randomly and that other, similar-looking targets are nearby that may be confused with the intended target. Uncertainty exists about both the position and velocity of the target; the amount of uncertainty depends on the performance of the satellite and its radar as well as on the unpredictability of changes in the (assumed) random movement of the target. As the model simulation progresses, the uncertainty can build, making it increasingly difficult for a tracking algorithm to separate the real target from the "confusers."

In reality, targets do not move randomly. More-sophisticated tracking algorithms can take advantage of that fact and even use particular aspects of the radar return to help identify the correct target. However, modeling that type of algorithm requires extensive knowledge about its design as well as a detailed scenario; such modeling is beyond the scope of this analysis.

The BAH tracking model uses various inputs:

- Mean access time,
- Mean gap time between access periods,
- Revisit interval,
- Confuser density (the number of objects other than the desired target that the radar might detect),
- The radar's probability of detecting an object (P_D),
- Target location error (the range over which the target's location could vary), and
- Target velocity error (the range over which the target's velocity could vary).

CBO used the BAH model in a series of Monte Carlo simulations to estimate the range of possible mean track lives for the access periods afforded by the various alternatives, given reasonable ranges for the inputs listed above.[13] All of the simulations assumed a P_D of 0.95 and a revisit interval of 10 seconds. As input for the Monte Carlo simulations, CBO used the range of values that it calculated in the area-coverage analysis for the duration of each target access period, gap times between those periods, and signal-to-noise ratio (which affects P_D and target location error). CBO generated distributions of those parameters under the conditions required for observing a moving target with a radar cross section of 10 square meters and a velocity of 10 meters per second. Nominal target location accuracy in the range direction was assumed to be 1 meter; target location accuracy in the cross-range direction was estimated from the signal-to-noise ratio using published relationships.[14] CBO varied the confuser density from 0.5 to 2 targets per square kilometer and the target velocity error from 0.5 to 2 meters per second.

That analysis suggests that mean track life would range between only about 1 minute and 4 minutes for the 40-square-meter radar in Alternatives 1, 2, and 4 (see Figure 4-11). For each of those alternatives, switching from the conservative STAP assumption to the aggressive one roughly doubles the mean track life, because of the improved access time and higher signal-to-noise ratio that better signal processing allows. Mean track life would be slightly higher for the 100-square-meter radar in Alternative 3: about 5 to 6 minutes. Under the most favorable conditions, however, that alternative could maintain a track for as long as 16 to 19 minutes (as indicated by the 90 percent confidence intervals in Figure 4-11).

Those estimates assume that a satellite maintains a fixed yaw angle while the radar is scanning. However, the ability to maneuver the satellite during scanning makes little difference to the results. Those track lives are generally inadequate for engaging a target in the absence of other surveillance systems because they are unlikely to provide enough time for strike aircraft to locate the target.

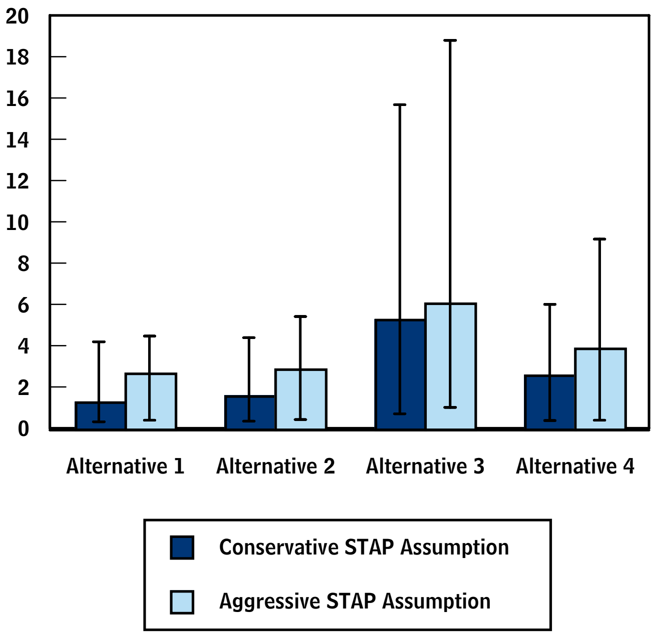
13. Monte Carlo simulation involves running a model many times, each time using values for the various inputs that are randomly drawn from the range of probable values. Generating a large enough set of such simulations reveals the range of possible outcomes and their likelihood.

14. David K. Barton, *Radar System Analysis and Modeling* (Boston: Artech House, 2005).

Figure 4-11.

Mean Track Life for a Single Target in North Korea Moving at 10 Meters per Second

(Minutes)



Source: Congressional Budget Office.

Notes: Bars denote mean track lives, assuming that a satellite's yaw angle is fixed. Lines denote the 90 percent confidence range for each track life based on Monte Carlo simulations.

Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

STAP = space-time adaptive processing.

Performance Against Mobile Missile Launchers

CBO's analyses thus far have examined the percentage of time that a given location can be observed, the average time to make the observation, the size of the area that can be monitored, and the time that a moving target, once detected, may be tracked. Those analyses have highlighted the limitations of the relatively small constellations that CBO examined. The question remains, how many satellites does the Space Radar system need? The answer depends on the particular mission being performed. Constellations of 5 to 21 satellites may be adequate to observe the movement of large military units, whose intent can be discerned even with infrequent and incomplete observations. Small units and individual vehicles require frequent and more-thorough surveillance.

One highly challenging mission that the Space Radar system could potentially support is attacking mobile launchers for tactical ballistic missiles. During the 1991 Persian Gulf War, mobile Scud missiles proved highly elusive. Although their military usefulness is subject to debate, extensive resources were devoted to attempting to destroy them. In this analysis, CBO used a simplified scenario involving truck-based transporter erector launchers as one possible—albeit demanding—means of determining the number of Space Radar satellites that might be necessary.

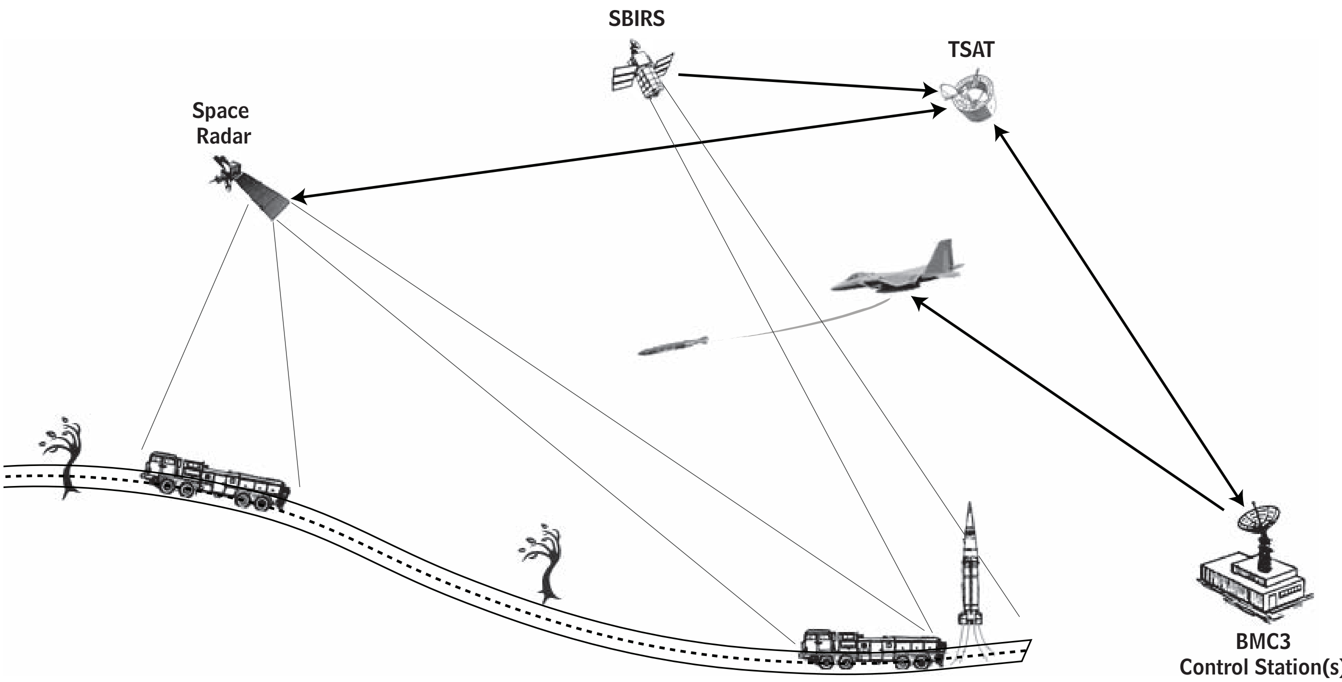
In that scenario, the launch of a mobile tactical ballistic missile is first detected by a satellite of the Air Force's planned Space-Based Infrared System (SBIRS), which cues the Space Radar constellation. Through a combination of SAR and GMTI, Space Radar detects the TEL and tracks it until a strike aircraft can fly to the area, locate the TEL, and launch an air-to-surface weapon at it (see Figure 4-12). CBO assumed that a short delay (30 seconds to 1 minute) would be needed to authenticate the missile launch and communicate the information to Space Radar's control element. Tasking the Space Radar constellation was assumed to require another 30 seconds to 1 minute. If, once a missile is launched, the TEL takes 5 minutes to tear down and get ready for moving to another location, only 3 to 4 minutes will be left in which to locate the launcher before it moves.[15] (CBO assumed that once the TEL had left its known location, it would be impossible to distinguish unambiguously from other vehicles that might be in the area.)

