Chapter 4

ASAT Capabilities and Countermeasures

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ASAT Capabilities and Countermeasures

ORGANIZATION OF THIS CHAPTER

A variety of technological options are available for space surveillance systems, stand-off weapons, and weapon and sensor platforms for anti-satellite uses. Current and projected U.S. and Soviet ASAT capabilities, including space surveillance capabilities, are described in the first section of this chapter. More advanced ASAT capabilities which could be deployed by the United States or the U. S. S. R-. are described in the second section of this chapter. Some possible U.S. responses to Soviet development of such capabilities are described in the third section of this chapter. The principal conclusions about ASAT capabilities and countermeasures are summarized in the final section of this chapter. The actual military utility of these capabilities will be discussed in appendix D to this report, which is classified;

CURRENT AND PROJECTED ASAT CAPABILITIES

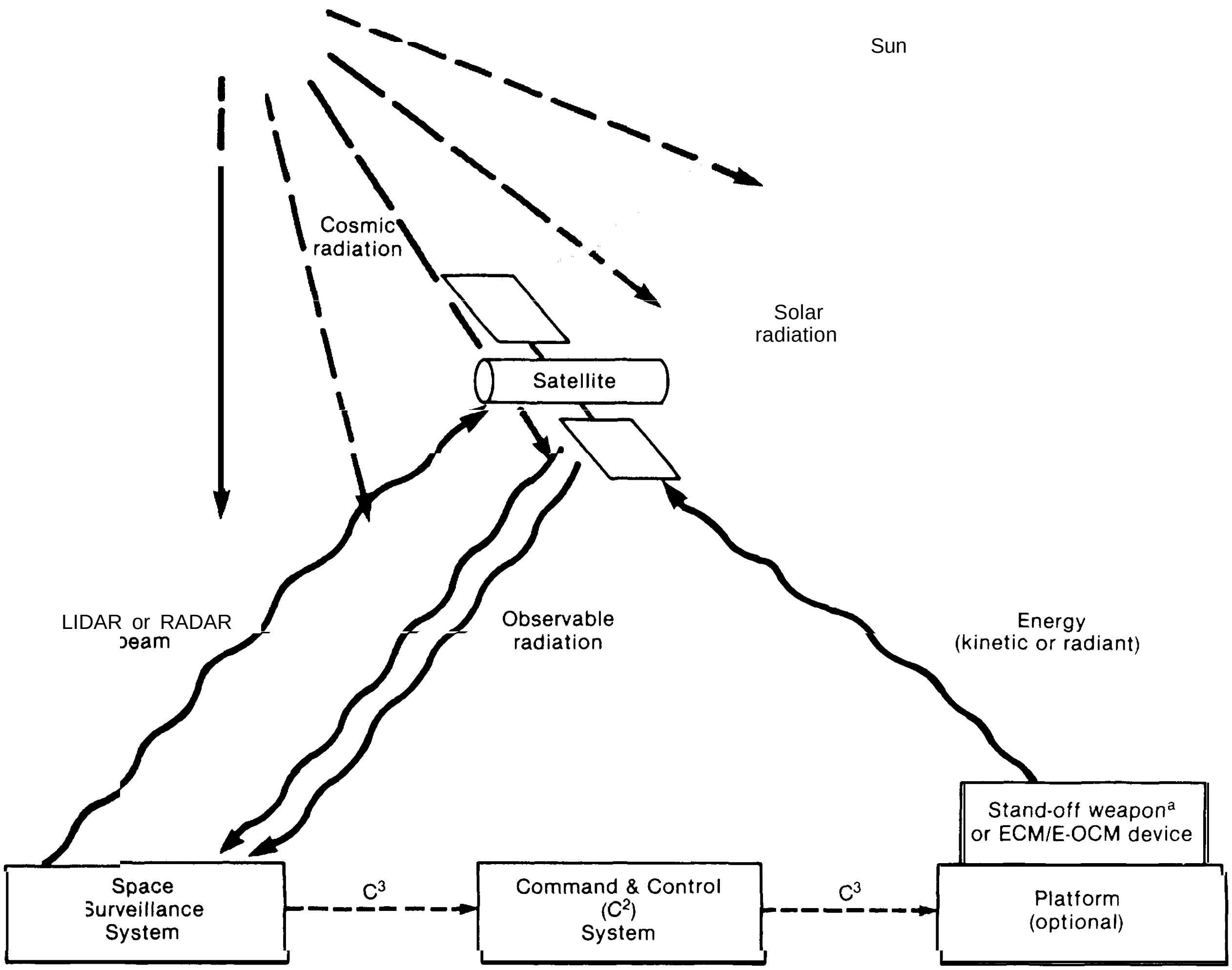
Generic ASAT System Components

A space defense system could include both passive countermeasures for protecting satellites and an ASAT system for interfering with enemy satellites in time of war. An ASAT system, whether deliberate or expedient, must be controlled by an associated command, control, communications, and intelligence (C^3I) system, which itself will have three types of subsystems, as illustrated abstractly in figure 4-1. First is the intelligence collection part-the space surveillance system—which would detect electromagnetic radiation emitted or reflected by a satellite and, using these measurements, attempt to track the satellite and determine its orbit. Careful interpretation of this information may allow characterization of the satellite-i. e., determination of its mass, shape, and other features—and even determination of the function of the satellite. On the basis of this interpretation, information would be communicated over command, control, and communications (C^3) links to command and control (C*) centers, where authorities would consider the information in the context of other relevant information and possibly issue orders to *negate* the satellite or to interfere with its functioning nondestructively (e.g., using electronic countermeasures). If so, other C* elements would generate detailed instructions for an attack, and these would be communicated by C^3 links to an ASAT weapon system.

An A SAT system would have either nondestructive ASAT devices such as jammers or other electronic or electro-optical countermeasures, or A SAT weapons capable of damaging satellites (in which case it would be an A SAT *weapon* system), or both. In general, each weapon would consist of a *stand-off* weapon capable of damaging a satellite at a distance and either carried by a *platform* such as a satellite, rocket, airplane, or land vehicle, or else based on the ground at a fixed site. The stand-off weapon could be a kinetic-energy weapon (KE W) such as a gun or a fragmentation warhead, a directed-energy weapon (DEW) such as a laser or particle accelerator, or an ordinary "isotropic" nuclear warhead (so called because it would release roughly equal amounts of energy in all directions).

The weapon platform (if any) would carry the stand-off weapon to within lethal range of a targeted satellite. A highly maneuverable platform could pursue and collide with a targeted satellite; such a vehicle would be a "hit-to-kill" kinetic-energy weapon which would

Figure 4-1.—Generic Components of an ASAT System



[a]Directed-energy weapon, kinetic-energy weapon, or isotropic nuclear weapon.

not need to carry a stand-off weapon. Alternatively, if the stand-off weapon had sufficient lethal range, it would not need to be maneuvered toward a targeted satellite but could instead be based on the ground or on a nonmaneuvering platform.

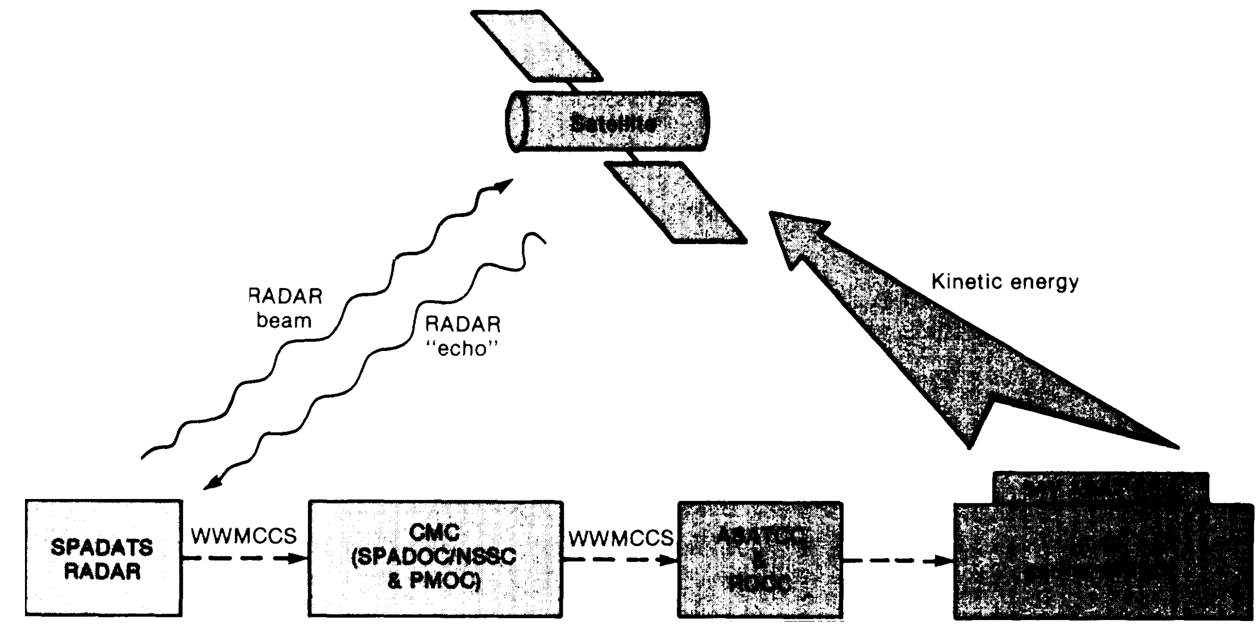
Figure 4-2 illustrates a portion of the U.S. Space Defense System as it will appear when the planned anti-satellite weapon system is added, showing examples of its space surveillance, command and control, and ASAT weapon systems.

Soviet ASAT Capabilities

Space Surveillance

The ASAT capabilities of the Soviet Union depend on Soviet space surveillance systems.

Figure 4-2.—Illustrative Components of the U.S. Space Defense System



Key:

ASATCC: ASAT Control Center (ASAT carrier aircraft base: prelaunch C^2)
CMC: Cheyenne Mountain Complex
MV: Miniature Vehicle (satellite interceptor warhead)
NSSC: National Space Surveillance Center
PMOC: Prototype Mission Operations Center
ROCC: Regional Operations [military air traffic] Control Center (post-launch C^2)
SPADATS: SPAce Detection and Tracking System
SPADOC: SPAce Defense Operations Center
WWMCCS: World-Wide Military Command and Control System

The Soviet Union operates extensive military and civil networks of radar, LIDAR[1], and pho tographic space surveillance sensors linked together by satellite and terrestrial communications systems.[2] Soviet missile early warning radars and satellites can detect foreign satellite launches. Soviet radio/radar tracking ground stations can presumably detect and track satellites in low-Earth orbit and track satellites in higher orbits. In addition, the radars used by the Soviet ABM system and radio telescopes can be used to detect, track, and characterize satellites. The U.S.S.R. also uses ships for satellite tracking and communications and operates some tracking stations in foreign territory.

Soviet deep-space detection capabilities necessarily rely upon passive sensors, primarily telescopic cameras similar to the Baker-Nunn cameras formerly used by the United States and upon radio telescopes and ground-based military signal intelligence collection[3] systems. Passive optical sensors, whether photographic

[1] LI DAR is an acronym for L Ight Detection And Ranging; it refers to a radar-like sensor system which transmits pulses of light, typically produced by a laser, and looks for reflections from objects. Ranges to objects can be inferred from the time delay of pulses reflected from it.

[2] *Soviet Space Programs: 1976-80,* Part 1, Committee Print, Committee on Commerce, Science, and Transportation, Senate, 97th Cong., 2d sess., December 1982. [USGPO 98-515 O]

[3] Such systems, which perform direction-finding or signal intercept functions, are called electronic support measure (ESM) systems.

or electro-optical, can detect sunlight reflected by a high-orbit satellite; the power of the reflected sunlight received by a distant optical sensor decreases only as the square of the range to the target, so passive optical 'sensors are more useful than radar for detecting high-orbit satellites.[4] Similar considerations make passive radio systems—i.e., radio telescopes or military electronic support measure systems—useful for detection and tracking at long range, provided the target is emitting a radio signal of some kind.

It is possible that the U.S.S.R. may develop electro-optical tracking sensors in the future; such sensors could provide surveillance information more quickly than can camera systems, which require development of photographic film or plates. Neither photographic nor electro-optical telescopes can detect or track satellites from the ground in daytime or through overcast, as radar can.

Weapons

The Soviet Union has been conducting a series of tests of coorbital satellite interceptors ("killer satellites") since 1968.[5] An artist's conception of such an interceptor is shown in figure 4-3. The U.S. Department of Defense estimates that these anti-satellite weapons became operational in 1971.6 These weapons are believed to be capable of attacking satellites at altitudes up to 5,000 kilometers or even higher,[7] depending on their orbital inclinations; presumably they would be unable to attack satellites in orbits with unfavorable inclinations, i.e., very different from the latitude of the interceptor launch site. As of 1984 there appeared to be only two launch pads for Soviet coorbital interceptors, both located at the Tyuratam launch complex.[8] Several interceptors could be launched per day from this complex.[8]

In 1971 the testing of satellite interceptors was apparently suspended, then resumed in 1976, then again suspended in 1978, just before the U.S.-U.S.S.R. A SAT negotiations began, then again resumed in 1980 after suspension of those talks, then again suspended in August 1983 when Soviet President Yuri Andropov announced a unilateral moratorium on ASAT testing, stating that the U.S.S.R. would not test ASAT weapons if the United States did not. The U.S.S.R. continues to observe this unilaterally declared moratorium. The U.S.S.R. has never officially and publicly admitted developing or testing weapons of this type. However, on 29 May 1985, in an interview by a West German reporter in Geneva, Col. Gen. Nikolai Chervov, a senior department head on the Soviet General Staff, claimed that the U.S.S.R. had successfully developed a direct-ascent satellite interceptor similar to that tested by the United States in the early 1960s and operational until the mid-1970s.

'This is because the energy of a radar return, or "echo," from a satellite decreases as the fourth power of range to the target. Radar returns from satellites in high orbit are generally so weak that they cannot be detected by a radar rapidly scanning the sky; they can only be detected if the approximate position of the satellite is already known so that the radar can scan slowly for signals from that general direction, accumulating signal energy for a prolonged period of time. Hence ground-based radar can measure small changes of a high-altitude satellite's orbit but could not easily find a satellite which had maneuvered energetically since its last observation. Similar considerations limit the effective search range of LIDAR systems.

The energy of a radar echo also depends on the radar wavelength used. For example, at wavelengths much longer than a satellite's diameter, the echo energy decreases rapidly with increasing wavelength-as the inverse fourth power, according to Rayleigh's law. However, the echo also becomes more omnidirectional (as a consequence of Babinet's principle and—in the special case of spherical satellites—the Mie effect) and less dependent upon details of satellite shape and composition other than the electric susceptibility of the satellite, in accordance with Rayleigh's law.

[5]U.S. Department of Defense, Soviet *Military Power,* 4th cd., April 1985.

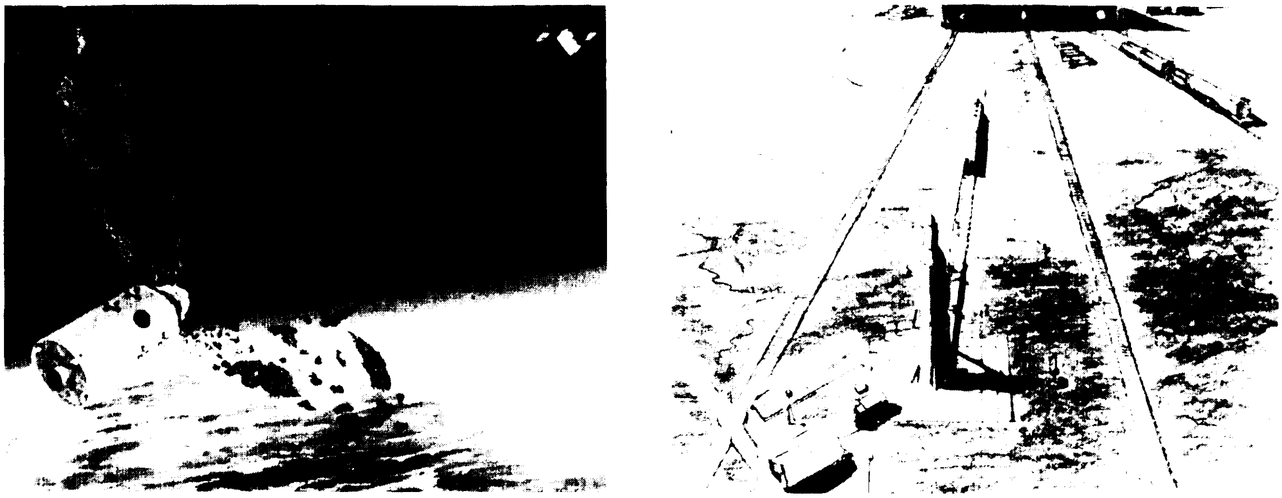
'Ibid., p. 55.

'Ibid., p. 56.

'U.S. Department of Defense, *Soviet Military Power,* 3rd cd., April 1984, p. 34.

'U.S. Department of Defense, *Soviet Mti'tary Power,* 4th cd., " April 1985, p. 56.

Figure 4-3.—The Soviet Coorbital Satellite Interceptor



Launchpad and storage facility for satellite Interceptors at Tyuratam

SOURCE U S Department of Defense

The Soviet Union has also been testing ground-based lasers which could have some ASAT capability [see figure 4-4]. The Department of Defense has stated that the Soviets “already have ground-based lasers that could be used to interfere with U.S. satellites.”[10] As of 1985, there are two experimental Soviet ground-based lasers with some ASAT capability, both at Sary Shagan.[11]

In addition to weapons designed specifically for ASAT use, the U.S.S.R. could attack low-altitude satellites with its ABM interceptor missiles [illustrated in figure 4-4],[12] and presumably with ICBMS and SLBMS, although these might require some modification for ASAT use. All of these weapons are presumably armed with nuclear warheads, and their use in a nonnuclear conflict would be viewed as escalator by the United States and presumably by the U.S.S.R. as well.

In addition to these destructive ASAT capabilities, the U.S.S.R. has a technological capability to jam satellite uplinks or downlinks with some effectiveness, and could use ground-based lasers for electro-optical countermeasures with some effectiveness.[13]

Operational Capabilities

Existing Soviet ASAT capability could be potentially effective for negating low-altitude U.S. MILSATS, such as those used for navigation (Transit) and meteorological surveillance (Defense Meteorological Satellite Program satellites). Commenting on this capability, the Honorable Richard Perle, Assistant Secretary of Defense (International Security Policy), has stated that:

> We believe that this Soviet anti-satellite capability is effective against critical U.S. satellites in relatively low orbit, that in wartime we would have to face the possibility, indeed the likelihood, that critical assets of the United States would be destroyed by Soviet anti-satellite systems,[14]

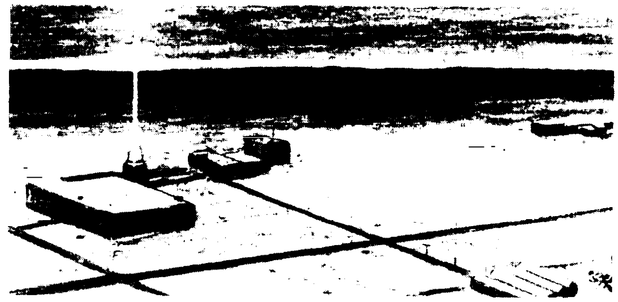
[10] Ibid., p. 56.
[11] Ibid., p. 58.
[12] Ibid., p. 56.

[13] Ibid., p. 56.
[14] Statement of The Honorable Richard Perle, Assistant Secretary of Defense (International Security Policy), in *Hearings Before the Subcommittee on Strategic and Theater Nuclear Forces of the Committee on Armed Services United States Senate, Testimony on Space Defense Matters in Review of the FY1985 Defense Authorization Bill* [S.Hrg. 98-724], March 15, 1984, Pt. 7, p. 3452.

Figure 4-4.—Soviet Anit.Sateltite Capabilities

Artist's conception of a Soviet ABM interceptor missile, named GALOSH by Western analysts GALOSH missiles might have capab!litles to attack satellites at low altltudes.

SOURCE U S Department of Defense



Soviet high-energy laser facility at Sary Shaaan Two lasers there may be capable of d"amagl ng unprotected satellites at low altltudes

The utility of these U.S. satellites in various types of conflicts is discussed in Appendix D to this report, which is a separate, classified document.

Projected Capabilities

The Soviet Union could develop weapons capable of attacking U.S. satellites at higher altitudes than can be reached by the current Soviet coorbital interceptor. Laser weapons, among other types, could be be used for this purpose. The U.S. Department of Defense estimates that:

> The Soviets are working on technologies or have specific weapons-related programs underway for more advanced anti-satellite systems. These include space-based kinetic-energy, ground- and space-based laser, particle beam, and radiofrequency weapons. The Soviets apparently believe that these technologies offer greater promise for future anti-satellite application than continued development of ground-based orbital interceptors equipped 'with conventional warheads,
>
> . . . In the late 1980s, they could have prototype space-based laser weapons for use against satellites. In addition, ongoing Soviet programs have progressed to the point where they could include construction of ground-based laser anti-satellite (ASAT) facilities at operational sites. These could be available by the end of the 1980s and would greatly increase the Soviets' laser ASAT capability beyond that currently at their test site at Sary Shagan. They may deploy operational systems of space-based lasers for anti-satellite purposes in the 1990s, if their technology developments prove successful. 15

The Soviet Union also has the basic technology required to build space-based neutral particle beam weapons. The U.S. Department of Defense estimates that:

> A prototype space-based particle beam weapon intended only to disrupt satellite electronic equipment could be tested in the early 1990s, One designed to destroy the satellites could be tested in space in the mid-1990s.[16,17]

[15] U.S. Department of Defense, *Soviet Military Power*, 4th ed., 1985.

[16] Ibid.

[17] However, as recently as 1984, while projecting this capability, the Administration noted that *We have, as yet, no evidence of Soviet programs based on particle-beam technology'* [President Ronald Reagan, "Report to the Congress: U.S. Policy on ASAT Arms Control,' " 31 March 1984 (u NC I, ASSIFIED)].

Future manned Soviet spacecraft, such as the expected Soviet "space shuttle' '—and, especially, the "space plane "-could have greater maneuverability and possibly non-cooperative rendezvous capability and, if so, some inherent ASAT capability .18

U.S. ASAT Capabilities

The U.S. Space Defense System is a network of systems used for space surveillance and for command and control. An anti-satellite weapon system will be added to it in the near future. Figure 4-2 illustrates a portion of the prospective U.S. Space Defense System as it will appear the planned anti-satellite weapon system is added. The figure shows examples of the space surveillance, command and control, and ASAT weapon systems which will be part of the U.S. Space Defense System.

Space Surveillance

U.S. ASAT capabilities, like those of the SO viet Union, depend on space surveillance capabilities. Like the U. S. S. R., the United States can use its missile attack warning radars and satellites to detect satellite launches and can track satellites after launch using ground-based and shipboard radar, LIDAR, passive optical, and passive radio sensors. The Space Detection and Tracking System (SPADATS) acquires, processes, stores, and transmits data from such sensors, including Naval Space Surveillance (NAVSPASUR) radar interferometers and Air Force Spacetrack radars and Ground-based Electr~Optical Deep-space Surveillance System (GEODSS) sensors [see figure 4-5]. The United States operates more foreign-based space surveillance facilities than does the U. S. S. R., and consequently relies less on shipboard systems, although such systems are used.

The effective search range of U.S. ground-based radar systems is limited to low-Earth orbit, although some radars can track a satellite out to geosynchronous altitude if the satellite's approximate position is already known." The range at which a ground-based radar can track low-altitude satellites is limited by the requirement for an unobscured line of sight to the satellite. For example, a satellite at an altitude of 185 kilometers (100 nautical miles) would be below the horizon if farther away than 1,590 kilometers slant range.[20]

For detection of satellites in deep space the United States relies on a system of telescopic electro-optical sensors called GEODSS, for Ground-based ElectroOptical Deep-space Surveillance System [see figure 4-6].[21] The GEODSS network, when completed, will provide world-wide deep-space surveillance coverage using sensors at five sites[22]:

- Socorro, New Mexico (Site I);
- Taegu, South Korea (Site II);
- Maui, Hawaii (Site III);
- Diego Garcia, *in* the Indian Ocean (Site IV); and
- Portugal (Site V).

The main telescopes at each GEODSS facility are designed to detect objects as dim as a star of visual magnitude 16.5, or a reflective sphere about the size of a soccer ball in geosynchronous orbit.

Command and Control

Under present policy, the U.S. National Command Authorities (NCA) would have to authorize satellite negation. Actual operational control of a negation mission would be exercised by the USAF Space Command

[18]Current manned Soviet spacecraft (Soyuz, Salyut) do not have a significant inherent ASAT capability: they have little maneuver capability and have not demonstrated coorbital rendezvous with non-cooperative spacecraft. Rendezvous with co-operative spacecraft is typically performed by an automatic system which relies on a transponder on the passive spacecraft.

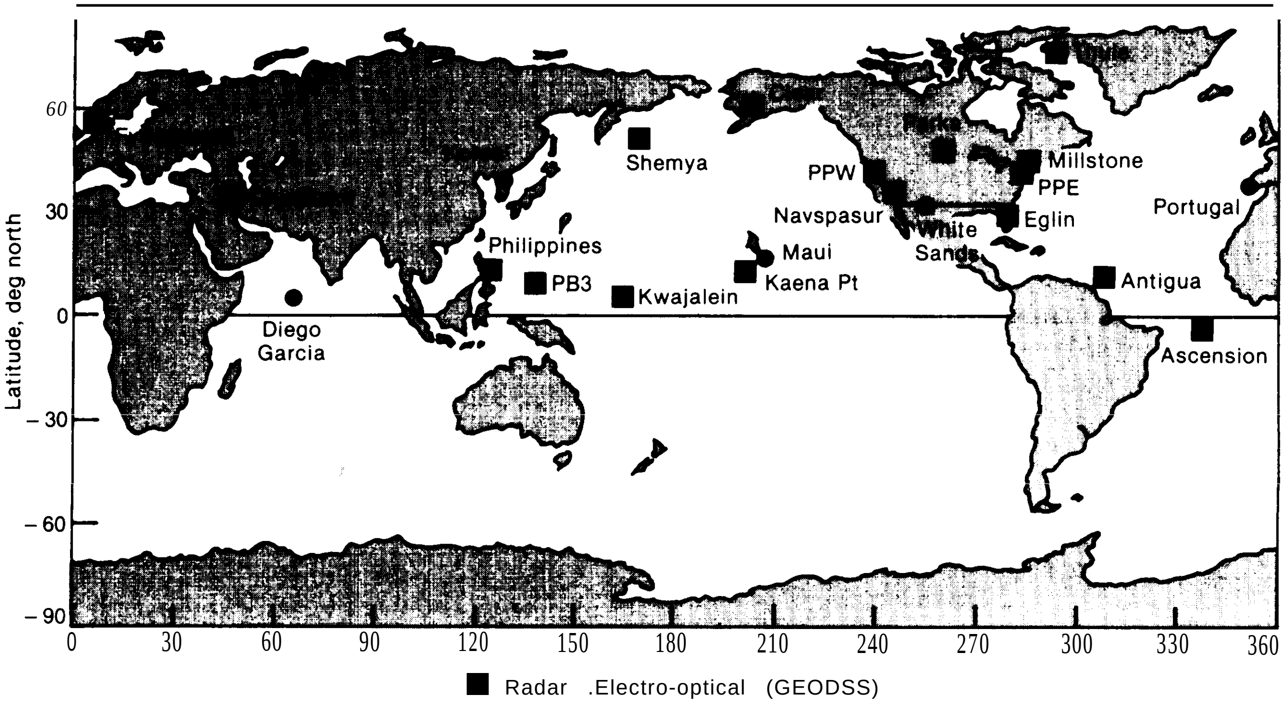
[19]See note 4, supra.

[20]I.e., 1,560 kilometer as projected on the Earth's surface. A closer satellite at this altitude might be below the horizon, if mountains or other terrain features obscured the view. In addition, the azimuthal coverage of some radars is limited.

[21]D.D. Otten, E.I. Bailis, and J.G. Klayman, "GEODSS: Heavenly Chronicler, " *Quest* (Redondo Beach, CA: TRW, Inc., August 1980), pp. 3-23.

[22]Sites I, II, and 111 are presently operational, and site IV should become operational this year. Sites I, II, and III each have two main 40-inch telescopes and one 15-inch auxiliary telescope, while sites IV and V will have three main telescopes each. Site equipment is designed to be relocatable within 2 weeks.

Figure 4-5.—Space Detection and Tracking System



SOURCE The Aerospace Corp

Space Defense Operations Center (SPADOC) in the Cheyenne Mountain Complex using other assets of the Space Defense Command and Control System [see Figures 4.7 and 4.8].[29]

On October 1, 1985, satellite negation will become the responsibility of a new unified space command which will also exercise operational command over U.S. military space systems which provide support to the combatant forces of other unified and specified commands. Creation of a unified space command was proposed in order to increase the effective ness and responsiveness of U.S. space systems and to ensure a clear chain of command from the NCA to combatant forces.[24] Creation of the U.S. Space Command was authorized by the President on November 30, 1984.

Weapons

In 1959 the United States successfully intercepted the Explorer VI satellite using an air-launched ballistic missile developed for other purposes and, the following year, began to develop—but abandoned before testing—a coorbital SAtellite Interceptor system (SAINT) designed specifically for the purpose of inspecting and destroying satellites. The United States also maintained an operational direct-ascent satellite interceptor capability from 1963 until 1975, using nuclear-armed Nike-Zeus missiles (Project Mudflap, 1963-1964) and Thor missiles (Project 437, 1964-1975).[25]

The United States has no deliberate operational ASAT capability at the present time, although its nuclear-armed ICBMS and SLBMS have some inherent ASAT capabilities, as was demonstrated by the nonnuclear exoatmospheric ABM Homing Overlay Experiment

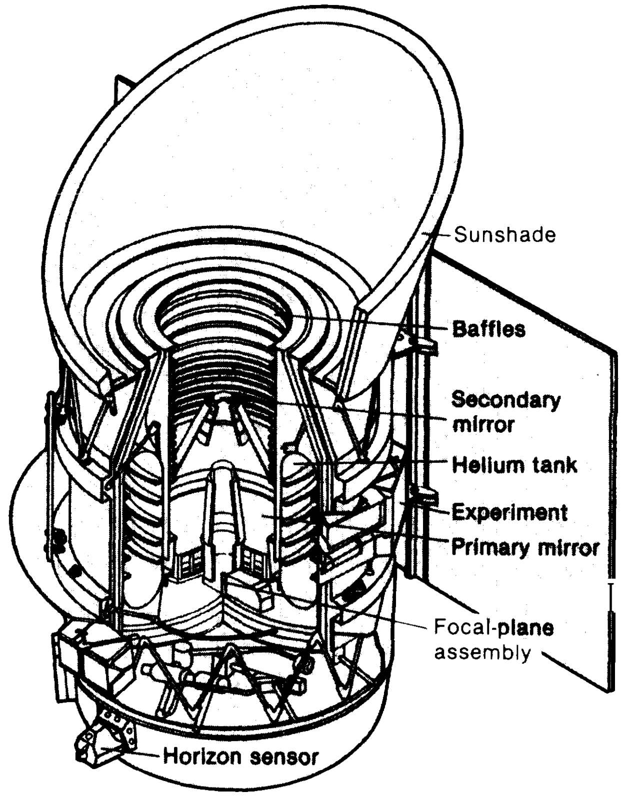
[23]R.S. Cooper, Director, Defense Advanced Research Projects Agency, *The U.S. Anti-sate llite(ASAT) Program*, statement before the Senate Foreign Relations Committee, 25 April 1984.