For that scenario, CBO examined the approximate relationship between response time and constellation size. Response time depends on numerous factors and differs considerably with the latitude of the target and the design of the constellation. For its scenario, CBO used a latitude in North Korea and considered constellations of up to 54 satellites, varying the configuration of the constellation for each size considered to minimize the response time. CBO then calculated the 95th percentile of the

15. Alan J. Vick and others, *Aerospace Operations Against Elusive Targets* (Santa Monica, Calif.: RAND Corporation, 2001), p. 65.

Figure 4-12.

Scenario for Using Space Radar to Detect and Track Mobile Missile Launchers



Source: Congressional Budget Office.

Note: SBIRS = Space-Based Infrared System; TSAT = Transformational Satellite Communications System; BMC3 = battle management command, control, and communications.

response time for each constellation and performed a linear regression with that time as the dependent variable and the number of satellites as the independent variable. In that way, CBO determined the approximate number of satellites that would be necessary to achieve a high likelihood of detecting a TEL within 3 to 4 minutes.

Depending on the design assumptions, 35 to 50 satellites with 40-square-meter radars would be required to ensure that the response time did not exceed 4 minutes. Under the best circumstances—varying yaw angle and aggressive signal-processing performance—only about 35 such satellites would be needed (see Table 4-2). Under the conservative signal-processing assumption and with a satellite that could not maneuver during scanning, about 50 of those satellites would be necessary.

The performance of the 100-square-meter radar would be similar to that of the smaller radar under the aggressive STAP assumption. Thus, with those larger radars, a constellation of 35 to 40 satellites would be required to achieve a 95 percent probability that the response time was no longer than 3 to 4 minutes.

Data Processing and Communications Bandwidth

The performance analyses described above mainly deal with the ability of various satellite constellations to collect radar observations of selected areas of the Earth's surface. Once those data are collected, however, they must be processed and communicated to the ground in order to generate useful intelligence products. The ability of the Space Radar system—and its supporting communications systems—to perform those tasks could limit the amount or timeliness of the intelligence produced.

The radar systems considered in this report would be capable of generating large amounts of raw data. While making observations, each of the more than 100,000 transmit/receive modules in the AESA radar would "listen" for radar returns during the 85 percent of the time they were not transmitting pulses. The signals collected at

Table 4-2.

Number of Satellites with 40-Square-Meter Radars Needed to Counter Mobile Missile Launchers

	Fixed Yaw Angle		Varying Yaw Angle	
	Conservative STAP Assumption	Aggressive STAP Assumption	Conservative STAP Assumption	Aggressive STAP Assumption
Number of Satellites Needed for CBO's Counter-TEL Scenario	~ 50	~ 40	~ 45	~ 35

Source: Congressional Budget Office.

Notes: STAP = space-time adaptive processing; TEL = transporter erector launcher.

The numbers shown here are the number of Space Radar satellites that would be necessary to achieve a 95 percent probability that the system's response time for a TEL in North Korea did not exceed 3 to 4 minutes. The performance of satellites with 100-square-meter radars would be similar to that of satellites with 40-square-meter radars under the aggressive STAP assumption.

those modules could be combined into a more manageable set of around 20 subarrays and then digitized. Even in that form, however, the raw data stream from the entire AESA radar could exceed 100 billion bits per second (100 Gbps) in high-resolution SAR mode.

As raw data are processed, the volume of the data stream grows smaller. Thus, the communications bandwidth—the rate at which data must be downlinked to Earth—depends on how much of the processing is done on board the satellites. Onboard processing carries various risks, requiring algorithms that (ideally, at least) are fully developed and tested well before the satellites are launched and processors that can operate at high speeds and low power.[16]

Space Radar data could be downlinked by several methods. Observations of particular urgency could potentially be transmitted directly to a theater using portable ground stations, but those stations have limited downlink-rate capability. Permanent ground stations with larger antennae at selected locations could provide higher downlink rates. In either case, to communicate directly with a ground station, a satellite must wait until it has a direct line of sight to the station's antenna, which could often result in significant delays.[17] Alternatively, high downlink rates would be possible by transmitting the data to a satellite communications backbone system, which would then relay the data to the ground. That method would not require a Space Radar satellite to be at any particular position (since the satellite backbone would have global coverage) and might thus avoid the potential delays involved in communicating directly with ground stations.

For its analysis of communications bandwidth requirements, CBO assumed that the preferred method of downlink would be through a backbone system—specifically, CBO used the Air Force's TSAT system and NASA's Tracking and Data Relay Satellite System to represent the downlink capabilities that could be available from future and current backbone systems, respectively.[18]

SAR Data Rates

Downlink rates for SAR data depend not only on the amount of onboard processing that occurs but also on how the radar system is used. The analysis of SAR coverage earlier in this chapter assumed that the Space Radar system would be fully employed while it was over a region of interest and would image as large an area as possible. Those assumptions lead to the maximum data rates described below. However, it is possible that Space Radar's tasking for SAR imagery could be more selective,

16. It is possible to reprogram onboard processors once a satellite is in orbit. However, the ability to do that requires more-flexible and less-efficient processors, which makes the requirement for high speed and low power harder to meet.

17. Estimates of the potential delays in direct communications with ground stations would depend on the specific positions and capabilities of those stations; such estimates are beyond the scope of this analysis.

18. The Department of Defense has not indicated that it would employ TDRSS to downlink Space Radar data. CBO used the system as a benchmark for comparison in this analysis because TDRSS is a widely used, currently available communications system whose performance parameters are well known.

limiting the size of each area imaged to the location of immediate interest. If so, both the data rates and the required communications bandwidth would be smaller.

Selectivity in tasking might also be necessary to reduce the workload for imagery analysts, given the large number of images that the system would be capable of generating. For example, the 21-satellite constellation in Alternative 4 would be able to image about 130,000 separate sites each day at 1-meter resolution, with an average area of more than 170 square kilometers per image.

If Space Radar's SAR imagery was fully processed on board the satellites, systems with very large communications bandwidth would not be needed for downlinking those data. For example, in the case of a 21-satellite constellation imaging North Korea at 1-meter resolution, the average data rate required would be about 200 million bits per second (Mbps)—compared with TDRSS's maximum single-channel capacity of 800 Mbps. Peak data rates for that constellation could exceed the maximum single-channel capacity of TDRSS for brief periods, with potential delays of less than a minute. Even higher data rates (and longer potential delays) would occur if the satellites' full coverage capability was used to produce images with 0.1-meter resolution. However, such high-resolution images would probably be limited to the immediate area of interest to facilitate their analysis, which would reduce the required downlink data rate. Thus, the communications bandwidth of an existing system like TDRSS (assuming that a channel was available) would be sufficient for SAR imagery in that case.[19]

Fully processing SAR data on board the Space Radar satellites could present a challenge, however. Of the various SAR satellites now in orbit, none of them (to CBO's knowledge) fully process their data on board. If some processing of Space Radar's SAR data was done on the ground, the peak communications bandwidth required for those data would most likely exceed the capacity of a system like TDRSS. The result would be some delays in processing and disseminating the images, unless a communications system with higher data rates—such as the planned TSAT system—was available.

19. TDRSS has a total of six Ka-band 800-Mbps channels available for sharing among all users.

GMTI Data Rates

Timely communications with the ground would be an even bigger challenge when Space Radar was operating in GMTI mode. Information about moving vehicles is especially time sensitive, particularly when it is used to target weapons. Moreover, given the current level of maturity of GMTI data processing, it is likely that some of the processing would be done on the ground, requiring high communications bandwidth. In particular, for the data rates described below, CBO assumed that STAP processing would occur on the ground.

Data rates for GMTI depend on the size of the area being scanned and the range resolution required. CBO estimated pre-STAP data rates for three potential GMTI operating modes:

- Low resolution in the range direction (15 meters), with a wide area scan;
- High range resolution (1 meter), with a wide area scan; and
- High range resolution, with the scan limited to a single 10-kilometer by 10-kilometer area, and a revisit interval of 10 seconds (such as might be used for tracking a single vehicle).[20]

In the first two modes, data rates would exceed the 800 Mbps available from one of TDRSS's Ka-band channels (see Table 4-3). In the second mode (a high range resolution and wide area scan), the average data rate would also substantially exceed the 5 to 10 Gbps anticipated for TSAT. In that mode, delays of 2 to 7 minutes could occur in downlinking tracks, even if TSAT was available. (Those waits would be in addition to any delays involved in turning the partially processed data into a usable intelligence product and getting that product from the central processing facility to the end user.) If communications bandwidth was constrained and delays were unacceptable, the area subjected to high-resolution scanning could be reduced.

20. Those estimates were adapted from formulas in R.A. Coury and others, *Discoverer II Performance Analysis Tool Modeling Report* (prepared by M.I.T. Lincoln Laboratory for the Defense Advanced Research Projects Agency, July 28, 1999); and Gérard Maral and Michel Bousquet, *Satellite Communications Systems: Systems, Techniques, and Technology,* 4th ed. (Chichester, England: John Wiley and Sons, 2002).

Table 4-3.

Potential Delays in Transmitting GMTI Data from Space Radar Satellites to the Ground

GMTI Operating Mode	Average Pre-STAP Data Rate (Gbps)	Potential Delay (Minutes): Using TDRSS Ka-Band Channel at 800 Mbps	Potential Delay (Minutes): Using TSAT System at 10 Gbps
Low Range Resolution, Wide Area Scan	1.2	0–4	Negligible
High Range Resolution, Wide Area Scan	18.1	40–180	2–7
High Range Resolution, 10 x 10 km Area, with a 10 Second Revisit Interval	0.2	Negligible	Negligible

Source: Congressional Budget Office based on R.A. Coury and others, *Discoverer II Performance Analysis Tool Modeling Report* (prepared by M.I.T. Lincoln Laboratory for the Defense Advanced Research Projects Agency, July 28, 1999), and Gérard Maral and Michel Bousquet, *Satellite Communications Systems: Systems, Techniques, and Technology,* 4th ed. (Chichester, England: John Wiley and Sons, 2002).