[24]Hon. Verne Orr, Secretary of the Air Force, *USAF FY85 Report to the 98th Congress of the United States of America*, 8 February 1984; reprinted in S. Hrg 98-724.

[25]M. Smith, "Anti-satellites (Killer Satellites), " CRS Issue Brief IB81123, 22 August 1983.

Figure 4-6.—Deep Space Surveillance Systems

Left: Today, surveillance of deep space IS performed by ground-based electro-optical surveillance systems such as the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system, which IS operated by the U.S. Air Force Space Command as part of the Space Detect Ion and Tracking System (SPADATS) Here, an operator at a GEODSS control and display console studies a 21 field of view of deep space. On a clear night, a GEODSS main telescope can automatically survey over 500 such fields per hour and detect reflective satellites as small as soccer balls at geosynchronous altltudes



SOURCE U S AIr Force

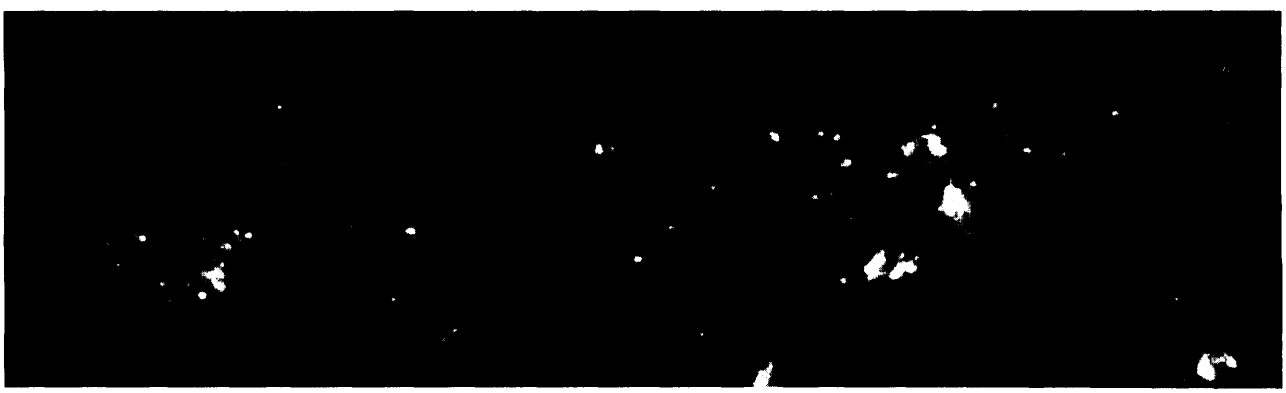
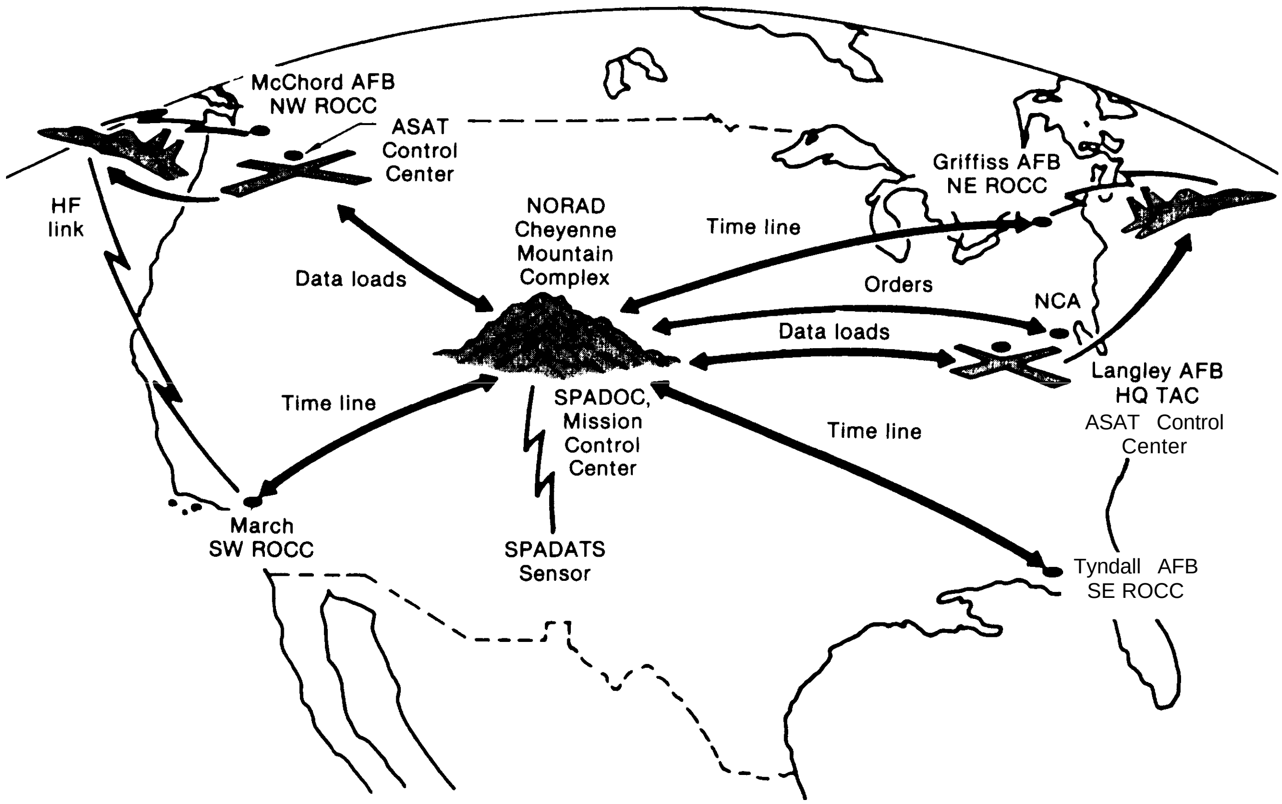


Figure 4-7.—ASAT Mission Operations Concept



This illustration shows communication links which would be used for a satellite negation operation.

SOURCE: The Aerospace Corp

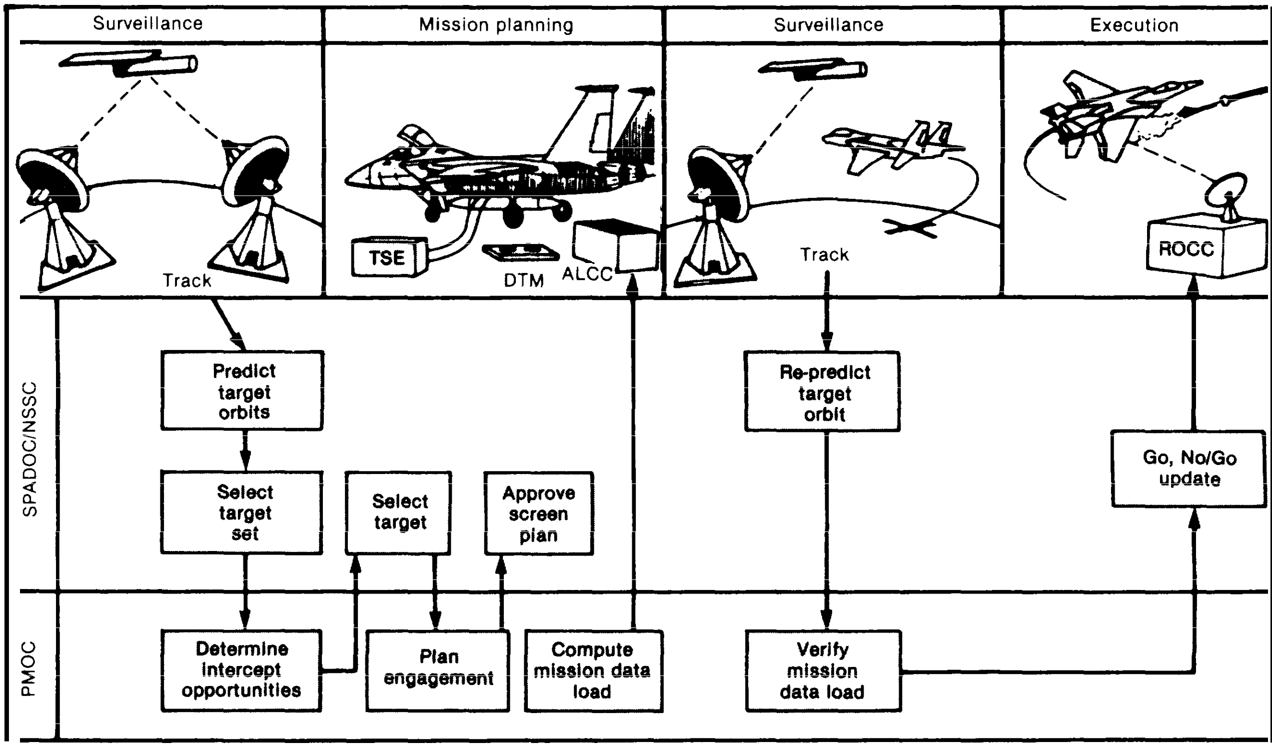
(HOE) test of 10 June 1984. However, the U.S. Air Force is flight-testing an air-launched, direct-ascent anti-satellite weapon called the Miniature Vehicle ("MV"). This infrared-guided nonnuclear kinetic-energy weapon [see figure 4-9] is mounted on a two-stage SRAM/ALTAIR booster which is carried aloft and launched from an F-15 aircraft. F-15 carrier aircraft are to be deployed at Langley Air Force Base in Virginia and at McChord Air Force Base in Washington state [see figure 4-10]. When operational, it will be able to attack low-altitude Soviet satellites which perform reconnaissance and targeting functions; these are viewed as most threatening by the United States.[28] If based as planned, these weapons will not be able to attack Soviet satellites which provide missile attack warning, navigation, and advanced communications functions.[27]

The Air Force plans to hold 12 flight tests of the ASAT system. Two of the twelve tests have been held–the first in January 1984 and the second in November 1984. In the January test, the ASAT missile was targeted at a point in space to determine whether the two-stage SRAM/ALTAIR booster could deliver the miniature homing vehicle to the vicinity of the target point. The Air Force considered the test a success: the proper functioning of the first and second stage propulsion systems and the

[28] President Ronald Reagan, *Report to the Congress: U.S. Policy on ASAT Arms Control*, 31 March 1984 [UNCLASSIFIED].

[27] R.S. Cooper, Director, Defense Advanced Research Projects Agency, *The U.S. Anti-satellite (ASAT) program*, statement before the Senate Foreign Relations Committee, 25 April 1984.

Figure 4-8.— Mission Control Events



Execution of a satellite negation mission using the USAF MV ASAT weapon would begin with an alerting order. The target would then be tracked by SPADATS and its ephemeris would be updated by the National Space Surveillance Center (NSSC) for use in generating mission tapes to be loaded on the carrier aircraft for targeting of the ASAT weapon. After an execution order is issued from the Prototype Mission Operations Center (PMOC) in the Cheyenne Mountain Complex (CMC), the carrier aircraft would take off and the missile would have to be launched before sensor coolant exhaustion. Before missile launch, the carrier aircraft would receive updated information and instructions by high-frequency radio data link from a Regional Operations Control Center (ROCC), which is an element of the current military air traffic control center.

SOURCE The Aerospace Corp

missile guidance system was successfully demonstrated.[28]

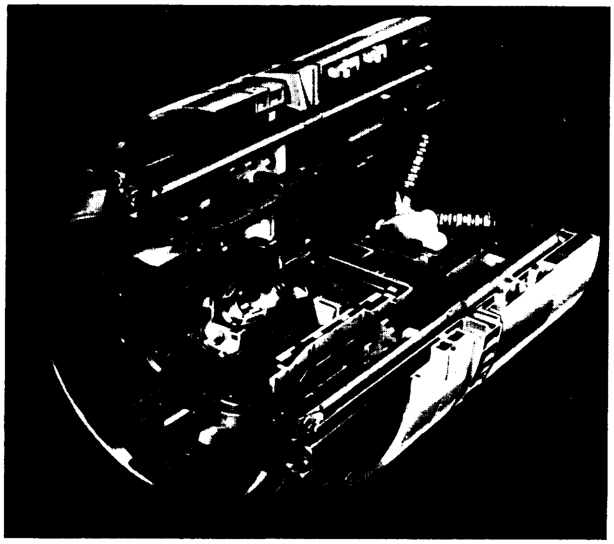
The objective of the November 1984 test was to reaffirm the performance of the missile and to demonstrate the capability of a miniature homing vehicle to acquire and track an infrared-emitting body (in this test, a star) against the radiant background of deep space. The Air Force considered the test a partial success.[29]

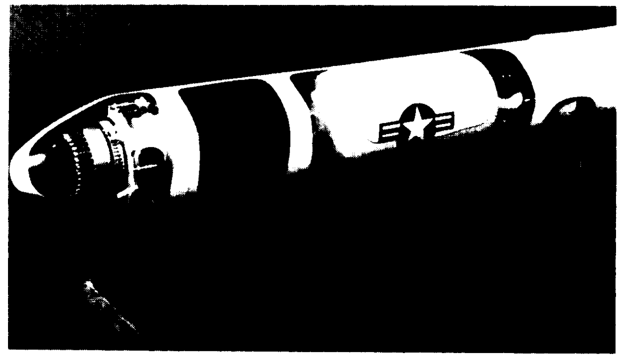
Successful completion of U.S. ASAT tests would provide confidence that the weapon could perform as specified if actually used. Funds for completion of the planned flight test program have been appropriated by Congress subject to certain limitations, partly because of concern that once the weapons are proven effective, the Soviet Union would cease to observe its self-imposed moratorium on the testing of ASAT weapons and might be reluc-

[28]U.S. Congress, General Accounting Office, "Report to the Honorable George E. Brown, Jr., House of Representatives: Status of the U.S. Antisatellite Program," report GAO/NsIAl)-85-104, June 14, 1985.

[29]Ibid.

F gu e 4 9 he USAF M n a u e Veh e





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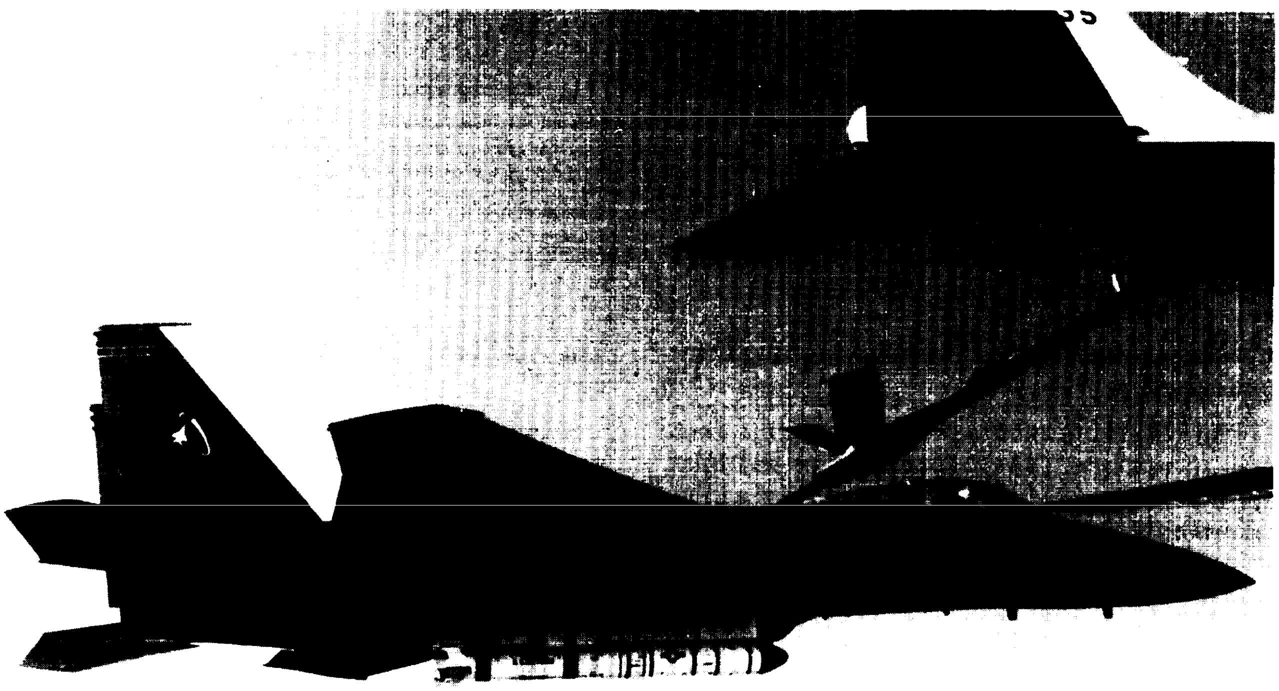
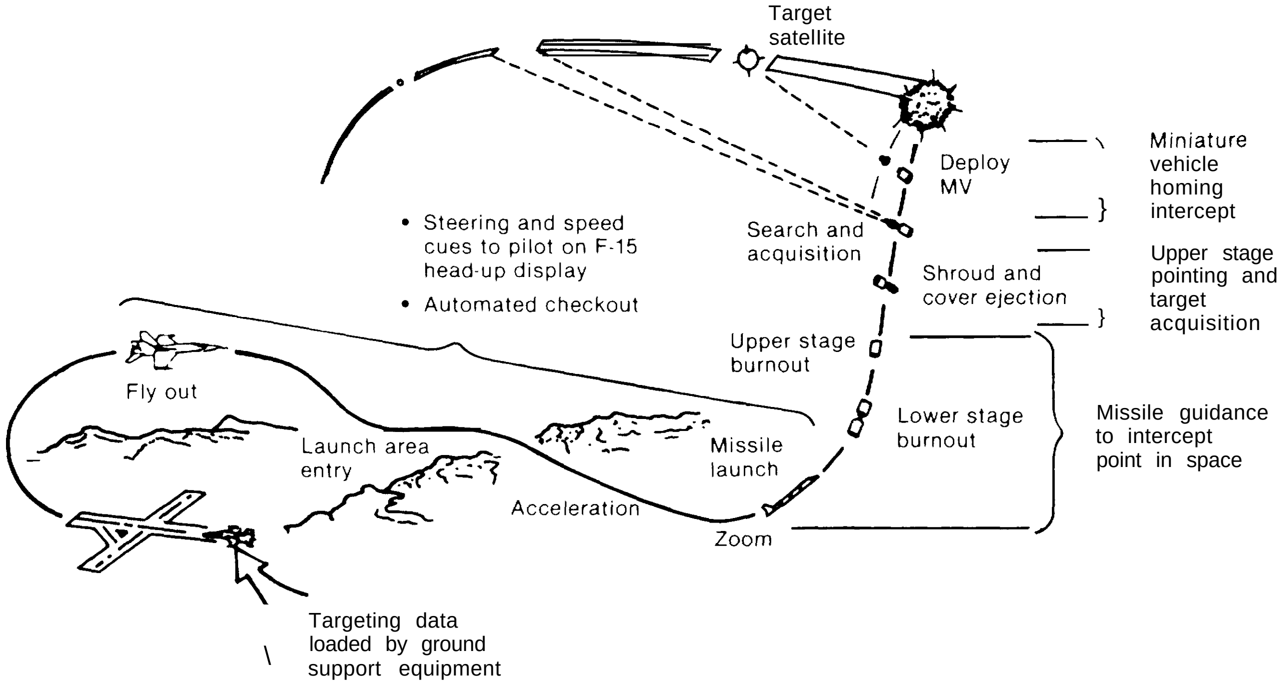


ASAT missile carried by F-15 fighter during refueling operation

SOURCE U.S Alr Force

Figure 4-.10. **—ASAT Mission Profile**



SOURCE The Aerospace Corp

tant to agree to arms control measures which would ban them. Because the small weapons could be easily concealed, if they are proven effective and then banned by agreement, Soviet authorities might suspect that the United States retained a capability to use hidden ASAT weapons.

The estimated costs of the U.S. ASAT program are listed in table 4-I.

Table 4.1 .—Estimated Costs of the U.S. Air Force Space Defense and Operations (ASAT) Program

Activity	Cost		Reference
Research, development, testing and evaluation (Program element 64406F)	$1.40	B	1)
Procurement (missiles and aircraft)	$2.64	B	1)
Military construction (Program element 12450F)	$0.04	B	1)
Operation and maintenance, FY 1986	$0.009	B	2)
Operation and maintenance, FY 1987	$0.0129	B	2)
Operation and maintenance, FY 1988	$0.0283	B	2)
Operation and maintenance, FY 1989	$0.0453	B	2)
Operation and maintenance, FY 1990	$0.0461	B	2)
Total	$4.2416	B	

SOURCES: 1) U.S. Congress, General Accounting Office, "Report to the Honorable George E. Brown, Jr., House of Representatives: Status of the U.S. Antisatellite Program," report GAO/NSIAD-85-104, June 14, 1985.
2) U.S. Air Force.

POSSIBLE ADVANCED-TECHNOLOGY ASAT WEAPON SYSTEMS

It will be possible in a few years to build space surveillance systems, ASAT weapon systems, and ASAT countermeasure systems much more capable than those used by the United States or expected to become operational soon. These advanced systems could use technologies expected to be available eventually in both the United States and the Soviet Union. The variety of possible systems is so great that this report will discuss only those which seem most promising or threatening with respect to criteria of responsiveness, survivability, altitude reach, economy, early availability, controllable lethality (for destructive applications), and usefulness at nonnuclear levels of conflict. The most promising ASAT technologies will be discussed in this section as possible U.S. options. Space surveillance systems, although essential components of space defense systems, will not be discussed in this section, because the most promising space surveillance technologies would be used to best advantage in space-based space surveillance systems; these were discussed in chapter 3 as possible advanced-technology MILSAT capabilities.

Table 4-2 lists the major categories of ASAT weapons, organized, according to physical means of causing damage, into three categories: isotropic (nondirectional) nuclear weapons, kinetic-energy weapons (projectiles), and directed-energy weapons (particle beam weapons, radio-frequency weapons, and laser weapons). Because the boundary between destructive directed-energy devices (weapons) and nondestructive directed-energy devices (e.g., radio jammers, lasers used to overload optical sensors, or particle-beam generators used to upset the functioning of electronic systems) is blurred, being one of power or mode of use rather than kind, nondestructive directed-energy devices will not be distinguished from directed-energy weapons except where necessary.

Isotropic Nuclear Weapons

Ordinary nuclear weapons, when detonated in space, radiate energy and disperse debris more or less uniformly in all directions. Hence they will be called isotropic nuclear weapons (INW) to distinguish them from nuclear explo-

Table 4-2.—Types of ASAT Weapons

Isotropic nuclear weapons (INW):
Ground-based
—Coorbital interceptor
—Direct-ascent ("pop-up") interceptor
Space-based
—Coorbital interceptor (nuclear "space mines")[a][b]
Kinetic-energy weapons (KEW):
Ground-based
—Coorbital interceptor
—Direct-ascent ("pop-up") interceptor
Space-based
—Coorbital interceptor ("space mines")[a]
—Noncoorbital interceptor
Directed-energy weapons (DEW):
Ground-based
—High-power radio-frequency (HPRF) and active electronic countermeasures (ECM)
—High-energy laser (H EL) and active electro-optical countermeasures (E-OCM)
Space-based
—High-power radio-frequency (HPRF) and active electronic countermeasures (ECM)
—High-energy laser (HEL)[d] and active electro-optical countermeasures (E-OCM)
—Neutral-particle beam (NPB)

[a]A "space mine" Is an expendable ASAT weapon predeployed in space so as to be capable of destroying enemy satellites almost Instantly They could be armed with INW, KEW, or DEW I f armed with a short-range weapon, a space mine must be coorbital
[b]Prohibited by the 1967 Outer Space Treaty
[c]Intercepts targets at high velocity from parking orbit
[d]Including nuclear explosive powered X-ray lasers (X RLs), Which are nuclear directed-energy weapons (NDEW)

sive-powered directed-energy weapons (NDEW) which will be discussed subsequently. INW could be carried to within lethal range of a satellite or satellites by a rocket and detonated. Early U.S. ASAT weapons were of this type, and the United States or the U.S.S.R. could use nuclear-armed ICBMS, SLBMS, and ABM interceptors in this manner. Alternatively, INW could be used as nuclear space mines: they could be concealed aboard satellites which are continuously or occasionally within lethal range of enemy satellites and detonated on command.

As ASAT weapons, nuclear weapons have several legal, political, and strategic disadvantages: they can only be used at the nuclear level of conflict-or in any case their use would escalate a conflict to the nuclear level—and when used they may upset or damage unhardened friendly and neutral satellites at ranges which depend on weapon yield but which can be very large. In addition, they cannot legally be based in orbit, this being prohibited by the Outer Space Treaty of 1967. Moreover, existing U.S. procedures for safeguarding nuclear weapons and for preventing their unauthorized use are expensive and time-consuming, and the Soviet Union may have similar safeguards now and incentives to retain them in the future. On the other hand, the advantages of isotropic nuclear weapons are their present availability, their economy (relative to other weapons of comparable range), their concealability (from present surveillance systems), their great lethal range (as compared to kinetic-energy weapons) against unhardened satellites, the difficulty of hardening satellites against nuclear detonations at close range, and their adaptability for delivery by a variety of launch vehicles and orbital platforms, including those with poor guidance accuracy and no pointing capability.

By comparison, nuclear directed-energy weapons are not now available and, if developed, would require platforms with moderately accurate pointing capability. However, it is possible in principle to build nuclear directed-energy weapons, such as X-ray lasers, which could have far greater lethal range than the nuclear explosive devices which power them and which could be feasibly and economically delivered by platforms with adequate pointing capability. The theoretical potential of such weapons,[34] if realized in practice, would make them superior to isotropic nuclear weapons for ASAT applications. The *potential* ASAT capabilities of NDEW, therefore, deserve greater concern than do those of isotropic nuclear weapons which are, however, of more immediate concern because of their existence and *demonstrated* capability.

Existing nuclear-armed Soviet ABM missiles could be used against low-altitude satellies. Prior testing of such weapons against satellites would not be required to demonstrate the reliability of subsystem operation.

[34]See, e.g., F.V. Bunkin, V.I. Derzhiev and S.1. Yakovlenko, "Specification for pumping X-ray laser with ionizing radiation, " Soviet *Journal of Quantum Electronics,* vol. 11, No. 7, July 1981, pp. 971-972, and note that many such lasers could be powered by *one* "exotic" source of pulsed x-radiation.

Isotropic nuclear weapons concealed aboard satellites used as "space mines" could attack without warning and would pose a greater threat because reactive countermeasures could not be used for protection. Nuclear space mines could be lethal against satellites as hard as any now operational at such range that the testing of their trailing capability -e.g., in geostationary orbit—although observable, might not be interpreted as such. Protection against such weapons would require evading them during placement (which would be relatively economical only for a small, cheap satellite), opposing their placement by defending an agreed or unilaterally declared "keep-out zone" around satellites from penetration by any spacecraft which might contain a nuclear weapon, or possibly, after penetration and trailing by such a spacecraft, evading (e.g., under cover of smoke and chaff) it until out of its probable lethal range, at which time it could be attacked by ASAT weapons of greater range, if available.

Development and, when necessary, operation of closelook inspection satellites equipped with gamma-ray spectrometers or other instruments capable of detecting materials used in nuclear explosives would afford additional protection: if inspection by such satellites were anticipated, the designer of a nuclear space mine would have to shield its nuclear explosive device with tons of material[85] in order to prevent collection of *prima facie* evidence of having placed a nuclear weapon in orbit in violation of the Outer Space Treaty of 1967. Placing so massive a space mine into orbit would be more costly, and it could be evaded at less relative cost than a smaller, unshielded space mine could be.

[85] U.S. and Soviet scientific spacecraft, landers as well as orbiters, have carried gamma-ray spectrometers capable of detecting low concentrations of fissionable materials as deep as half a meter below lunar and planetary surfaces [U.S. National Aeronautics and Space Administration, *A Forecast of Space Technology 1980-2000,* NASA Special Report SP-387, 1976; and cf. the recent Soviet "VEGA" Venus/Halley's Comet probe.]. The United States could develop such sensors for use on satellites for purposes of monitoring compliance with the Outer Space Treaty.

The risk which such weapons may pose to U.S. spacecraft now or in the future is mitigated to some extent by the fact that they would be useful only in a nuclear war, in which the ground segments of space systems would also be significantly vulnerable and might be attacked by preference, and more rapidly. This and the other aforementioned disadvantages of ASAT INW pose disincentives against developing them, attempting to base them in orbit covertly, and using them at nonnuclear levels of conflict

Several conclusions follow from these considerations:

1. It is feasible to build direct-ascent and coorbital isotropic nuclear weapons.
2. Weapons of this type could be as small and inexpensive as many existing satellites.
3. Such weapons could be developed and tested covertly.
4. Soviet nuclear weapons could threaten U.S. satellites at low and high altitudes now and in the future but only at nuclear levels of conflict.
5. Protection of U.S. satellites from coorbital INW may require defense of a keep-out zone around low-altitude satellites or designing future low-altitude satellites to beat least as small and inexpensive as the nuclear space mines which threaten them. Many more options are available for defending high-altitude satellites from direct-ascent nuclear interceptors.