Note: GMTI = ground moving-target indication; STAP = space-time adaptive processing; Gbps = gigabits per second; TDRSS = Tracking and Data Relay Satellite System; TSAT = Transformational Satellite Communications System; Mbps = megabits per second; km = kilometer.

Delays could be especially problematic in the third operating mode, the one most relevant to tracking a target for engagement in a tactical situation. In that case, delays with the 800-Mbps TDRSS channel could be avoided if Space Radar was cued—either by another system or by another satellite in the constellation that had viewed the target earlier—to search for a moving target in a particular 10-kilometer by 10-kilometer area. If the area to be searched was larger than that, some delays might occur if TDRSS was used. If TSAT or another high-capacity system was available, however, there would probably be no delays for single tracks, even over a large area.

If space-time adaptive processing techniques were sufficiently mature to run on board a satellite, GMTI data could be downlinked without a wait in all of the cases shown in Table 4-3. Further, the resulting GMTI "tracks-only" data rates would be low enough (less than 5 Mbps) to allow transmission directly to end users with little or no delay.

APPENDIX

A

Cost Estimates for the Alternative Space Radar Systems in CBO's Analysis

For each of the four notional Space Radar constellations described in Chapter 3, the Congressional Budget Office (CBO) estimated the costs, in 2007 dollars, to acquire the satellites and their associated equipment, to launch the satellites into orbit, and to operate the satellites and process the data they produce for 20 years (see Table A-1). The estimates assume that, in each alternative, the first satellites are placed into orbit by 2015 aboard Delta IV or Atlas V launch vehicles. Total costs for the options range from about $26 billion to $94 billion, depending on the number and type of satellites to be deployed and the technical risks associated with a particular alternative.

CBO used various methods to estimate the costs of research and development (R&D), procurement, and operations for the alternative Space Radar constellations. Many of those methods rely on a mathematical expression that relates cost as the dependent variable and weight as the independent variable. In particular, CBO used the weight-based methods outlined in the eighth edition of the Unmanned Space Vehicle Cost Model, which was developed by Tecolote Research. (That model also contains methods that rely on other technical characteristics of space systems to estimate costs; however, CBO did not use those methods because it did not develop a detailed engineering design for Space Radar.)

Cost estimates for systems that are defined only conceptually or that depend on the development of new technologies—as is the case with Space Radar—entail more uncertainty than do estimates for well-defined programs that are based on proven technologies. To account for the potential effects of such uncertainty, CBO estimated a range of costs for the Space Radar systems it evaluated. For each alternative, the lower end of the range represents what the system might cost if few technical difficulties arose in making it fully operational. The higher end of the range takes into account the growth in costs that has commonly occurred for other space-based systems of the Department of Defense (DoD).

A Summary of the Alternatives and Their Costs

Alternative 1 consists of a constellation of five satellites, each with a radar whose aperture measures 16 meters in length and 2.5 meters in height, or 40 square meters (see Table A-2). The satellites would be placed in a Walker 5/5/1 constellation.[1] Because each of the five satellites would be in a different orbital plane, a total of five launch vehicles would be necessary to put them into orbit in the desired configuration. Total costs for that version of the Space Radar system would range between $26 billion and $40 billion (in 2007 dollars), CBO estimated.

Alternative 2 consists of nine satellites carrying the same 40-square-meter radars as in Alternative 1. The satellites would be placed in a Walker 9/3/2 constellation. CBO estimated that each launch vehicle would be able to carry three of those satellites; thus, a total of three launch vehicles would be needed to put the nine satellites into three orbital planes. Because of the larger number of satellites, that Space Radar constellation would cost more than the one in the first alternative: between $35 billion and $52 billion.

Alternative 3 also comprises nine satellites but with larger radars. Those radars' apertures would be 25 meters long and 4 meters high, or 100 square meters. As in the previ-

1. For information about the Walker notation system for describing symmetrical constellations of satellites in circular orbits, see Box 3-1 on page 20.

Table A-1.

Costs for the Alternative Space Radar Systems in CBO's Analysis

(Billions of 2007 dollars)

	Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Low	High	Low	High	Low	High	Low	High
Research and Development								
Payload and spacecraft	9.7	16.4	9.7	16.4	12.1	20.5	9.7	16.4
Ground equipment	1.6	2.4	1.6	2.4	2.0	3.0	1.6	2.4
Launch vehicle	0	0	0	0	0	0	0	0
Subtotal	11.3	18.8	11.3	18.8	14.1	23.5	11.3	18.8
Procurement								
Payload	1.8	2.1	3.6	4.2	8.0	9.5	9.4	11.1
Spacecraft	0.3	0.4	0.6	0.8	0.7	0.9	1.7	2.1
Integration and assembly	0.3	0.3	0.6	0.6	1.1	1.3	1.5	1.7
Ground equipment	1.2	1.7	2.2	3.0	3.5	4.8	5.0	7.0
Launch vehicle	1.0	1.0	0.6	0.6	1.2	1.2	1.4	1.4
Program management	0.7	0.8	1.1	1.4	2.2	2.6	2.8	3.5
Subtotal	5.3	6.3	8.7	10.6	16.7	20.2	21.8	26.7
Operations (Over 20 years)								
Satellite operations	2.8	3.9	5.0	7.0	5.0	7.0	11.8	16.4
Tasking, processing, exploitation, dissemination	1.6	3.1	2.8	5.6	4.5	9.0	6.5	13.1
Sustaining engineering	0.8	3.2	0.8	3.2	0.8	3.2	0.8	3.2
Replacement space radars	3.0	3.6	5.4	6.4	11.1	13.1	12.6	14.9
Replacement launch vehicles	1.0	1.0	0.6	0.6	1.2	1.2	1.4	1.4
Subtotal	9.2	14.8	14.6	22.8	22.6	33.4	33.1	49.0
Total	**25.7**	**39.8**	**34.6**	**52.2**	**53.4**	**77.1**	**66.2**	**94.4**

Source: Congressional Budget Office.

Note: Alternative 1 consists of five satellites with radars of 40-square-meter aperture; Alternative 2 consists of nine satellites with radars of 40-square-meter aperture; Alternative 3 consists of nine satellites with radars of 100-square-meter aperture; and Alternative 4 consists of 21 satellites with radars of 40-square-meter aperture.

ous option, the nine satellites would be placed in a Walker 9/3/2 constellation. But because the 100-square-meter radar would be much heavier than the 40-square-meter radar, each launch vehicle could carry only two satellites, CBO estimated. As a result, placing the nine satellites into the desired constellation would require a total of six launch vehicles (two for each of the three orbital planes). Costs for that version of the Space Radar system are estimated to total between $53 billion and $77 billion.

Alternative 4 features 21 satellites, each with the 40-square-meter radars used in Alternatives 1 and 2. The satellites would be placed in a Walker 21/7/3 constellation using a total of seven launch vehicles. That Space Radar constellation would be the most expensive of the options that CBO analyzed, with total costs ranging from $66 billion to $94 billion.

CBO's Estimating Methods

Costs for the Space Radar system can be divided into three categories, which correspond to different phases of the system's implementation:

- Research and development—the engineering activities needed to design and develop the satellites, their radar payloads, and the associated ground equipment. Payloads include radar structural panels, transmit/receive (T/R) modules, electronics, and communications equipment. Ground equipment includes command-and-control centers that support spacecraft operations,

Table A-2.

Characteristics and Components of the Space Radar System Under Each Alternative

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
		System Characteristics		
Number of Satellites in Constellation	5	9	9	21
Failure Rate (Percent)				
Space radar	10	10	10	10
Launch vehicle	0	0	0	0
Satellite Life (Years)[a]	10	10	10	10
Aperture Size (Square meters)	40	40	100	40
Number of Orbital Planes	5	3	3	7
Number of Satellites in Each Orbital Plane	1	3	3	3
Maximum Number of Satellites That Could Be Launched on Each Launch Vehicle	1	3	2	3
		Components Purchased		
Number of Satellites in Initial Constellation	6	10	10	23
Number of Launch Vehicles Needed to Place Initial Constellation into Orbit	5	3	6	7
Number of Replacement Satellites[a]	5	9	9	21
Number of Replacement Launch Vehicles[a]	5	3	6	7

Source: Congressional Budget Office.

a. The total life of the Space Radar constellation is assumed to be 20 years, meaning that each satellite would need to be replaced once.

as well as hardware and software that receive and process data from the radars. The R&D phase also involves testing the components of the radar system and integrating the system into the military's existing infrastructure. (R&D costs exclude the cost of designing a new launch vehicle, because CBO assumed that existing Delta or Atlas launch vehicles would be used to put the satellites into orbit.)

- Procurement—production of the Space Radar system's components (including the payload, spacecraft, and ground equipment) and of the vehicles to launch the satellites.

- Operations—routine efforts to maintain, operate, and replenish a constellation of Space Radar satellites over 20 years.

The rest of this appendix describes the methods that CBO used to produce the lower cost estimates for each of those three categories (see Table A-3).

To calculate the higher cost estimates, CBO increased the lower estimates by factors that reflect past cost growth for comparable systems.[2] For example, CBO estimated that R&D costs could grow by 69 percent for the payload and spacecraft and by 48 percent for the ground equipment. Procurement costs could increase by 19 percent for the payload and spacecraft and by 38 percent for the ground equipment. CBO estimated that costs for tasking the

2. Those cost-growth factors are based on unpublished updates to Jeanne M. Jarvaise, Jeffrey A. Drezner, and D. Norton, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports*, MR-625-OSD (Santa Monica, Calif.: RAND Corporation, 1996).

Table A-3.

Summary of CBO's Cost-Estimating Methods for Space Radar Systems

	R&D Costs	Procurement Costs	Operations Costs
Hardware, Materials, Fabrication			
Payload			
Radar panels	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on a statistical cost-estimating relationship by Tecolote Research that uses the weight of radar panels to estimate their procurement costs	n.a.
Transmit/receive modules	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on past costs of modules adjusted for manufacturing advances and cost risk associated with space components	n.a.
Electronics	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on a statistical cost-estimating relationship by Tecolote Research that uses the weight of electronics to estimate their procurement costs	n.a.
Communications	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on a statistical cost-estimating relationship by Tecolote Research that uses the weight of communications equipment to estimate its procurement costs	n.a.
Spacecraft	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on a statistical cost-estimating relationship by Tecolote Research that uses the weight of a spacecraft to estimate its procurement costs	n.a.
Integration and assembly	n.a.	Assumed to equal 12 percent of procurement costs of hardware and materials	n.a.
Ground Equipment	Based on Air Force estimates adjusted for differences in aperture size of radar	Based on Air Force estimates adjusted for differences in constellation and aperture size	n.a.
Launch Vehicle	No R&D needed because options would use launch vehicles already in use for military payloads	Based on budget data provided by the Air Force and used in a previous CBO study[a]	n.a.

Continued

Table A-3.

Continued

	R&D Costs	Procurement Costs	Operations Costs
Program Management	n.a.	Assumed to equal 15 percent of the other procurement costs of the Space Radar system (Including ground equipment and launch vehicle)	n.a.
Satellite Operations	n.a.	n.a.	Based on a statistical cost-estimating relationship by NASA that uses a spacecraft's R&D and procurement costs to estimate its operating costs
Tasking, Processing, Exploitation, Dissemination	n.a.	n.a.	Based on Air Force estimates adjusted for differences in constellation size and data-processing workload
Sustaining Engineering	n.a.	n.a.	Based on the assumption that 200 engineers would be retained to ensure timely and efficient upgrades
Replacement Space Radars	n.a.	n.a.	Based on the same estimating methods used for initial spacecraft and payload
Replacement Launch Vehicles	n.a.	n.a.	Based on the same estimating methods used for initial launch vehicles

Source: Congressional Budget Office.

Note: R&D = research and development; n.a. = not applicable; NASA = National Aeronautics and Space Administration.

a. Congressional Budget Office, *Alternatives for Future U.S. Space-Launch Capabilities* (October 2006).

radar, processing data, and exploiting and disseminating intelligence derived from those data could double, and costs for postlaunch ("sustaining") engineering could triple. Other types of operations costs would increase in proportion to the growth in R&D and procurement costs, CBO estimated. (No cost growth was assumed for the launch vehicles because they are already in production and have stable costs.)

Research and Development Costs

At the low end, R&D costs would total about $11 billion for the options that use 40-square-meter radars (Alternatives 1, 2, and 4) and about $14 billion for the option that employs 100-square-meter radars (Alternative 3).

To gauge development costs for the 40-square-meter radar, CBO first estimated the cost of developing the entire Space Radar system, by applying a distribution curve to the Air Force's planned spending for the system through 2011. The distribution curve (developed by the National Aeronautics and Space Administration) spreads costs over time, which allowed CBO to isolate the costs of various phases of development and to project total costs.[3] That method is ideal for R&D activities in which costs build up slowly during the initial years and then escalate as the midpoint of the work approaches. By that method, if the R&D phase was assumed to last through 2020 (about five years after the first launch), research and development costs for a Space Radar system with 40-square-meter radars would total $11.3 billion (see Table A-1). Of that amount, $9.7 billion would go toward developing the payload and spacecraft and procuring the first two satellites[4]; the other $1.6 billion would be spent on developing ground equipment, according to CBO's analysis of information from the Air Force.

To assess the reasonableness of those figures, CBO compared them with other estimates. For example, the Air Force has estimated that R&D costs for the Space Radar system would total about $10 billion, according to the Government Accountability Office.[5] And information provided by DoD to the Congress indicates that R&D costs for two satellite programs that are still in the R&D phase but that should near production in the next few years—the Space-Based Infrared System in high earth orbit and the National Polar-Orbiting Operational Environmental Satellite System—are estimated to total about $8 billion to $9 billion. That amount is similar to CBO's $9.7 billion estimate of R&D costs for the Space Radar's payload and spacecraft.

To calculate development costs for the 100-square-meter radar, CBO increased its estimates for the 40-square-meter radar by 25 percent to account for additional technical challenges. For instance, the larger radar would require more folding to fit into the fairing of a launch vehicle.[6] Also, the requirement to maintain precise alignment over the entire surface of the radar (as described in Chapter 3) would be substantially more difficult for the larger array. In addition, the data stream from the 100-square-meter radar would be much bigger during the early stages of data processing, possibly requiring the development of a more capable onboard data processor.

3. See National Aeronautics and Space Administration, *NASA Cost Estimating Handbook, 2004*, available at www.ceh.nasa.gov/webhelpfiles/Cost_Estimating_Handbook_NASA_2004.htm.

4. Air Force satellite programs typically purchase the first two satellites of a system with R&D funds.

5. Government Accountability Office, *Defense Acquisition: Assessments of Selected Major Weapon Programs,* GAO-06-391 (March 2006), available at www.gao.gov/new.items/d06391.pdf.

6. The fairing is the shroud, or nose cone, that protects the third stage of a launch vehicle and its satellite payload during launch.

Procurement Costs

At a minimum, total procurement costs for the Space Radar system would range from $5 billion in Alternative 1 to $22 billion in Alternative 4, CBO estimated. Those estimates include manufacturing costs for the satellites themselves, the equipment they would carry, and the ground equipment that would communicate with them, as well as the costs of the launch vehicles that would put the satellites into orbit. Manufacturing costs are based on production of the remaining satellites in each constellation (production of the first two satellites is included in R&D funds), plus spares. Assuming a 10 percent chance of the catastrophic loss of a satellite, CBO included one spare satellite for the five- and nine-satellite constellations, and two spare satellites for the 21-satellite constellation.

Payload. The payload aboard each Space Radar satellite consists of the radar structural panels, T/R modules, electronics, and communications equipment. Most of the methods that CBO used to estimate procurement costs rely on the weight of those components. CBO based its weight calculations on information that the Massachusetts Institute of Technology's Lincoln Laboratory produced for NASA's Discoverer II radar system, which was comparable in size to the 40-square-meter radar analyzed in this study. CBO adjusted Lincoln Laboratory's weight estimates to reflect the technical differences between the two systems.

All of the estimates of procurement costs for payload components include costs for contractors' overhead and fees. Costs for integration and assembly and for government overhead are discussed separately later in this appendix.

Radar Panels. To estimate procurement costs for radar panels, CBO used a cost-estimating relationship (CER) developed by Tecolote Research that is based on the weight of the panels.[7] On the basis of that relationship, CBO estimated that, at the low end, panels for a 40-square-meter radar would cost about $4 million, and

7. Tecolote Research, Inc., *The Unmanned Space Vehicle Cost Model,* 8th ed. (Goleta, Calif.: Tecolote Research, June 2002).

Table A-4.

Estimated Procurement Costs per Satellite

(Millions of 2007 dollars)

	Alternatives 1, 2, and 4 ($40m^2$ radar)		Alternative 3 ($100m^2$ radar)	
	Low	High	Low	High
Payload				
Radar panels	4	5	9	11
T/R modules	260	310	650	770
Electronics	170	200	330	390
Communications	12	14	12	14
Subtotal	450	530	1,000	1,180
Spacecraft	80	100	90	110
Integration and Assembly[a]	70	80	140	160
Total	**600**	**710**	**1,230**	**1,450**

Source: Congressional Budget Office.

Notes: To produce the high estimates, CBO applied a 19 percent cost-growth factor to the low estimates. That factor was prepared by the RAND Corporation on the basis of unpublished updates to Jeanne M. Jarvaise, Jeffrey A. Drezner, and D. Norton, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports,* MR-625-OSD (Santa Monica, Calif.: RAND, 1996).

m^2 = square meter; T/R = transmit/receive.

a. No cost-growth factor was applied to integration and assembly costs. For both the low and high estimates, those costs were assumed to equal 12 percent of the total costs of the radar panels, transmit/receive modules, electronics, communications, and spacecraft.

panels for a 100-square-meter radar would cost about $9 million (see Table A-4).

Transmit/Receive Modules. An industry study in the late 1990s concluded that a T/R module costs about $10 to $20 per square millimeter. In the radar designs that CBO considered, each T/R module would be 17.5 millimeters wide and 22 millimeters high, or 385 square millimeters. Assuming an average cost of $15 per square millimeter would put the cost of those T/R modules at about $5,800 apiece. By comparison, T/R modules built for various programs over the past 10 years have cost between $4,000 and $11,000 each, CBO estimated.

All of those estimates reflect the use of a conventional design and manufacturing process in which electronic components are individually packaged and integrated onto rigid panels. However, industry experts predict that in the future, T/R modules will be directly integrated with the electronics on a flexible thin-film membrane, which could reduce their weight and cost dramatically. Thus, in this analysis, CBO assumed the T/R modules built for the Space Radar system would cost about $2,500 apiece. That estimate accounts for anticipated reductions in price from using the new manufacturing processes. But it also increases the unit price to reflect the cost risk associated with modifying a surface-based technology to meet the more stringent requirements of operating in space.

With each module measuring 385 square millimeters, a 40-square-meter radar would require about 104,000 modules, CBO determined, and a 100-square-meter radar would need about 260,000. Multiplying those numbers by the unit cost of $2,500 per module results in a total module cost of about $260 million for a 40-square-meter radar or $650 million for a 100-square-meter radar (see Table A-4).