Kinetic-Energy Weapons

Anti-satellite kinetic-energy weapons pursue satellites and destroy them by direct impact or at close range using a gun or a fragmentation warhead. One example of an ASAT KE W is a coorbital interceptor which approaches its target at a low closing velocity before destroying it. Another example is a direct-ascent ("pop-up") interceptor which is launched from the Earth's surface or from an airplane and which approaches its target at a high closing velocity. Such an interceptor could also be based in space in a parking orbit, from which it could enter a transfer orbit in which it would close with its target at high velocity, just as a pop-up interceptor would. "Pop-up" interception requires less energy per unit interceptor payload than does coorbital interception, particularly at low altitudes. A coorbital interceptor, on the other hand, could be used as a "space mine, continuously observing and trailing its target, prepared to destroy it almost instantly on command or (if salvage-fused) when attacked or disturbed in specified ways. Used in this way, a coorbital ASAT KEW could take advantage of the element of surprise in an attack, leaving an enemy no time to react with active defenses or reactive passive countermeasures such as evasion or deployment of decoys or smoke.

A coorbital interceptor could pursue a target (its 'quarry") indefinitely if it had as much velocity change capability ("delta-V") as its quarry. If it also had as much acceleration capability as its quarry, it could, with tracking capability, pursue its quarry continuously, otherwise its quarry would be able to maneuver out of lethal range temporarily. Under some conditions, an interceptor may be able to trail its quarry using less delta-V than its target uses for evasion; however, calculation of required velocity change is complicated,[36] particularly in the case of many-against-one interception. In any case, if comparable propulsive technologies are available to both pursuer and evader, pursuit can be successful if the interceptor's mission payload—its armament (if any) and guidance and fuzing systems—is lighter than that of its quarry.

It should be possible to build space mines with very lightweight armament. For example, a directional fragmentation warhead similar to that of a Claymore mine could project 100,000 one-gram pellets in a pattern which would cover a 100 x 100 meter area with 10 pellets per square meter at a range of 1 kilometer. This would be adequate to destroy unarmored satellites as small as about a meter in diameter with high probability. The pellets for such a warhead would weigh 100 kilograms, and its explosive charge could weigh less than that. Even lighter warheads of this type may be possible, possibly having dispersion angles as small as those of shotguns or even high-power rifles (e.g., 10 centimeters dispersion at a range of 1 kilometer).

Guns and rockets could also be used as armament by a KEW space mine. For example, a single unguided rocket which deploys a 10 x 10 meter net weighing about 1 kilogram and having a l-gram weight at each of its 100 nodes (knots) could achieve the same kill probability as the Claymore-type warhead if its aiming error were less than 5 milliradians (5 meters at 1 kilometer) after rocket burnout and net deployment. A space mine using such a rocket as armament might weigh as little as 50 kilograms but could destroy much heavier unhardened satellites.

It would not be relatively economical to use such mines to attack smaller, cheaper satellites, which could be useful for some military applications, such as communications.[37] However, it would be economical to use space mines to attack larger satellites. If such satellites are armored as a countermeasure, the space mine could also be made more lethal, and this would probably require less mass than would be required for armor against it at the assumed lethal range[38]. There appears to be no relatively economical means of protecting large satellites against a surprise attack by such mines, once they are emplaced. Safety from such attacks would require opposing their placement by defending an agreed or unilaterally declared "keep-out zone" around satellites, or else, once they are emplaced, evading them (e.g., under cover of smoke and chaff) until out of their range, at which time they could be attacked by ASAT weapons of greater range.

[36]G.M. Anderson, "Differential Dynamic Programming Feedback Control for a Pursuing Spacecraft with Limited Fuel, "(New York, NY: American Institute of Aeronautics and Astronautics, AIAA Paper A78-31925, 1978).

[37]For example, the U.S.S.R. operates a constellation of lightweight satellites in low orbit, and as early as 1961 the United States operated SYNCOM communications satellites weighing only 31 kilograms in geosynchronous orbit.

[38]See the discussion of hardening in the discussion of countermeasures, below.

Space mines the size of those assumed (2 meters in diameter) could be detected by ground-based radars if at low altitude or, if at high altitude, by electro-optical sensors (e.g., GEODSS) if they do not employ measures (e.g., black paint) to evade detection or by space-based long-wavelength infrared space surveillance sensors even if they do employ such measures. In order to demonstrate reliability, they would have to be tested in space by trailing satellites or space debris. This activity could be observed and would be noticeable.

The U.S. Department of Defense has estimated that the U.S.S.R. views development of directed-energy weapons as a more promising approach for improving future antisatellite capabilities than further development of ground-based kinetic-energy ASAT weapons.[39] However, Soviet development and testing of interceptors of the type which is currently operational have demonstrated an interest, and some capability, in coorbital, nonnuclear kinetic-kill approaches to ASAT capability. Given sufficient incentive, the U.S.S.R. might choose to continue these efforts and, if so, could eventually produce smaller, cheaper weapons of longer endurance. Once testing of such weapons in space is observed, there might be insufficient time for the United States to react by developing new generations of small, inexpensive satellites against which use of small space mines would be uneconomical.[40]

It can be concluded from these considerations that it is feasible to build coorbital kinetic-energy ASAT weapons. Weapons of this type could be smaller and cheaper than most satellites as presently designed. If such weapons are deployed by the U. S. S. R., protecting future U.S. satellites from them may require defense of a keep-out zone around U.S. satellites or designing future satellites to be at least as small and inexpensive as the space mines which threaten them.

Directed-Energy Weapons

Several types of directed-energy weapons could be used for ASAT purposes, including ground- and space-based systems powered by nuclear explosives, nuclear reactors, or non-nuclear energy sources. They include high-power radio-frequency (HPRF) generators, high-energy laser (HEL) weapons, and neutral particle beam (NPB) weapons. They could also include non-laser sources of short-wavelength radiation.

High-Power Radio-Frequency Weapons and Electronic Countermeasures

HPRF weapons–which include high-power microwave (HPM) weapons—are devices capable of producing intense, damaging beams of radio-frequency radiation.[41] HPRF generators could be used to overload and damage satellite electronic equipment at high power levels or, at lower power levels, merely to temporarily overload satellite electronic systems (i.e., for "jamming")." Radidrequency (RF) generators could therefore be useful at all levels of conflict.

HPRF weapons could be ground-based or based in space. Ground-based HPRF weapons, unlike ground-based laser weapons, could operate through cloud cover. However, the maximum pulse energy per unit area which can be beamed through the atmosphere is limited.[43] Space-based HPRF weapons would not be so limited, but, like ground-based HPRF weap-

[39] U.S. Department of Defense, *Sow"et Military Power,* 4th cd., April 1985, p. 44.

[40] For example, Soviet testing of interceptors of the type now operational was first observed in 1968, and the U.S. Department of Defense has judged, in retrospect, that an operational capability with these interceptors was achieved three years later, in 1971. [Ibid., p. 55.]

[41] I.e., electromagnetic radiation at wavelengths of 1 millimeter or longer,

[42] This continuum of HPRF effects makes distinction between "weapons" and "jammers" difficult. For arms control purposes, however, a distinction could be made based on power-aperture product, as is done in the ABM Treaty. Wavelengthdependence should be considered as well, because at a given power-aperture product, shorter wavelengths can be radiated with greater brightness and deliver more power per unit area at long range.

[43] The maximurn pulse energy per unit area which can be beamed through the atmosphere is limited to about 1 joule per square meter by the phenomenon of dielectric breakdown of the atmosphere, which occurs at higher energy fluence levels.

ens, would have to be very large in order to concentrate their HPRF energy into a narrow beam. Even a relatively wide beam might be able to damage satellites of existing designs at considerable range, but this is uncertain, and hardening satellites against HPRF radiation is possible.

The lethality of HPRF weapons would be less certain than the lethality of other DEW because of uncertainties about target vulnerability, i.e., about the beam energy per unit area required to damage a particular enemy satellite, This will depend on details of the design of the satellite and would be difficult to predict with accuracy even if those details were known. Moreover, even though it is possible in principle to harden satellites to withstand intense HPRF radiation, it is difficult to verify by modeling and simulation, and exorbitantly expensive to verify by testing, the actual degree of hardness achieved. Hence, although many concepts for HPRF weapons have been studied, none of them are as resistant to countermeasures as are some HEL and neutral particle beam concepts.

Radio-frequency generators of lower power will continue to be valuable for providing capabilities to jam and spoof (i.e., deceive) satellite radio systems.[44] The vulnerability of satellites to jamming and, especially, spoofing, is also uncertain and probably varies greatly among satellites. However, low-power RF generators useful for jamming and spoofing would be much cheaper than HPRF generators; indeed, some existing electronic countermeasure systems could be used against satellite links. Because of the prevalence and ambiguity of these capabilities, it would be difficult or impossible to eliminate the non-destructive A SAT capabilities of ECM systems by means of arms control agreements. Use of passive electronic counter-countermeasures, when necessary, would be preferred.

High-Energy Laser Weapons and Electro-Optical Countermeasures (Ground-Based)

High-energy laser weapons are devices capable of producing intense, damaging beams of optical radiation[45] by means of the phenome non of stimulated emission of radiation. High-energy lasers could be used to permanently damage satellites, or, at lower power levels, to jam optical communication systems and to "dazzle" optical sensor systems (i.e., to overload them, temporarily blinding them). This continuum of effects makes the distinction be tween "laser weapons" and "active electro-optical countermeasures" one of degree rather than kind and therefore difficult.[46] Lasers of several types, employing different materials and physical processes and operating at different wavelengths, might be suitable for use as weapons; some of these types are described in the box entitled "Types of Lasers. "

HEL weapons could be space-, ground-, air-, or sea-based. Of the many possible types of lasers useful as ground-based A SAT weapons, continuous-wave deuterium-fluoride chemical lasers have been of particular interest because of their simplicity, the maturity of their technology, and the possibility of focusing their infrared beams using mirrors of relatively rough surface quality (compared to that which would be required at shorter visible and ultraviolet wavelengths).

Repetitively-pulsed free-electron lasers and electric-discharge excimer lasers have also been of interest because they would operate at short wavelengths at which small beam divergence angles could be achieved using smaller mirrors than would be required for infrared beams, although they would have to be

[44] Even at very low power levels radio-frequency generators might be able to confuse ("spoof' satellites by beaming deceptive signals at them. Some possible spoofing techniques have been described by Col. Robert B. Giffin, USAF. in *US Space System Survivability: Strategic Alternatives for the 1990s*, National Security Affairs Monograph Series 82-4, National Defense University Press, Fort Leslie J. McNair, Washington, DC, 1982; p. 26. Electronic counter-countermeasures can be used to reduce the susceptibility of MILSATs to spoofing.

[45] I. e., electromagnetic radiation at wavelengths shorter than 1 millimeter,

[46] For arms control purposes, however, a distinction could be made based on power-aperture product, as is done in the ABM Treaty. Wavelength-dependence should be considered as well, because at a given power-aperture product, shorter wavelengths can he radiated with greater brightness and deliver more power per unit area at long range.

Types of Lasers

A laser is described by the lasant material it uses as a source of coherent optical radiation (e.g., deuterium fluoride), the characteristic wavelength or wavelengths at which the lasant emits such radiation, the method of pumping (i.e., energizing) the lasant (e.g., chemical lasers, electric-discharge lasers, optically pumped lasers, gasdynamic lasers, etc.), the source of energy used for pumping (e.g., chemical electrical, nuclear reactor, nuclear explosive, etc.), and its pulse waveform (e.g., single-pulse, repetitively pulsed, or continuous-wave).

Many materials can be used as lasants; these can be in solid, liquid, or gaseous form (consisting of molecules or atoms) or in the form of a plasma (consisting of ions and electrons). Lasant materials useful in highnergy lasers include carbon dioxide, carbon monoxide, deuterium fluoride, hydrogen fluoride, iodine, xenon chloride, krypton fluoride and selenium, to mention but a few, Some of these-e.g., xenon chloride and krypton fluoride-are molecules which cannot exist under ordinary conditions of approximate thermal equilibrium but must be created by special "pumping" processes in a laser. Such molecules are called excimers, a contraction for "excited dimer" (a dimer is a molecule consisting of two atoms).

Free-electron lasers do not use lasants but instead generate radiation by the interaction of an electron beam with a static magnetic or electric field. Loosely speaking, free-electron laser technology resembles and evolved from that used by particle accelerators ("atom smashers"), while other (i.e., bound+lectron) lasers use Iasants heated by electrical current or chemical combustion and resemble fluorescent lamps or rocket engines in some respects. Some lasers use mirrors, lenses, diffraction gratings, or other optical elements to recirculate the laser beam through the lasant in order to achieve adequate amplification; such lasers are called cavity lasers, and the arrangement of optical elements used to recirculate the beam is called the laser cavity or resonator. In other lasers, the beam passes through the lasant only once; such cavity-less lasers are called superradiant lasers, and the process of singk+pass beam generation they use is called superradiance, superfluorescence, or amplified spontaneous emission.

of higher optical quality. Free-electron lasers can probably be 'made more efficient than other short-wavelength lasers and could be ground- or space-based. Electric-discharge excimer lasers might be available sooner, but probably cannotbe made as efficient as free-electron"lasers can be, nor can they be tuned, as free-electron lasers can be, to wavelengths which would minimize beam degradation by atmospheric effects (in the case of ground-based 'lasers) and optimize target damage.[47]

Beams from ground-based HEL weapons would be subject to a variety of phenomena which would disturb their propagation through the atmosphere. These phenomena include absorption, scattering, thermal blooming, dielectric breakdown, and the refractive effects of atmospheric turbulence. Most serious is beam absorption and scattering by clouds: ground-based HEL weapons, unlike ground-based HPRF weapons, could not operate through cloud cover.[48]

"Soviet laser development has emphasized other technologies than these; the "best" laser technologies for near-term Soviet weapons may differ from those which would be "best" for near-term U.S. weapons. Cf. N.N. Sobolev and V.V. Sokivikov, "The Carbon Monoxide Laser: Review of Experimental Results, " *Soviet Journal of Quantum Electronics*, vol. 2, Jan. -Feb. 1973, p. 305 ff.; M.M. Mann, "CO Electric Discharge Lasers, " *AIAA Journal,* vol. 14, No. 5, May 1976, pp. 549-567; A.A. Stepanov and V.A. Schlegov, "Continuous-Wave Reaction-Product Chemical Lasers (Review), Soviet *Journal of Quantum Electronics,* vol. 12, No. 6, June 1982, pp. 681-707; and S. Kassel, Soviet *Free-Electron Laser Research* (Santa Monica, CA: The Rand Corporation, report R-3259-ARPA, May 1985);

'*Dielectric breakdown is not as serious at optical wavelengths as it is at radio wavelengths. Scattering causes beam degradation, especially at short wavelengths, but is not insurmountably problematic in clear weather. Thermal blooming of a beam focused on a distant satellite can be controlled by phase compensation techniques, or by using a laser which operates at a wavelength at which atmospheric absorption is not severe. A deuterium fluoride laser, for example, operates at such a wavelength and future free-electron lasers could also operate at such wavelengths.

The effects of atmospheric turbulence also pose a serious problem for ground-based lasers: without compensation, the beam of a ground-based laser would diverge at so great an angle that it would be unable to damage anything other than the most sensitive earth-pointed optical sensors on satellites at geostationary altitude. Such compensation appears possible, in principle.

Another serious problem for ground-based lasers is the infrequency with which a low-altitude satellite would pass within view of a ground-based laser site. The interval between such passes might be days or weeks, and, until it exhausted its maneuver fuel, a maneuvering satellite could completely avoid coming within range. Deployment of a large number of ground-based lasers would provide more fre quent opportunities to engage satellites and would increase the difficulty and expense of evasive maneuver and of attempts to attack the laser sites. It would also increase the probability that a number of the lasers would not be overcast by impenetrable cloud cover. Of course, such proliferation would be expensive.