Electronics and Communications Equipment. To estimate procurement costs for the electronics and communications equipment on board a Space Radar satellite, CBO used other weight-based CERs developed by Tecolote Research. Those relationships suggest that, at a minimum, the electronics would cost about $170 million for a 40-square-meter radar and about $330 million for a 100-square-meter radar. Communications equipment would be much cheaper to procure: about $12 million for either size radar.

Spacecraft. Production costs for a Space Radar satellite that would carry a 40-square-meter radar would average at least $80 million, according to another Tecolote CER. A satellite capable of carrying the larger radar would cost slightly more to produce: at least $90 million, on average, CBO estimated.

Integration and Assembly. Using another cost-estimating relationship from Tecolote, CBO estimated that the costs of assembling a payload and integrating it into the spacecraft would add about 12 percent to the total cost of the components. Thus, integration and assembly costs would total about $70 million for a satellite with a 40-square-meter radar and about $140 million for a satellite with a 100-square-meter radar.

Ground Equipment. Besides the various equipment on board the satellites, a Space Radar system would include command-and-control centers on the ground that would provide tasking to the satellites and equipment that would receive and process the data transmitted by the satellites. CBO estimated procurement costs for that ground equipment using information from the Air Force's analysis of alternatives for ground moving-target indication. In that analysis, the Air Force estimated that the ground equipment sufficient for a constellation of 21 satellites would have total R&D, procurement, and operations costs of about $11 billion in 2007 dollars. To allocate those costs among its three categories, CBO assumed that all of the spending before 2008 would be for R&D activities, spending between 2008 and 2015 would go for procurement, and spending after 2015 would be for operations.

On that basis, CBO estimated that procurement costs for the ground equipment associated with the 21 satellites in Alternative 4 would total about $5 billion—or $240 million per satellite—at the low end. If the costs of procuring ground equipment were proportional to the number of satellites in a constellation, those costs would total at least $1.2 billion for Alternative 1 and $2.2 billion for Alternative 2 (see Table A-1).

The 100-square-meter radars used in Alternative 3 would have greater global access than the 40-square-meter radars used in other options. The larger radar could generate about 60 percent more observations per satellite, CBO estimated, and would require a proportional increase in the amount of data-processing equipment. As a result, procurement costs for the ground equipment in Alternative 3 would total at least $3.5 billion.

Launch Vehicle. In this study's alternatives, Space Radar satellites would be launched into orbit by Atlas or Delta launch vehicles that are currently in production. Specifically, CBO assumed that DoD would use a medium launcher that had a fairing diameter of 5 meters and was equipped with four strap-on solid-fuel motors to provide a lift capability of about 13 metric tons. A previous CBO analysis suggests that those launch vehicles would cost about $200 million apiece—roughly $100 million for the hardware and $100 million for the launch services.[8]

The options that CBO examined would require between three and seven launches to place the satellites into the desired constellation. At the low end, procurement costs for those launch vehicles would range from $0.6 billion in Alternative 2 to $1.4 billion in Alternative 4.

Program Management. Systems engineering and program management would add 15 percent to the total procurement costs of the Space Radar system, CBO estimated. That percentage is consistent with the costs of other programs that use state-of-the-art satellite technologies.

Operations Costs

Once the Space Radar system had been designed, built, and launched, it would continue to generate costs throughout its assumed 20-year lifespan. Those costs would involve such activities as operating the satellites, processing the data they produced, providing continual engineering support, buying replacement radars, and launching them into orbit. Over 20 years, those operations costs would total at least $9 billion to $33 billion, CBO estimated, depending on the size of the constellation and its radars (see Table A-1).

Satellite Operations. To estimate the costs of controlling the satellites while they are in space, CBO used a cost-estimating relationship developed by NASA that calculates average annual operations costs on the basis of the type of mission and the investment cost of the space segment of the program.[9] (For investment cost, CBO included total R&D and procurement costs for the payload and spacecraft but not for the ground equipment and launch vehicles.) Applying that relationship to the 21-satellite constellation in Alternative 4 suggests that routine spacecraft operations would cost about $30 million a year per satellite—or about $12 billion over the 20-year operational life of the system. Costs for satellite operations would be proportionally lower for Alternatives 1, 2, and 3 because their constellations would be smaller.

Tasking, Processing, Exploitation, and Dissemination. The category of activities known as TPED involves collecting requests for intelligence, translating them into tasking orders for the satellites, processing the resulting radar data into intelligence products, and disseminating those products. CBO assumed that the Space Radar sys-

8. Congressional Budget Office, *Alternatives for Future U.S. Space-Launch Capabilities* (October 2006).

9. See National Aeronautics and Space Administration, "Cost Estimating Web Site: Mission Operations Cost Model" (January 21, 2005), available at www1.jsc.nasa.gov/bu2/MOCM.html.

tem would be operated like other DoD intelligence satellites. CBO based its estimate of TPED costs on an Air Force estimate that, for a constellation of 21 satellites, such costs would total about $400 million to $500 million a year. In 2007 dollars, that amount equals about $15 million a year per satellite, CBO estimated—or about $6.5 billion over 20 years for the system in Alternative 4. TPED costs would be proportionally lower for Alternatives 1 and 2 because they would operate fewer satellites.

As it did with procurement costs, CBO estimated TPED costs for Alternative 3 by adding 60 percent to its estimate for Alternative 2. That increase reflects the additional intelligence products that would have to be handled with a system of 100-square-meter radars.

Sustaining Engineering. After the Space Radar satellites were deployed, engineering work would continue during their operational life to resolve problems and incorporate new technologies. CBO assumed that DoD could accomplish those tasks by retaining a support team of about 200 engineers. Costs for that sustaining engineering would total about $40 million a year, CBO estimated, or about 5 percent of average annual spending during the R&D phase.

Replacement Space Radars and Launch Vehicles. In all of the alternatives, satellites were assumed to last for about 10 years. Thus, over the 20-year operational life of the Space Radar system, the satellites would need to be replaced once to maintain the system's effectiveness.

CBO estimated costs for the replacement Space Radar satellites in the same way that it calculated procurement costs for the initial constellation in each alternative. Those replacement radar satellites would cost at least $3.0 billion to $12.6 billion, depending on the alternative. DoD would also need to buy additional launch vehicles to put the new satellites into orbit, at a minimum cost of $0.6 billion to $1.4 billion, CBO estimated.

APPENDIX

B

SAR and GMTI Analysis Methodologies

In the performance analysis described in Chapter 4, the Congressional Budget Office (CBO) compared how well four illustrative Spare Radar architectures would provide synthetic aperture radar (SAR) imagery or ground moving-target indication (GMTI) under various conditions. The comparison focused on the performance metrics of access, response time, coverage, and (in the case of GMTI) mean track life. This appendix describes the methods that CBO used to calculate that performance.

SAR Analysis Methodology

To compute SAR access and response times for the alternative constellations, CBO employed a software application called STK (published by Analytical Graphics Inc.). STK can be used to calculate and visualize satellite orbits and compute access and response times directly. To estimate area coverage, CBO used STK to compute azimuth angle, elevation angle, and range from the satellites to various regional targets; the computed values for those measures then served as inputs in performing radar calculations, as described in the next section.

CBO derived the relationship between area coverage rate and image resolution by manipulating well-known SAR equations. Because members of the military and the intelligence community generally require high-resolution imagery (higher than is typically achievable in strip-map mode), CBO assumed that spotlight mode would always be used to generate SAR images. In that mode, along-track (or azimuth) resolution can be expressed as a function of dwell time; finer resolution can be achieved by dwelling on a target longer. Range resolution, by contrast, is a function of signal bandwidth.

CBO's notional satellite design includes a higher bandwidth (1 gigahertz) than that of past or present spacecraft, but that bandwidth may not be adequate for very fine resolution. Thus, advanced signal-processing techniques must be used. CBO assumed that "stretch" processing—which increases the effective bandwidth by expanding the time scale of the radar's waveform—would be employed for Space Radar data.[1] Stretch processing uses a hardware oscillator to convert the incoming signal to a lower frequency so that it can be digitized. That technique can improve range resolution beyond what is normally achievable with a given signal bandwidth, but at the expense of range-swath width.[2] The width of the radar footprint in the along-track direction, however, is simply a function of range, aperture size, and wavelength. CBO assumed that along-track resolution equals azimuth resolution (which is generally desirable, though not essential) so that those relationships could be combined to yield an expression for area coverage rate as a function of desired resolution.

Two more limits must be imposed on the relationship between imagery and resolution. The first constraint is that the radar signal must be strong enough at the receiver to form an image. CBO chose clutter-to-noise ratio (CNR) as the metric for SAR image quality. CNR is similar to signal-to-noise ratio, the metric used in other

1. Stretch processing is also known as dechirping or deramping.

2. E.C. Farnett and G.H. Stevens, "Pulse Compression Radar," in M. Skolnik, ed., *Radar Handbook* (New York: McGraw-Hill, 1990). More-complex techniques that use composite waveforms (in which each pulse encompasses a different frequency range) have also been proposed. Those techniques do not suffer from the same limits on range-swath width as stretch processing does, but they are much more difficult to implement. See, for example, Byron Keel, "Space Based Radar Waveform Trades" (briefing presented at a Georgia Institute of Technology short course, Las Vegas, August 1-4, 2005).

radar applications.[3] (In SAR imaging, the clutter is the signal.) CNR is affected by the grazing angle of the signal, the reflectivity of the terrain, and the desired resolution and may vary within a location being imaged.

Clutter-to-noise ratio can be expressed by:

$$CNR = \frac{PG^2\lambda^2\sigma_0}{(4\pi)^3R^4LkT_0\beta F} \bullet T\beta \bullet N$$

where:

P is peak transmit power,
G is antenna gain,
λ is wavelength,
σ_0 is the radar cross section of the illuminated clutter patch,
R is range,
L is additive losses,
k is the Boltzmann constant,
T_0 is noise temperature,
β is bandwidth of the radar pulse,
F is noise figure,
T is uncompressed pulse width, and
N is the number of pulses integrated.

Antenna gain is expressed by:

$$G = \frac{4\pi A}{\lambda^2}\cos^{1.5}\alpha$$

where:

A is aperture area, and
α is squint angle.[4]

In the constant-gamma clutter model (described below), the radar cross section of the clutter patch is given by:

$$\sigma_0 = \delta_{at}\delta_r\gamma\sin\Psi$$

where:

δ_{at} is along-track resolution,
δ_r is range resolution,
γ is normalized clutter reflectivity, and
ψ is grazing angle.

The pulse width is:

$$T = DutyCycle \bullet \frac{1}{PRF}$$

where PRF is pulse repetition frequency.

The number of pulses integrated is:

$$N = PRF \bullet T_{dwell}$$

Along-track resolution is a function of dwell time, so dwell time can be expressed as a function of along-track resolution:

$$T_{dwell} = \frac{\lambda R}{2V\delta_{at}\cos\alpha}$$

where V is the satellite velocity.

If along-track resolution is set to equal range resolution and those relationships are combined, the clutter-to-noise ratio can be expressed as:

$$CNR = \frac{PA^2\cos^2\alpha\delta_r\gamma\sin\Psi \bullet DutyCycle}{8\pi\lambda R^3LkT_0FV}$$

With that equation rearranged, range resolution can be expressed as a function of the desired CNR:

$$\delta_r = \frac{8\pi \bullet CNR \bullet \lambda R^3LkT_0FV}{PA^2\cos^2\alpha\gamma\sin\psi \bullet DutyCycle}$$

At shallower grazing angles, clutter reflectivity decreases and range increases, leading to decreased CNR. Also, as image resolution in the range direction becomes finer, CNR becomes smaller. Thus, if a minimum CNR is to be

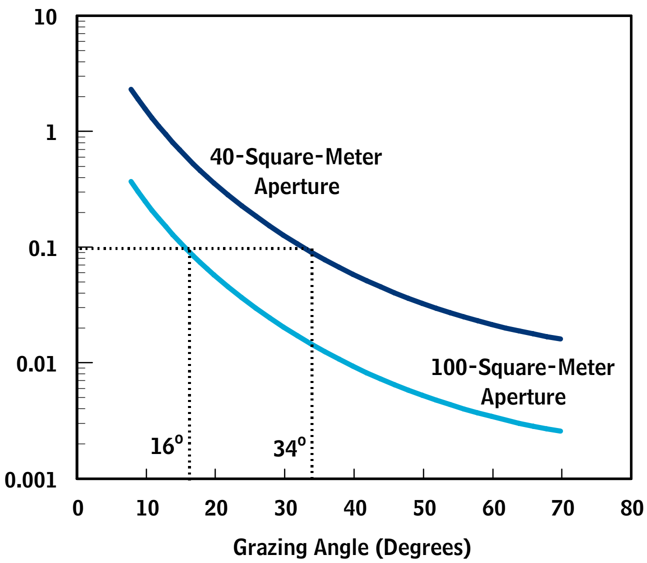
3. An alternative measure of SAR image quality is noise-equivalent sigma zero (NESZ), which is the signal that produces a received power equal to the receiver's thermal noise power. An NESZ of -25 decibels is sometimes specified as a maximum (smaller values are better). That criterion is generally more difficult to satisfy than the criterion of a 6-decibel clutter-to-noise ratio that CBO used.

4. For electronic steering of the beam to some squint angle α relative to the perpendicular to the antenna, CBO used a scan loss function of the cosine of the squint angle to the 1.5 power. See Larry Corey, "Space Antenna & T/R Module Technology," in Samuel Piper, ed., "Space-Based Radar" (briefings presented at a Georgia Institute of Technology short course, Las Vegas, August 1–4, 2005).

Figure B-1.

Minimum Range Resolution as a Function of Grazing Angle

(Meters)



Source: Congressional Budget Office.

Note: This figure assumes a normalized clutter reflectivity of 0.08 (-11 decibels) and a minimum clutter-to-noise ratio of 6 decibels.

maintained, there is a limit to the grazing angle that may be used, and that limit is a function of image resolution.

Although images can be formed with very low CNRs, their contrast will be poor and their usefulness low. For analytic purposes, it is necessary to cut off the CNR, and thus the grazing angle, at some point. For this study, CBO assumed that a clutter-to-noise ratio of at least 6 decibels (dB) was required to form a clear and useful image.[5]

To calculate terrain reflectivity, CBO used the simple constant-gamma clutter model, in which the terrain backscattering coefficient is expressed as the product of a constant normalized clutter reflectivity (γ) and the sine of the grazing angle. CBO used a γ value of 0.08 (-11 dB)—which approximates verdant, hilly terrain—in all of the analyses.[6] Gamma values can vary from -5 dB for mountains to -20 dB for flat terrain; with different assumptions about terrain, the results presented in this report would vary accordingly.

The combination of CBO's assumptions about terrain reflectivity, required CNR, radar transmit power, receiver noise, and antenna efficiency leads to the following grazing-angle limits at 0.1-meter resolution (see Figure B-1):

- 34 degrees for the 40-square-meter aperture radar, and
- 16 degrees for the 100-square-meter aperture radar.

The second constraint on SAR performance that must be considered is the limit that the pulse repetition frequency imposes on the grazing angle. The PRF must be low enough that radar echoes from consecutive pulses do not overlap (so that there is no range ambiguity among the pulses). That maximum PRF constraint decreases with the grazing angle (that is, with increasing range), since the range swath widens. At the same time, the PRF must be high enough that the required Doppler frequencies can be measured unambiguously (the azimuth effect). At small grazing angles, those limits will overlap. That PRF limit imposes the following grazing-angle constraints on CBO's notional radar designs:

- 15 degrees for the 40-square-meter aperture radar, and
- 8 degrees for the 100-square-meter aperture radar.

GMTI Analysis Methodology

CBO began the GMTI performance analysis by using the STK software to compute azimuth, elevation, and range from the satellites to the particular locations of interest. For each location, CBO then used Microsoft Excel and MathWorks MATLAB to point the satellite, determine whether the target of interest was in the radar's field of regard, and perform the radar calculations. Those calculations involved the following steps:

- Estimating the performance of the space-time adaptive processing (STAP) filter for the radar's coherent processing interval (CPI), expressed by the signal-to-interference-plus-noise ratio (SINR) function;

5. See, for example, Roger Sullivan, *Radar Foundations for Imaging and Advanced Concepts* (Raleigh, N.C.: SciTech, 2004), p. 211.

6. Fawwaz T. Ulaby and M. Craig Dobson, *Handbook of Radar Scattering Statistics for Terrain* (Boston: Artech House, 1989).

- Estimating the number of CPIs that need to be noncoherently integrated to achieve the desired probability of detection and probability of false alarm, which yields the required dwell time; and

- Calculating the area that can be covered during each access period, given the radar beam's footprint, the required dwell time, and the specified revisit interval.

SINR is a generalization of the traditional radar signal-to-noise ratio that includes interference (that is, jamming) in the denominator.[7] The SINR function is used for GMTI radars and expresses the signal-to-noise ratio as a function of target velocity. The faster the target is moving (in the direction of the radar), the higher the signal-to-noise ratio (or the SINR) will be, and the easier the target will be to detect. The SINR loss function is the SINR function minus the target's radar return and the system noise; thus, it is zero decibels (that is, unity) for high target velocities. The SINR loss function is a means for comparing the performance of different GMTI radars after removing the effects of radar power, the target's radar cross section, and system noise.[8]

The CPI, or "coherent dwell," is the period of time during which returned pulses may be integrated before trying to detect a target using the total integrated magnitude of the signal. After a fairly short period, combining pulses coherently is no longer possible (because the phase of the returning pulses cannot be preserved). Detection must then be based on each CPI individually, and the results must be combined "noncoherently." CBO has assumed that the CPI for Space Radar would be 50 milliseconds.

Estimating STAP filter performance is perhaps the most difficult and controversial aspect of CBO's analysis. The theoretical STAP mathematics are challenging; the effects of relaxing the usual assumptions about clutter homogeneity and stationarity (see Chapter 3) are difficult to address; and few test data are available. The Georgia Tech Research Institute has published SINR loss functions for a Discoverer II configuration and altitude, including clutter motion, but not other potential limiting factors.[9] The effects of reduced-rank STAP have also been well documented.[10] Traditional pulse-Doppler filtering techniques, such as those used on JSTARS, can readily be analyzed.[11] Those "exoclutter" techniques are likely to perform much worse than the "endoclutter" techniques to be employed on Space Radar. CBO believes that operational STAP performance, as affected by real-world variations in clutter, will fall between the two extremes of theoretical STAP performance and traditional pulse-Doppler performance (see Figure B-2).

The performance of the pulse-Doppler filter varies with the geometry of the radar and target in much the same way that the performance of the STAP filter does, but it is far easier to compute. Thus, CBO used the pulse-Doppler filter relationships as a starting point to approximate STAP performance. That approximation involved scaling the target velocity of the Doppler filter's SINR function by an appropriate factor at each point along the computed curve of pulse-Doppler SINR loss versus target velocity (the dotted line in Figure B-2). CBO analyzed constellation performance using two alternative SINR approximations: an "aggressive" assumption, which simulates published STAP results that include clutter motion and a penalty for reduced-rank processing, and a "conservative" assumption, which halves all of the velocities from the pulse-Doppler relationships.