An alternative approach would be to base ASAT lasers on ships, which would have some flexibility to remain in clear weather near the ground tracks of high-priority targets and distant from most anti-shipping threats. Another solution to the coverage problem would be to deploy steerable reflectors on satellites to relay the beams from ground-based lasers to targets or to other relay satellites. The operational capabilities provided by such a system would be similar to those provided by space-based laser weapons with an unlimited power supply, except that beam availability would be contingent on the absence of overcast at at least one ground-based laser site and on the survival of both a ground-based laser and an orbital reflector.

A high-altitude satellite, on the other hand, would be within view of a ground-based laser site for a prolonged or indefinite period. For example, a ground-based laser could irradiate a satellite in geostationary orbit continuously, weather permitting.

High-Energy Laser Weapons and Electro-Optical Countermeasures (Space-Based)

The beams of space-based laser weapons would not have to pass through the atmosphere and could damage unhardened satellites at great range. A much smaller force of such lasers than would be required for effective ballistic missile defense could pose a threat to a nation's most critical satellites. However, space-based laser weapons, like other satellites, would be subject to attack by ASAT weapons.

Several types of lasers could be used as space-based laser weapons, each having some particuhu- advantage. For example, of those lasers which could damage satellites by overheating them, hydrogen-fluoride chemical lasers are particularly attractive because of their simplicity, while carbon-monoxide electric-discharge lasers are attractive because of their potentially high electrical efficiency. Free-electron lasers are attractive because they can operate at short wavelengths at which small beam divergence angles can be achieved using small mirrors. Excimer lasers would be bulky and less suitable for space basing.

Space-based lasers of very low power, if of an appropriate wavelength, could dazzle or permanently blind optical sensors used by other weapons for homing guidance or for beam pointing. More powerful lasers could be used to attack and damage a satellite by overheating it and possibly melting its "skin," or tearing its "skin' as a result of the hammer-like mechanical impulse which pulsed laser radiation can generate on a target surface.[49]

[49]The amount of mechanical impulse which a given amount of beam energy can generate can be estimated on the basis of published impulse-coupling models, such as that of P.E. Nielson, "High-Energy Laser-Matter Coupling in a Vacuum, " *Journal of Applied Physics*, vol. 50, No, 6, June 1979, pp. 3938-3943, modified to account for the depth to which the beam radiation will penetrate before surface vaporization begins. In *Directed Energy Missile Defense in Space* IOTA Background Paper OTA-BP-l SC-26, April 1984], Dr. Ashton Carter estimated that a laser beam fluence of 20 kilojoules per square centimeter would produce an impulse intensity of 10 kilotaps [10,000 dyne-seconds per square centimeter], i.e., an impulse coupling of 0.5 dyne-seconds per joule. This estimate assumes that the laser pulse is so brief that little heat is conducted to a depth greater than

Spacebased reflectors could relay beams from ground-based lasers to a target, or another reflector, beyond the horizon. These could be used in much the same manner as space-based lasers and would be, in effect, space-based lasers with an unlimited fuel supply.

All of these weapons have certain disadvantages, however. They would use large, expensive, power-handling mirrors; they would engage targets sequentially, thus giving other enemy satellites time to use reactive passive countermeasures (e.g., smoke); and they would be subject to attack by expendable, singleshot weapons (INW, KEW, or DEW) against which reactive countermeasures and shoot-back would be ineffective. Hence space-based lasers which can damage one or several targets instantly, without warning, using a single pulse and which are cheap enough to be considered expendable, if feasible, would be most attractive. Because they would exhaust their fuel or destroy themselves as soon as they were used, they would be invulnerable to shoot-back although subject, and possibly vulnerable, to preemptive attack.

One type of laser which might be useful as an expendable, single-shot, space-based weapon is the X-ray laser. X-ray lasers are presently only in the earliest stages of development.[50] X-ray lasers (also called "x-rasers" or XRLS) could be very simple in design; they might be thin fibers of lasing material powered ("pumped") by intense, pulsed radiation from another laser, a nuclear explosion, or some other source. The beam from such a device would diverge at an angle roughly equal to the square root of its wavelength divided by the square root of the length of the fiber.[51]

The U.S. Department of Energy is investigating the feasibility of developing nuclear-pumped X-ray laser weapons. Nuclear explosive pumping is of interest because even if only a small fraction of the energy of a nuclear explosion could be converted into X-ray laser beams, it could still be lethal at great range. Most details of this research, except for the fact of its existence, are classified. However, the U.S. Department of Energy has stated that:

1. The U.S. Department of Energy is interested in and is conducting research on certain types of nuclear explosive powered directed-energy weapons (NDEW)–viz., X-ray lasers, visible-light weapons, microwave weapons, and charged-particle beam weapons—as well as on nuclear explosive powered kinetic-energy weapons (NKE W).
2. Underground nuclear tests at the Nevada Test Site have been and continue to be a part of this research.
3. NDEW could engage multiple targets using multiple beams, providing high leverage.
4. NDEW could damage targets at ranges of thousands of kilometers.
5. Nuclear explosive powered X-ray laser weapons would damage targets by means of ablative shock.

the depth to which the beam radiation will penetrate before surface vaporization begins. Longer pulses can produce a much greater impulse coupling. For example, an impulse coupling of 20 dyne-seconds per joule has been measured in experiments using infrared lasers [P. Bournot, et al., "Mesure de la Pression Induite sur une Cible Metallique par une Laser CO_2 Impulsionnel," *Journal de Physique,* Tome 41, Suppl. au No. 11, Colloque C9, Novembre 1980, pp. 81-86].

[50] Successful operation of an X-ray laser was claimed by a Lawrence Livermore National Laboratories group headed by Dennis Matthews at the meeting of the Division of Plasma Physics of the American Physical Society in Boston on October 29, 1984. Their laser operated at two wavelengths near 20 nanometers. The design of the laser is described by D.L. Matthews, et al., in "Demonstration of a Soft X-Ray Amplifier," *Physical Review Letters,* 54:110-113, *1985.* More recently, the U.S. Department of Energy has stated that the nation's nuclear-weapons laboratories conducted an underground test of a nuclear explosive powered X-ray laser at the Nevada Test Site laser and achieved lasing [see note 52, infra].

[51] Provided the square of this angle is greater than twice the cross-sectional area of the fiber divided by the square of its length. For example, a thin, one meter long XRL operating at a wavelength of 20 nanometers would produce a beam with a divergence angle of 100 microradians. This divergence angle is large compared to those achievable by lasers operating at longer wavelengths at which mirrors can be used, and only a small fraction of the energy in a beam diverging at such an angle would would be intercepted by a satellite-sized target, at a range of thousands of kilometers. X-rays cannot be focussed using conventional lenses and mirrors, but they can be focussed using diffraction gratings and other special optical elements [R. W. Waynant and R.C. Elton, *Proceedings of the IEEE, vol. 64, No. 7,* July 1976, pp. 1059-1092]. Such techniques may be useful for generating X-ray laser beams of very high brightness.

6. Lasing by a nuclear explosive powered X-ray laser has been demonstrated in an underground nuclear test at the Nevada Test Site.[52]

Weapons powered by nuclear explosions would have several disadvantages compared to nonnuclear weapons: nuclear explosives are banned from orbit by the Outer Space Treaty [53], they would require elaborate, costly, and time-consuming command and control arrangements under present U.S. policy, they would be useful only at the nuclear level of conflict or would signal escalation to that level, and they might disrupt radio propagation and damage allied and neutral satellites when used, depending on burst times, locations, and details of weapon design. For these reasons there is also interest in developing expendable, single-pulse non-nuclear laser weapons, if these should prove feasible and economical. Such lasers might operate at short X-ray and gamma-ray wavelengths[54] or at longer wavelengths (e.g., iodine lasers). Non-laser sources of singlepulse directional radiation may also be useful as weapons.

Neutral Particle Beam Weapons

Powerful particle accelerators similar to those used for scientific research, isotope production, and fusion power applications could be used as particle-beam weapons to attack satellites. Because electrically charged particles would travel along spiraling paths within the Earth's magnetic field, electrically neutral particles such as atoms of hydrogen, deuterium, tritium, or heavier elements would be used by such weapons. Because such atoms would become ionized and hence charged if they passed through matter as dense as the upper atmosphere, such weapons must be based in space and are useful only against targets in space, although relatively small weapons of this type could be kept on the ground ready for launch into orbit and, after some on-orbit testing and calibration, for use.

A neutral particle beam (NPB) weapon might consist of a negative ion source, a particle accelerator, beam focusing and pointing magnets, and a "stripping" device-e. g., a gas ce11[56]—which strips the negative ions of their extra electrons, thereby neutralizing them, as well as a power source and other ancillary equipment,[58] as shown in figure 4-11. These components could resemble those presently in use for other purposes and need not be much larger to provide a modest ASAT capability. For example, the hydrogen atoms produced by an accelerator at the Los Alamos Meson Physics Facility (LAMPF) have energies of 800 million electron volts" (MeV) and could

'*On January 14, 1983, in the first official public discussion of U.S. research on nuclear explosive pumped X-ray lasers, the Presidential Science Advisor, Dr. George Keyworth, suggested that such lasers might eventually be of great military significance, and he called the "bomb-pumped X-ray laser' program "one of the most important programs that may seriously influence the nation's defense posture in the next decades. " [Quoted by William J. Broad, in "Reagan's 'Star Wars' Bid: Many Ideas Converging, " New *York Times,* Mar. 4, 1985, p. Al ff.]. Subsequently, Major General William W. Hoover, USAF (Ret.), Assistant Secretary of Energy for Defense Programs, elaborated on the U.S. nuclear directed-energy research, saying that the nation's nuclear-weapons laboratories conducted an underground test at the Nevada Test Site of an X-ray laser and achieved lasing. More recently, the Department of Energy has released the other statements quoted here.

[53]Some have, however, questioned this interpretation, arguing that the intent of the Outer Space Treaty was to ban weapons of mass destruction from orbit, not ASAT or BMD weapons which would cause minor collateral damage, if any.

"One concept for a short-wavelength X-ray laser envisions using a very brief and intense laser pulse to stimulate coherent, collective radioactive decay of nuclei which have been energized by exposure to neutrons in a reactor [C.B. Collins, et al., "The Coherent and Incoherent Pumping of a Gamma Ray Laser with Intense Optical Radiation, *Journal of Applied Physics,* vol. 53, No. 7, July 1982, pp. 4645-4651]. Recent experimental results [B. D. DePaola and C.B. Collins, "Tunability of Radiation Generated at Wavelengths Below 1 A by Anti-Stokes Scattering from Nuclear Levels, " *Journal of the Optical Society of America B, vol.* 1 December 1984, pp. 812-817,; C.B. Collins and B.D. Paoli, "Observation of Coherent Multiphoton Processes in Nuclear States, " *Optics Letters, vol.* 10, January 1985, pp. 25-27] have verified that some of the problems of developing such a laser can be solved. However, it is not yet known whether nuclei suitable for use in such a laser exist.

[55]T.D. Hayward, et al., Negative *Ion Beam Processes,* Los Alamos National Laboratory, report UC-34c, January 1976, UNCLASSIFIED; J. H. Fink, "Photodetachment Technology," American Institute of Physics, *Conference Proceedings No.* 111, pp. 547-560, 1984; V. Vanek, et al., "Technology for a Laser Resonator for the Photodetachment Neutralizer,' American Institute of Physics, Conference Proceedings No. 111, pp. 568-584, 1984.

[56]K. Boyer, "Directed-Energy Beam Weapons, " *Proceedings of the Society of Photo-Optical Instrumentation Engineers,* Volume 474, 1984, pp. 79-86.

[57]The electron volt (eV) is a unit of energy; about 6.25 quintillion electron volts equals one joule, the Systeme Internationale unit of energy.

Table 4-3.—A Comparison of Laser Weapons

	Space-based laser (single-pulse)	Space-based laser (repetitive pulse or continuous wave)	Ground-based laser	Ground-based laser and space-based reflectors
R				
	N			

F gu e 4 A s s Concep o a Neu a Part c e Beam Weapon

penetrate aluminum shielding 1 meter thick. The hydrogen atom beam produced by this accelerator has a current of 1 milliampere; irradiation of an unhardened satellite at a range of 40,000 kilometers for several minutes by a beam of this current and particle energy could upset the functioning of its electronic circuits.

A turboalternator-powered NPB weapon might require about 25 tons of liquid hydrogen, liquid oxygen, tankage, and other "overhead,"[58] to deliver an absorbed dose of 10 kilograys[59] through shielding at a range of 40,000 kilometers, regardless of the thickness of the shielding, provided that maximum shield thickness is known or assumed in advance and that the weapon is designed to penetrate a shield of such thickness.[60] An absorbed radiation dose of about 10 kilograys would permanently damage most radiation-resistant high-density silicon integrated circuits. Many existing and planned spacecraft use, or will use, high-density integrated circuitry with a radiation hardness three or four orders of magnitude lower.[61] Ten times this mass–250 tons–would be required to damage circuits hardened to withstand 100 kilograys, at this range.[62] On the other hand, only 1.6 tons would be required to damage such circuits at a range of 1,000 kilometers, and perhaps as little as a kilogram would suffice to upset or damage integrated circuits of existing hardness levels at a range of 1,000 kilometers.

Although it may prove possible to harden high-density electronics to withstand 10 kilograys without suffering permanent damage, it is unrealistic to expect that all satellites will be hardened to that extent; transient upset of electronics, possibly causing memory loss in computers, could occur at doses several orders of magnitude lower. Hence a neutral particle beam weapon could attack not only satellites, but decoys for satellites presumed subject to upset, using very little fuel and overhead—e.g., 250 kilograms to deliver a dose of 10 grays at a range of 40,000 kilometers (the distance from low orbit to geosynchronous orbit).

According to some estimates, a NPB weapon with sufficient fuel to operate for 1,000 seconds must weigh about 4 tons per megawatt of beam power[63] The U.S. Space Shuttle, or its expected Soviet counterpart, could deploy into low orbit a NPB weapon weighing as much as 30 tons [see figure 4-12].[64] A heavier weapon could be launched into low orbit by the anticipated Soviet heavy-lift launch vehicle, which is expected to carry payloads as large as 150 tons. Even heavier weapons could be assembled in space by the United States or the Soviet Union.

A neutral-particle beam could be made to diverge at a small angle and would therefore

‘*Such as fuel for propulsion of the extra weapon fuel, oxidizer, coolant, and tankage.

[59]A gray (Gy) is the Systeme Internationale unit for absorbed energy dose. One gray is one joule per kilogram, or 100 rads. One kilogray is a tenth of a megarad.

[60]A hydrogen atom having a kinetic energy of 50 MeV could penetrate about a centimeter of aluminum shielding. If the thickness of the shield were increased, particle energy, and hence also weapon size, would have to be increased in order to penetrate the shielding, but the amount of beam energy and weapon fuel required need not increase. The *reason* for this is that as particle energy is increased, beam divergence can be decreased, and the same number of particles per unit area per second could be delivered (over a smaller area) with a lower total beam current (particles per second). Hence a high-energy, low-current weapon could penetrate thicker shielding and deliver the same radiation dose in the same time over a smaller cross-sectional area of a target than could a lower-energy, higher-current weapon of equal beam power (which equals particle energy times beam current).