In any detection problem, a trade-off exists between the likelihood of detecting a target (the probability of detection, or P_D) and the number of false targets presented (expressed by the probability of false alarm, or $P_{F/A}$). The P_D can be increased by lowering the detection threshold, thus raising the $P_{F/A}$. Alternatively, the $P_{F/A}$ can be decreased by increasing the threshold, thereby lowering the P_D. For the GMTI analysis, CBO chose a fixed P_D of 0.95, with a $P_{F/A}$ of one one-millionth per range-Doppler bin. On a typical scan, about 0.25 false alarms

7. CBO did not explicitly account for jamming in this analysis.

8. In all of the GMTI computations, CBO assumed that the target had a radar cross section of 10 square meters (or 10 decibels relative to a 1-square-meter perfectly reflective reference target).

9. Bill Melvin, "Adaptive Detection Techniques for Space-Based Radar," in Samuel Piper, ed., "Space-Based Radar" (briefings presented at a Georgia Institute of Technology short course, Las Vegas, August 1-4, 2005).

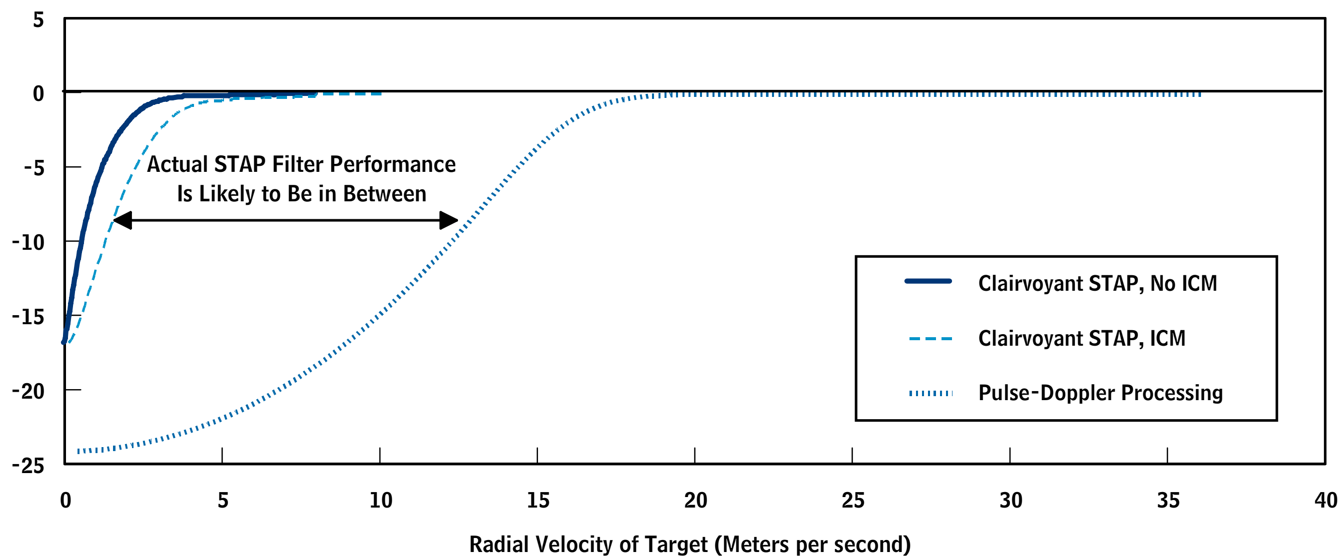
10. J. Ward, *Space-Time Adaptive Processing for Airborne Radar* (report prepared by M.I.T. Lincoln Laboratories for the Defense Advanced Research Projects Agency, December 1994).

11. Sullivan, *Radar Foundations for Imaging and Advanced Concepts.*

Figure B-2.

Estimated SINR Loss Functions for a Discoverer II Satellite

(Decibels)



Source: Congressional Budget Office based on data from Georgia Tech Research Institute.

Notes: Clairvoyant STAP means that the STAP algorithm is assumed to be able to characterize the background perfectly.

SINR = signal-to-interference-plus-noise ratio; STAP = space-time adaptive processing; ICM = intrinsic clutter motion.

would be expected with the 40-square-meter radar and slightly fewer with the 100-square-meter radar.[12]

Various techniques can be used to combine radar returns from several CPIs to improve the probability of detecting a target. CBO assumed that noncoherent integration would be used to combine up to 10 CPIs. According to one radar textbook, "Noncoherent integration is easier to implement than coherent integration, especially for searching when the target velocity is not known, because it avoids the limitations associated with coherent integration (e.g., precise knowledge of target radial velocity, phase stability), and because it may provide better performance against fluctuating targets."[13] CBO used published relationships that relate the CPI signal-to-noise ratio to the number of CPIs required to achieve specified probabilities of detection and false alarm.[14] The time required to obtain the desired P_D and $P_{F/A}$ was then combined with the footprint area of the radar beam and the specified revisit rate to calculate the area covered in the access period. If 10 CPIs were not sufficient to obtain the desired P_D and $P_{F/A}$ at a particular geometry, then CBO concluded that access was not available.

CBO compared the results obtained using the aggressive signal-processing assumption with results that the Massachusetts Institute of Technology's Lincoln Laboratory published for the Discoverer II program. On the basis of that comparison, CBO "tuned" the scaling factor used for the SINR function to approximately match the published results for instantaneous area-coverage rates.

To analyze how well a Space Radar constellation could track ground targets, CBO used a statistical tracking model developed by Booz Allen Hamilton (BAH).[15] The model estimates the average time that a single target in a

12. Relaxing the $P_{F/A}$ by a factor of 10 would decrease the required SINR by only about 1 decibel and thus would have little impact on this analysis.

13. G. Richard Curry, *Radar System Performance Modeling* (Boston: Artech House, 2005), p. 95.

14. See David K. Barton, *Radar System Analysis and Modeling* (Boston: Artech House, 2005).

15. Edward F. Splitt, "Probability of Sequential Association of Discrete Target Data Accounting for Sensor Gaps and P_d" (draft, Booz Allen Hamilton, June 23, 2005).

field of randomly distributed identical targets can be tracked. Both the target and the confusing targets around it are assumed to move at random, with varying velocity. The model relies on a previous finding that describes the probability of correctly picking the true target from the field of confusing targets after a small time increment.[16] The BAH model uses that finding in an iterative fashion that accounts for access and gap times, as well as revisit time within each access period, to obtain a mean track life. CBO used the BAH model in a Monte Carlo simulation to estimate the range of track lives given previously simulated distributions for access and gap time and reasonable assumptions about target location accuracy, velocity variation, and density of confusing targets.

16. Shozo Mori, Kuo-Chu Chang, and Chee-Yee Chong, "Performance Analysis of Optimal Data Association with Applications to Multiple Target Tracking," in Yaakov Bar-Shalom, ed., *Multitarget-Multisensor Tracking: Applications and Advances,* vol. 2 (Boston: Artech House, 1992).

Glossary

A

Access: A radar performance metric, defined as the percentage of time that a given geographic location, treated in isolation, can be observed by at least one satellite of a constellation (the sum of all of the access periods divided by the total time elapsed).

access period: A period of time in which at least one satellite of a constellation is able to view a particular area.

ADC: analog-to-digital converter. An electronic device that converts analog (continuous) signals into digital (discrete) values.

AESA: active electronically steered array. An antenna consisting of a matrix of numerous transmit/receive modules, in which timing differences between the signals at each module are used to form and steer the radar beam.

along-track direction: In a coordinate system based on a satellite's ground track, the along-track direction is parallel to the ground track. Also referred to as the azimuth direction. (See the diagram on the inside front cover.)

aperture: The area of a radar's antenna, which determines the amount of reflected energy the antenna intercepts.

azimuth angle: In a coordinate system based on a satellite's ground track, azimuth angle is the angle relative to the ground track in the plane of the Earth's surface. (See the diagram on the inside front cover.)

azimuth direction: Same as along-track direction.

B

Bandwidth: In general, the range of frequencies spanned by a band of electromagnetic radiation. In this report, bandwidth typically refers to the range over which the frequency varies in a linear frequency modulated pulse (see Figure 3-2 on page 15).

C

Carrier frequency: The frequency of an unmodulated radar wave. In a linear frequency modulated pulse, the waves of the carrier frequency are combined with waves that change frequency over the duration of the pulse (see Figure 3-2 on page 15).

C band: A set of radar carrier frequencies between 4 GHz and 8 GHz, as standardized by the Institute of Electrical and Electronics Engineers.

clutter: In general, unwanted radar returns from sources other than the target, such as the ground or precipitation. In SAR imaging, however, the goal is to create an image of the ground, so the "clutter" is actually the target.

CNR: clutter-to-noise ratio. The ratio of the returning energy from clutter to the energy from noise (usually thermal) within a radar system. (See Appendix B for more details.)

communications bandwidth: The capacity for data transfer within an electronic communications system, usually expressed in bits per second.

constant-gamma clutter model: A model to describe the strength of radar reflections from terrain, in which the terrain backscattering coefficient is expressed as the product of a constant normalized clutter reflectivity (γ) and the sine of the grazing angle. (See Appendix B for more details.)

constellation: An arrangement of the orbits and relative positions of multiple satellites to optimize coverage of the Earth's surface. This report uses the Walker notation system to describe constellations (see Box 3-1 on page 20).

coverage: A radar performance metric. For the SAR mission, coverage is defined as the area that can be imaged by a constellation per unit of time (such as a day). For GMTI, coverage is defined as the average area that can be observed continually by a constellation during an access period; it varies with the revisit interval.

CPI: coherent processing interval. The time during which a radar signal can be received and processed coherently (that is, with stable phase relationships between reference and received signals).

cross-track direction: In a coordinate system based on a satellite's ground track, the direction along the Earth's surface perpendicular to the ground track. (See the diagram on the inside front cover.)

dB: decibel. A unit for describing the ratio of two power levels, defined as 10 times the logarithm (base 10) of the ratio of the power levels.

DMZ: The Korean demilitarized zone. An area stretching two kilometers on either side of the Military Demarcation Line between North and South Korea.

Doppler shift: A change in the frequency of a wave originating or reflected from a moving target; that change is proportional to the radial velocity of the target (that is, the component of its total velocity that lies along the line connecting the target and the observer).

dwell time: The length of time in which signals must be collected from a given target to achieve the desired resolution (in the case of SAR) or the desired probability of detection (in the case of GMTI) for a given observation geometry.

Elevation angle: The angle between the "satellite plane" (the plane that contains the satellite's velocity and that is perpendicular to the line connecting the satellite to the Earth's center) and the line between the satellite and the target. (See the diagram on the inside front cover.)

Field of regard: The area of the Earth, as specified by angular ranges, that a radar has access to within its normal range of motion. In this study, the field of regard for SAR is ±45 degrees in azimuth, on both sides of the satellite, with the grazing angle limited to 15 to 70 degrees. For GMTI, the field of regard is more complicated and must take into account the rate at which the satellite can yaw.

footprint: The area of the Earth's surface illuminated by the radar.

Fourier transform: A mathematical method to decompose a signal into its component frequencies and their amplitudes.

Gbps: gigabits per second (1 billion bits per second).

geosynchronous: An orbit with an altitude of about 36,000 kilometers and an orbital period of 24 hours. When it is directly above the equator, this orbit is referred to as geostationary, since the satellite appears fixed over a spot on the Earth.

GHz: gigahertz (1 billion cycles per second).

GMTI: ground moving-target indication. An operating mode in which the Space Radar system would detect targets moving on land.

grazing angle: The angle between the surface of the Earth and a line joining the satellite to the target. (See the diagram on the inside front cover.)

ground track: The satellite's orbital trajectory as projected onto the Earth's surface. (See the diagram on the inside front cover.)

H

Heterogeneous clutter: A nonideal case in which the statistical properties of clutter vary in range or angle.

high-resolution terrain information: An operating mode of Space Radar that would allow for precise measurement of the height of surface terrain using interferometry between observations at slightly different angles.

I

Inclination: The angle between the plane of a satellite's orbit and the equator (an inclination of zero is equatorial, and an inclination of 90 degrees is polar).

interferometric SAR: A method that uses the phase differences between synthetic aperture radar data collected at slightly different positions to reconstruct the height of targets or terrain.

IPO: Integrated Program Office.

J

JSTARS: Joint Surveillance Target Attack Radar System. An Air Force system consisting of a modified Boeing 707 aircraft with a side-looking phased-array radar to detect moving targets.

K

Ku band: A set of radar carrier frequencies between 12 GHz and 18 GHz, as standardized by the Institute of Electrical and Electronics Engineers.

L

L band: A set of radar carrier frequencies between 1 GHz and 2 GHz, as standardized by the Institute of Electrical and Electronics Engineers.

LEO: low earth orbit. An orbit located between the top of the atmosphere and the inner Van Allen radiation belt (typically at an altitude between 500 kilometers and 1,000 kilometers).

linear frequency modulation: Also known as chirp or pulse compression. A method to improve the range resolution of a pulsed radar by using pulses that consist of a carrier frequency combined with a signal whose frequency increases linearly over the duration of the pulse (see Figure 3-2 on page 15).

M

Mbps: megabits per second (1 million bits per second).

mean track life: The average length of time that an individual ground target might be tracked by the Space Radar system.

MEO: medium earth orbit. An orbit located between the inner and outer Van Allen radiation belts (typically at an altitude between 5,000 kilometers and 15,000 kilometers).

MHz: megahertz (1 million cycles per second).

modulate: To vary some characteristic (frequency, amplitude, or polarization) of a wave in order to transmit information.

Monte Carlo: A computer simulation technique that uses random sampling from distributions of parameters.

N

Nadir hole: An area on the Earth's surface directly beneath a satellite; neither SAR nor GMTI is possible in that area.

NASA: National Aeronautics and Space Administration.

NESZ: noise-equivalent sigma zero. A measure of SAR image quality that is defined as the signal that produces a received power equal to the receiver's thermal noise power.

noise: Incoherent energy that obscures or interferes with a desired signal. Noise is usually generated by random or repetitive events such as thermal radiation or electronic fluctuations.

P

Phase: For oscillatory systems, the fraction of a full cycle that is completed at a given point in time, relative to some fixed reference.

phased array: An antenna that forms and steers a beam by applying phase differences between different elements of the antenna.

polarization: The alignment of the direction of the electric field of an electromagnetic wave relative to its direction of travel.

power-aperture: A radar's power multiplied by its aperture.

PRF: pulse repetition frequency. The number of radar pulses transmitted per second.

pulse compression: See linear frequency modulation.

pulse Doppler: A radar system that emits pulses and uses the echoes of those pulses to determine the distance to a target (based on the time interval until the echoes are received) and the target's motion (based on the phase shift of the returned pulses). This term can also refer to the radar waveform used by such a system.

R

Radar cross section: A description of how much of the energy of an incoming radar wave is reflected by an object. It is expressed in terms of the cross-sectional area (projected onto a plane perpendicular to the incoming wave) of a hypothetical, uniformly scattering sphere that would give rise to the same level of reflection as that observed from the object in question.

radar duty cycle: The fraction of its operating time that a radar is transmitting pulses rather than receiving them.

range: The distance from a radar to a target.

range swath: The extent of the radar's footprint, in the range direction, over which the radar is capable of detecting targets or forming an image.

reduced-rank STAP: Also referred to as partially adaptive STAP. A method of space-time adaptive processing in which the radar array is divided into a relatively small number of subapertures by grouping together signals from individual transmit/receive modules.

reflectivity: The ratio of the energy reflected by a surface to the energy striking the surface.

resolution: The minimum distance between two point targets such that they can be distinguished from each other in an image.

response time: A radar performance metric. The time interval between receiving a tasking order to observe a given location and actually observing that location. If the target is already within view of a satellite when the tasking is received, the response time is zero; if not, the response time is the time to the next access period.

revisit interval: The time interval between observations of a moving target. That interval will vary depending on the size and composition of the target and the time required for the target to change directions. (For a list of representative revisit intervals, see Table 4-1 on page 37.)

roll: For a satellite in orbit, rotation around the direction of the satellite's motion.

S

SAR: synthetic aperture radar. A terrain-imaging radar that uses movement of the radar platform to form a "synthetic" aperture that is much larger than the radar's physical aperture, thus improving along-track resolution. SAR systems rely on the time delay between transmission and receipt of a radar pulse to determine the range to a terrain cell; they use the frequency shift of the returning pulses to determine the azimuthal angle of terrain cells at the same range.

scan SAR: A mode of SAR operation in which the radar beam is slewed to image adjacent strips of terrain (see Figure 1-1 on page 3).

SINR: signal-to-interference-plus-noise ratio. In space-time adaptive processing, the ratio of the target signal to the sum of noise and interference (ground clutter and jamming).

SINR loss function: In space-time adaptive processing, the ratio of the ideal SINR to the observed SINR.

SNR: signal-to-noise ratio. The ratio of the power of the returning signal from a specified target to the noise power in the absence of that signal.

spotlight: A mode of SAR operation in which the radar is continuously steered to keep the beam on one spot (see Figure 1-1 on page 3). This mode increases the dwell time and thus the size of the synthetic aperture, improving along-track resolution.

squint angle: For an electronically steered beam, the angle between the center of the beam and an axis perpendicular to the face of the antenna.

STAP: space-time adaptive processing. A method of processing GMTI radar returns in which the statistical properties of the return from the surface terrain are estimated and mathematically removed from the incoming signal, leaving behind the returns from the target. In fully adaptive STAP, each transmit/receive module of the radar array is treated as an individual aperture, yielding tens of thousands of data sources and an intractable computational problem. In partially adaptive (or reduced-rank) STAP, the radar array is divided into a relatively small number of subapertures by grouping together signals from individual T/R modules. That process makes computation feasible but degrades the radar's performance to some extent.

stationarity: A condition in which clutter is not moving or changing in time.

strip map: A mode of SAR operation in which the radar beam is pointed in a fixed direction perpendicular to the direction of the satellite's velocity (see Figure 1-1 on page 3). The beam sweeps a long strip of terrain, and the processor creates a corresponding long image, or strip map.

subarray: Also called subapertures. A section of the full radar array.

TDRSS: Tracking and Data Relay Satellite System, a satellite communications system operated by NASA.

TEL: transporter erector launcher. A mobile missile launcher consisting of a vehicle carrying one or more missiles that is able to elevate the missiles to firing position and launch them without removing them from the vehicle.

terrain cell: A small area of terrain processed as a single target by a SAR processor, with dimensions equal to the along-track and cross-track resolution.

T/R module: transmit/receive module. The fundamental element of an AESA, each T/R module contains an antenna and associated electronics to allow both transmission and receipt of radar signals.

TSAT: Transformational Satellite Communications System, a satellite communications system being developed by the Air Force.

Walker notation: A notation system for describing symmetrical constellations of satellites in circular orbits (see Box 3-1 on page 20 for more details).

X band: A set of radar carrier frequencies between 8 GHz and 12 GHz, as standardized by the Institute of Electrical and Electronics Engineers.

Yaw: For a satellite in orbit, rotation around a line between the satellite and the center of the Earth. (See the diagram on the inside front cover.)