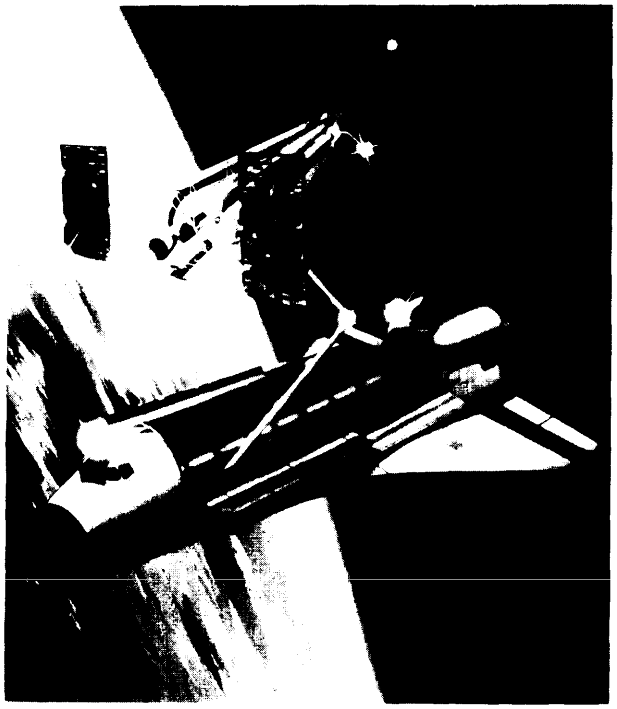
[61]Doses of 100 grays would probably upset electronic circuits on most satellites. It would be possible to shield such circuits, but the shield mass required would increase more rapidly than would the mass of a weapon which could penetrate it. On the other hand, it is possible to fabricate integrated circuits capable of withstanding radiation doses as high as 100 kilograys.

[62]Low-density gallium arsenide circuits which can withstand 100 kilograys have been fabricated, as have higher-density silicon circuits. For example, the Sandia National Laboratories of the U.S. Department of Energy has fabricated a pin-for-pin equivalent of the Intel Corporation's 8085 8-bit microprocessor chip which can function after absorbing a 100-kilogray dose of gamma radiation and can withstand single-event upsets caused by 140 MeV particles. Sandia plans to fabricate a 32-bit silicon microprocessor chip hardened to withstand 10 kilograys.

"E. g., see K. Boyer, "Directed-Energy Beam Weapons, " Proceedings of the Society of Photo-Optical Instrumentation *Engineers*, Volume 474, 1984, pp. 79-86.

"U.S. Department of Defense, Soviet *Military Power*, 3d cd., 1984, p. 44.

Figure 4-12.—Artist's Conception of the Space Shuttle Deploying a Neutral Particle Beam Weapon



SOURCE U S. Department of Energy, Los Alamos National Laboratory

have a relatively small diameter even at great distances-e. g., 40 meters diameter at a range of 40,000 kilometers. A beam this small must be pointed at a target with an accuracy of about 1 microradian, and this presents a more difficult problem in the case of a neutral particle beam than in the case of a continuous-wave or repetitively pulsed laser. The tracking and pointing systems of such lasers can quickly sense reflected beam energy from targets and thereby determine whether their beams are actually on target. However, a target would emit very little radiation when irradiated by a neutral particle beam. Sensors within several hundred kilometers of a target might be able, during NPB irradiation, to detect enough x-radiation or garoma or other radiation from the target to determine that the target had been hit, but it could not detect such radiation fast enough to correct beam pointing errors based on its presence or absence.

A neutral particle beam weapon could acquire (i.e., detect) a target using a passive long-wavelength infrared (LWIR) sensor; it could then track the target using an active optical tracker (LIDAR) and use this tracking information to determine the angle at which its beam must be pointed at the target. However, this approach only guarantees that the optical tracker is pointed at the target and cannot directly sense whether the beam itself is pointed at the target. That is, open-loop pointing must be used for neutral particle beams, while more accurate closed-loop pointing can be used by lasers. Determining whether open-loop pointing of a neutral particle beam can be done with an accuracy comparable to beam divergence angles may require testing of neutral particle beam generators in space against instrumented targets.

Aside from these difficulties of pointing and kill assessment, neutral particle beam weapons are among the most promising near-term options for nonnuclear ASAT weapons because of the maturity and demonstrated performance of their component technologies and the relative diseconomy of hardening targets against neutral particle beams. However, neutral particle beam weapons, like other space-based sequential-fire weapons, would be subject to attack by single-shot weapons against which shoot-back and other reactive countermeasures would be ineffective. They would have little operational effectiveness unless their survivability can be assured.

It appears, then, that if accurate open-loop beam pointing can be demonstrated, it will be feasible to build neutral particle beam weapons which, if deployed in low orbit, would pose a serious threat to satellites in low and high orbit. Against this threat only shoot-back would be economical for protecting low satellites, while hardening and deception might pro tect high-altitude satellites at low relative cost. At close range (1,000 kilometers), neutral particle beam weapons could damage satellite electronics of current hardness levels and upset harder future satellite electronics using relatively little fuel and tankage (etc.)—probably about 1 kilogram per shot. The cost per shot at a satellite hardened to this level, or at a decoy simulating such a satellite, would be very cheap relative to the cost per satellite or decoy. Hardening satellite electronics would increase the cost per shot, although probably not to the cost of the smallest satellites or precision decoys: damaging high-density electronics hardened to the greatest extent now foreseeable would require about 160 kilograms per shot.

Such weapons, if encountered, could place low-altitude satellites at risk at relatively low cost. They could also upset or damage unhardened electronics on satellites in synchronous orbit, from low orbit, using little mass per shot (e.g., 25 kilograms for a dose of 10 grays); however, hardening high-density electronics on such satellites to 10 kilograys and using upset-tolerant circuit design could increase the mass requirement for damage to perhaps 25 tons per shot and would increase required irradiation time enough to permit use of reactive passive countermeasures such as generation of smoke or deployment of reaction decoys. Shielding satellites-as distinct from hardening their electronics-would be economically unfavorable against larger weapons: a disproportionately small increase in weapon mass, with no increase in mass per shot, could compensate for an increase in shield mass.

POSSIBLE U.S. RESPONSES TO SOVIET ASAT CAPABILITIES

How might the United States respond to increasingly threatening Soviet A SAT capabilities? Several options are available. For example, an increase in U.S. ASAT capabilities might—but would not necessarily-be an appropriate response. Although useful for attacking Soviet MILSATS, they might be unable to protect U.S. MILSATS. Other possible responses include reduction of dependence on military satellites, augmenting U.S. combat forces (to offset possible loss of force enhancement as a result of an ASAT attack), use of passive or active countermeasures for defense or retaliation, and arms control efforts or other diplomatic initiatives intended to constrain foreign ASAT capabilities or reduce incentives to use them.

Reduction of Dependence on Military satellites

The United States routinely uses satellites to support its forces deployed worldwide to reinforce allies, protect sea lines of communication, and pursue other national interests. Routine use of satellites for such purposes has engendered a considerable degree of dependence on them. In the past, when satellites were less expensive and less vulnerable than other means to these ends, dependence on satellites was not risky. In the future, satellites may become so vulnerable that use, if possible, of more expensive but less vulnerable means of performing functions now performed by space systems may be required for adequate security.

Most functions now performed by space systems could be performed by alternative terrestrial systems, although terrestrial systems providing comparable performance of some functions would be unaffordable or politically unacceptable. Missile launch detection and space surveillance could be performed by airborne optical sensors; navigation by advanced inertial navigation systems which can recognize local gravity gradient patterns, nuclear detonation detection by ground-based overthehorizon electromagnetic pulse (OTH EMP) sensors, and radio communications relaying by MF ground-wave, HF ground-wave and sky-wave, VHF meteor-burst, UHF tropospheric scatter, and UHF/SHF/EHF and lightwave airborne repeaters. Reconnaissance could be performed in wartime by aircraft overflight at great expense and risk.

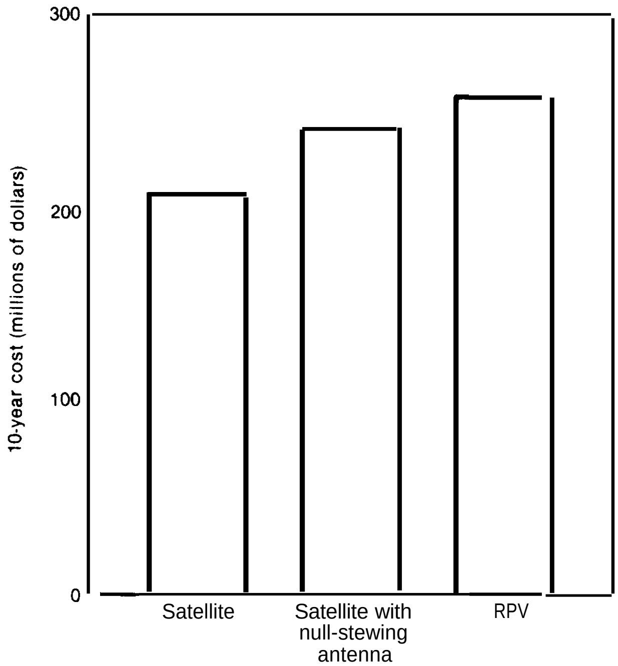
On the other hand, the kind of information presently collected by satellites in peacetime to monitor compliance with arms control agreements cannot be obtained by other means which are acceptable in peacetime. Unauthorized aircraft overflight, for example, would be unacceptable. However, arms control treaties—like other treaties except those defining "laws of war' '-are suspended during war between parties, so a survivable space-based means of performing this function is not required.

Although alternative terrestrial systems for performing some functions may be infeasible or very expensive, alternative terrestrial systems for performing other functions may be only slightly more expensive than space systems. For example, providing intra-theater single-channel UHF communications to mobile ground elements in the 1980s by means of satellite communications transponders would be less expensive than use of remotely piloted vehicles (aircraft) carrying transponders, but only slightly so [see figure 4-13]; a slight increase in satellite vulnerability would make the costs favor use of RPVS. Whether alternative terrestrial systems are worth their cost depends on the function to be performed and is a matter of judgment deserving periodic reconsideration.

Force Augmentation

As satellites have been acquired and integrated into military systems, they have presumably increased the effectiveness of force elements which would engage in direct combat, so that each such force element can now fight as well as, say, one and a half could without MILSAT support. Having become dependent on satellite support, if suddenly deprived of that support the effectiveness of a force element would be reduced, not just to that of a force element unaccustomed to such support but probably more so because of the disorganizing effect of losing sources of information it had come to count on. Nevertheless, it is possible, in principle, to augment current forces so that in the event of sudden loss of MILSAT support, larger future forces, although impaired in effectiveness, would fight as well as or better than would current forces using satellite support. The force augmentation required by this criterion might, under some circumstances, be modest.

Figure 4-13.—Cost Comparison: Satellite and RPV R-clays for Single-Channel UHF Tactical Theater Communications



Passive Countermeasures

"Passive" countermeasures against ASAT capabilities include hiding, deception, maneuver, hardening, electronic countermeasures and electro-optical countermeasures, and proliferation, as well as combinations of these measures [see table 4-4]. Some of these countermeasures—e.g., hardening-are truly passive, requiring no satellite activity for their effectiveness, while others—e.g., evasion—require satellite activity–and hence attack warning-and are not truly passive, although they are nondestructive.

For expository purposes it is convenient to discuss each type of countermeasure in isola-

Table 4-4.— Passive Countermeasures Against ASAT Attacks

Hiding
- e.g., satellite miniaturization and orbit selection

Deception
- e.g., deploying lightweight decoys

Maneuver
- e.g., evasion

Hardening
- e.g., use of shielding

Electronic countermeasures and electro-optical countermeasures
- e.g., use of shorter wavelengths and more highly directional antennas

Proliferate ion
- e.g., of on-orbit spare satellites

tion from the others in the context of a one-against-one ASAT attack, as will be done here. However, it is anticipated that such countermeasures, if used, might be used in combination in the context of a many-against-many (i.e., force-against-force) space battle. It is in such a context that the potential effectiveness of a countermeasure should be assessed. However, the number and complexity of possible contexts precludes any attempt at assessment of countermeasure effectiveness from being exhaustive or conclusive.

Hiding

"Hiding" measures are measures taken to evade detection by surveillance systems. In some sense the effective use of hiding, if feasible, would be most desirable, because it would eliminate the need for other countermeasures, all of which require increases in on-orbit mass in the form of decoys for deception, fuel for evasion, shielding for hardening, or spares for proliferation.

Different hiding measures are required against different types of surveillance sensors. Space surveillance systems may be of two types: active and passive. Active sensors irradiate a target with electromagnetic radiation in order to "see" it, while passive sensors look for electromagnetic radiation emitted by the target or reflected by the target from natural sources, e.g., the Sun. At optical wavelengths (infrared, visible, and ultraviolet), both active sensors (LIDAR) and passive sensors may be used[Gb] In general, passive optical sensors on satellites in low Earth orbit maybe able to detect satellites as small as a meter in diameter at altitudes between a few hundred kilometers and geosynchronous altitude.

Passive LWIR and visible light sensors can work better in combination than either can alone. For example, painting a satellite black would prevent it from reflecting sunlight and thereby make it invisible to passive visible light sensors. However, painting a satellite black would cause it to absorb more solar radiation and become hotter. In thermal equilibrium it would emit more LWIR radiation, making it detectable at greater range by a passive LWIR sensor [see box entitled "Long-wave Infrared (LWIR) Space Surveillance Sensors"].

Operating a satellite at very low altitude can make it difficult to detect using space-based infrared sensors which must view it against the radiant Earth or Earth limb background. More satellites would be required to perform a given function at lower altitude, and user equipment might also have to be more complex and expensive.

Deception

The use of decoys to induce an enemy to waste firepower on false targets-or to withhold fire for fear of doing so–can always be made effective, if the decoys are sufficiently realistic, i.e., "credible" to enemy space surveillance systems. A decoy can always be made credib~e at a cost less than or equal to that of the satellite it mimics, because a spare satellite could be used as a decoy, and it would be preferable to do so rather than spend as much on a nonfunctional decoy. The critical question is whether a decoy can be made credible at a much lower cost than that of the satel-

[65]In most cases passive sensors are preferable to active sensors because they do not require a high-power radiation source for irradiating targets, they are themselves consequently more difficult to detect, and their effective range can be increased more economically, because a twofold increase in range to a target decreases the irradiance received by a passive sensor only fourfold as compared to sixteenfold in the case of an active sensor.

Long-Wavelength Infrared (LWIR) Space Surveillance Sensors

The following discussion describes the physical basis for the estimated detection capabilities of passive LWIR sensors and for the ineffectiveness of hiding measures against them.

Every object emits electromagnetic radiation as a result **of** thermal processes; the amount of power emitted by an object increasesin proportion to its surface area and would increase sixteanfold if its temperature were doubled. A satellite at a typical operating temperature-about 300° K—emits most of its thermal radiation at a wavelength of about 10 microns [10 millionths of a meter], which is in the LWIR portion of the electromagnetic spectrum. The wavelength at which thermal radiation is most intense varies in inverse proportion to the temperature of its source; thus the surface of the Sun-which has a temperature of about 6,000° K-emits thermal radiation (sunlight) which is most intense at a wavelength of 0.5 microns, a wavelength in the visible portion of the electromagnetic spectrum Passive optical sensors which can detact LWIR radiation can detect the thermal radiation emitted by satellites, while those sensitive to visible radiation are best suited for detecting sunlight reflected by satellites. Visible light sensors are preferred for ground-based space surveillance systems because LWIR thermal radiation is absorbed strongly by the lower atmosphere, although LWIR telescopes have been operated on mountain peaks and on aircraft.

Passive LWIR and visible light sensors can work better in combination than either can alone. For example, painting a satellite black would prevent it from reflecting sunlight and thereby make it invisible to passive visible light sensors. However, painting a satellite black would cause it to absorb *more* solar radiation and become hotter.[x] In thermal equilibrium it would emit more LWIR radiation, making it detectable at greater range by a passive LWIR sensor. Conversely, making the satellite surface highly reflective would reduce its absorptivity and hence also its emissivity, which equals the absorptivity at each wavelength; this would make the satellite less visible to passive LWIR sensors.

Passive optical sensors may be designed to detect targets within view above the horizon (ATH) or below the horizon (BTH). BTH detection is more difficult than ATH detection, and the image processing required by BTH sensors is more complicated than that required by ATH sensors. ATH sensors are therefore preferred for passive optical space-based surveillance systems.

Space-based LWIR ATH sensors could not eady detect satellites which orbit at altitudes so low that they are actually within the upper atmosphere. Satellites at such low altitudes would be in the "Earth limb" as viewed by a space-based LWIR ATH sensor, which would have to view the satellite just above the horizon through a thick layer of air which would absorb much LWIR radiation and which would emit, reflect, and scatter LWIR background radiation against which the satellite would have to be viewed. Satellites at such low altitudes would experience considerable atmospheric drag and would slow down and reenter the atmosphere sooner unless they amid maneuver and carried enough fuel to compensate for the drag. Operating in such an altitude regime to evade detection by space-based LWIR ATH ***sensors*** would also impose operational penalties in some cases. For example, surveillance satellites could not "see" as far from lower altitudes.

Required image processing sophistication would be more difficult for general surveillance than for warning of interception of the satelllite carrying the sensor. This is because the spot of focused radiation from an interceptor approach ing a satellite-borne sensor "staring" at the celestial background in the direction of the approaching interceptor would not move on the sensor's focal plane, and a single detector element of the sensor could accumulate thermal radiation from the interceptor until sufficient energy for detection has been accumulated. By contrast, the spot of focused radiation from an interceptor traveling in some arbitrary direction would move on the sensor's focal plane, limiting the time available to a detector element for accumulating image energy.

'**S. Sternberg** and **V.P.** 141am **"Satellite Systems"** @h. 17), **R.E. Machol (ed.),** ***Systems Engineering Handbook*** *(New* York: **McGraw-Hill**, 1965).

If the target's angular position and velocity is approximately known by other means, the number of photons received by each detector **element over** which the target's image is expected to move could be added in order to accumulate image photons and average out the noise photons. However, if the target's angular position and velocity is not known accurately by other means, the number of possi ble averages which must be calculated in this way to detect the target reliably increases very rapidly with increasing uncertainty about target position and velocity, and the required mass of image-processing hardware required will increase correspondingly.

A low-orbit LWIR space surveillance satellite with a 1 meter nonemissive primary mirror and a focal plane detector army cooled to 77° K could detect a black-painted satellite 1.5 meters in diameter at a range of 35,000 kilometers using a l millisecond integration (energy accumulation) time. In one millisecond the image of a small satellite at geosynchronous altitude would move across the face of a detector element the size of the telescope's "spot size," if the teb scope were on a satellite at 1,000 kilometers altitude and "Stared" **Continuosly** toward the zenith. It would be feasible and affordable, but costly (several billion dollars), to deploy a constellation of satdlites of this performance which stare continuously in all directions above the horizon. Even smaller objects could be detected at greater range using a larger primary mirror, or-less economically in the limit-more image-processing hardware.

lite it mimics, as well as cheaper than an enemy's cost to identify it (e.g., by dispatching a coorbital interceptor to observe it at close range) or to attack it in a manner which would negate the satellite it simulates. This critical question remains unanswered.

Before any of these costs can be estimated, the designs of decoys and enemy surveillance and weapon systems must be specified. Many design choices are available. For example, for the same amount of money, a few highly realistic decoys (called "precision decoys" or "replica decoys") could be built, or a much larger number of less realistic but less expensive decoys could be built. A "precision" decoy designed to simulate an on-line satellite would probably have to simulate attitude control, stationkeeping, signal transmission, power generation and heat dissipation, and other observable functions and properties. The subsystems required to do this would be relatively expensive. If such decoys could not be distinguished from actual satellites, all such decoys would have to be attacked in a manner which would damage the satellites they simulate.

Alternatively, inexpensive "traffic" decoys could be made to simulate only those features of a capital satellite which might be measurable cheaply, quickly, and remotely. Reflective balloons or clouds of smoke and chaff could be used as "reaction decoy s," i.e., they could be deployed in reaction to warning of an impending attack." Even if such decoys could deceive an enemy for only a limited period of time, they could be effective in some situations. However, reaction decoys offer no protection against single-shot ASAT weapons (e.g., "space mines") which can destroy satellites almost instantly before reaction decoys can be dispensed. Ingeniously designed lightweight decoys might be both inexpensive and highly credible to passive remote sensors; whether they will be is uncertain.

[66]For example, a satellite under attack by a pop-up infrared-homing interceptor could dispense several lightweight decoys which resemble it, from a distance, in infrared brightness temperature and color temperature. If the interceptor cannot distinguish such decoys from the capital satellite until it has flown past, then the decoys would be adequately "credible." *Because* satellite mass cannot be measured both quickly and inexpensively, cheap, lightweight decoys could be effective as reaction decoys.

Even if lightweight decoys cannot be recognized as such after prolonged remote passive observation, it might be possible to recognize them using directed-energy devices.[87] However, use of directed-energy devices in such a manner might be provocative in peacetime and possibly more expensive than the cost of lightweight decoys.

If lightweight decoys cannot be distinguished from actual satellites, all such decoys would have to be attacked, although not necessarily in a manner which would damage the satellites they simulate, because the cost of attacking and observably damaging a lightweight decoy with some types of A SAT weapons could be comparable to, or smaller than, the cost of attacking a decoy in a manner which would damage a satellite which it simulates. For example, ground-based lasers might be able to attack lightweight decoys inexpensively. Neutral-particle beam weapons could also be used to attack decoys at long range, as could singlepulse lasers, although less economically.

The large number of possible designs for decoys and enemy surveillance and weapon systems renders assessment of the cost-exchange ratios[W] of future systems infeasible at this time. Furthermore, even if the decoy design were specified, it would be difficult to estimate decoy costs accurately. Rough preliminary estimates of satellite cost and of uncertainty in satellite cost are sometimes derived from estimates of satellite subsystem mass and complexity. However, analysis of historical cost data reveals considerable variation in satellite cost for satellites of comparable small mass.[og]

Deception is more advantageous when used in combination with other passive measures such as hardening and proliferation. For example, dormant spare satellites can be hardened and made to resemble cheaper decoys.

These considerations lead OTA to conclude that the question of whether decoys can be made credible at a much lower cost than that of the satellites they mimic or than an enemy's cost to identify them or to attack them in a manner which would negate the satellites they simulate remains unanswered, and that answering this question is essential in any attempt to assess prospects for making future satellites adequately survivable. An affirmative answer will probably require detailed designs for decoys which are inexpensive and lightweight as well as credible to possible future Soviet surveillance systems.

Maneuver

Satellites may maneuver in order to complicate enemy surveillance and targeting and to evade enemy fire. Satellites which do not *maneuver are* nevertheless unavoidably *mobile,* although in fixed orbits. Because of this property, the relation of maneuver to attrition is different in space than on land or at sea, and proximity in terms of orbital elements (e.g., apogee, perigee, inclination, etc.) has as much tactical significance as does momentary proximity in space. A maneuver, loosely speaking, is an action which changes a satellite's Keplerian orbital elements. Pursuit of another satellite and evasion of an interceptor are examples of maneuvers.

In order to continuously evade an interceptor—whether pop-up or coorbital-a satellite must have an acceleration capability and a ve locity change ("delta-V") capability about as

[67] **Referring** t. the **possibility** of active discrimination of decoys from ballistic missile reentry vehicles, Dr. **Gerold Yonas**, Chief Scientist of the Strategic Defense Initiative Organization, has written that "directed energy, even in a very early period, could be used in an interactive mode to assist in midcourse discrimination [**Gerold Yonas**, "Strategic Defense Initiative: The Politics and Science of Weapons in Space," *Physics Today*, June 1985, pp. 24-32; cf. remarks attributed to Dr. **Yonas** in **E.J**. Lemer, "Star Wars: Part II–Survivability and Stability, " *Aerospace America*, vol. 23, No, 9, Sept. 1985, pp. 80-84].

[68] **The relevant cost-exchange** ratio is the **minimax cost-ex**change ratio, i.e., the ratio of decoy costs to Soviet **ASAT** sensor and weapon costs which would be incurred if decoys were designed to **minimiz**e the maximum cost-exchange ratio which the U.S.S.R. could subsequently force on the United States by judicious choice of **ASAT** sensor and weapon designs. The **cost**-exchange ratio of a specific future system is of questionable relevance, unless the system can be shown to have a **cost**-exchange ratio close to the **minimax** cost-exchange ratio.

[69] **There** has been less variation in cost per kilogram among satellites of large mass.

great as those of the interceptor, but somewhat more or less, depending on initial positions and velocities.'" Acceleration and delta-V can be maximized by minimizing the mission payload, so that a large fraction of the spacecraft initial mass is contributed by its engines (for acceleration) and fuel (for delta-V). Because an interceptor's payload can be quite small-perhaps comparable to that of a shoulder-fired anti-tank missile—an interceptor might have acceleration and delta-V capabilities which would be much more costly to provide to satellites with large mission payloads such as long-range directed-energy weapons. If so, it would be difficult for such satellites to evade small but sophisticated interceptors.

Hardening

For each type of ASAT weapon, there exist hardening techniques which can reduce the range at which the weapon would be effective. For example, satellites may be hardened to withstand the effects of ordinary, isotropic nuclear weapons by avoiding reliance on photovoltaic cells—which are vulnerable to weapon X-rays—for power, by using massive shielding to block gamma radiation, and by using Faraday shielding, magnetic shielding, and fault-tolerant electronic design to reduce vulnerability to system-generated electromagnetic pulse. Of course, such practices cannot protect a satellite from a nearby nuclear explosion, but they can force an attacker to expend at least one nuclear warhead per satellite and credible decoy to destroy them with confidence.

Shielding, or armor, of different types can offer protection against some types of projectiles, pulsed or continuous lasers, and neutral particle beams. Different types of shields would be required for protection against different types of ASAT threats. For example, shields could be used against projectiles, pulsed lasers, and neutral particle beams, respectively. For example, NASA developed shields to protect a Halley's Comet probe craft from 0.1 g meteoroids impacting at 70 kilometers per second. '1 Such shields could be all-aspect shields which completely surround a satellite, or they could be "shadow shields" deployed between the defended satellite and a weapon which poses a threat to it. Shadow shields could be deployed on a boom or they could be independent, "free-flying" satellites.

Shadow shields could be lighter than all-aspect shields, but a separate shadow shield might be required for each known or suspected threatening weapon. All-aspect shields would be superior to shadow shields in that they could defend a satellite from multiple sequential *or* simultaneous attack from any direction or all directions and from covert weapons and they would require no power or warning information for their operation.

Massive shields could also protect satellites from laser radiation and from neutral particle beams. Relatively little shield mass would be required **to** protect a satellite from beam of low-energy particles (i.e., those having energies of less than 50 to 100 MeV), but the shield mass required would increase sharply if particles of higher energy, produced by larger NPB weapons, were used.

Semiconductor microelectronic circuits inside satellites could also be made more resistant to ionizing radiation such as would be produced by a neutral particle beam. For example, the Sandia National Laboratories of the U.S. Department of Energy have fabricated a pin-for-pin equivalent of the Intel Corp. 's 8085 8-bit microprocessor chip which can function after absorbing a 100-kilogray dose of gamma radiation and can withstand single-event upsets caused by particles with energies as great as 140 MeV.

The use of asteroidal materials such as nickel for large, massive, all-aspect shields has been proposed. Possible advances in space mining, manufacturing, and transportation—which would require large investments-might

'"G. M. Anderson, op. cit.

[71]J.P.D. Wilkinson, "A Penetration Criterion for Double-Walled Structures Subject to Meteoroid Impact, " *AIAA Journal,* vol. 7, No. 10, October 1969, pp. 1937-1943.

someday make use of asteroidal material for such purposes cheaper than use of terrestrial material.[72]

These considerations suggest that, in general, shielding against weapons of relatively low capability is feasible and in many cases may be less expensive than the weapons against which it can offer protection. However, as weapons are made larger, more capable, and more numerous, the cost of protection against such weapons generally increases more rapidly than the cost of the weapons and and begins to exceed the cost of the weapons at some point.

Electronic Countermeasures and Electro-Optical Countermeasures

Passive electronic and electro-optical countermeasures can provide protection-analogous to "hardening"—against nondestructive ASAT measures. For example, communication links can be made increasingly resistant to jamming by using more transmitter power (which ultimately becomes uneconomical) or signal bandwidth (which is limited except at extremely high radio frequencies and optical frequencies), or–in some applications-by using larger antennas or shorter wavelengths for greater directionality of transmission and reception, or by transmitting at a lower data rate. Command encryption can prevent spoofing, and use of spread-spectrum modulation and time-division multiplexing techniques can provide significant resistance against uplink and downlink jamming and against downlink exploitation (e.g., by anti-radiation missiles).

Proliferation-Replenishment

Another countermeasure against ASAT attack is proliferation of satellites, so that even if a large fraction of the satellites were damaged by hostile action, enough undamaged satellites would remain to perform their assigned functions. The number of additional satellites needed to assure survivability of a required number of them would depend on enemy ASAT capabilities. The extra satellites could be placed in orbit or else kept on Earth to be launched into orbit after an ASAT attack to replenish those satellites destroyed by the attack.

Unless on-orbit spare satellites are also deployed, replenishment could not be relied on to maintain uninterrupted performance of satellite function, which is essential for such applications as early warning of missile attack and other strategic command and control functions. If it is cost-effective for an enemy to negate an operational satellite, it would probably be cost-effective for the enemy to negate replacements, if enemy ASAT capability survives. It would also be cost-effective for an enemy to maintain enough ASAT weapons or fuel to avoid exhaustion of ASAT capability before replenished satellites can be negated. Hence replenishment appears unattractive as a countermeasure unless enemy ASAT capability can be destroyed before replenishment is attempted, and unless the satellites to be replaced need not function without interruption.

Proliferation-On-orbit Spares

Spare satellites could also be pre-deployed in orbit, where they could remain dormant until needed or else be used routinely to provide redundant capability in peacetime. Dormant satellites would need to listen for radio commands to activate and might need to report their status occasionally but in general would require little power generation, cooling, attitude control, or exposure of antennas or other sensors while dormant and could be made harder than operational satellites. Their armor could have a simple shape easily mimicked by inexpensive decoys; hence proliferation of on-orbit spares would work more effectively in conjunction with hiding, deception, and hardening measures. However, an enemy which can negate an operating satellite might be able, by the same means, to negate an on-orbit spare once it became operational. Proliferating and simulating dormant spare satellites will not preserve the functioning of a constellation of

[72] C. Meinel, "Near-Earth Asteroids: Potential Bonanza for Ambitious Military Space Projects, " *Defense Science* 2003 +, February-March 1985, p. 40 ff.

satellites if the spares can be identified and negated quickly and cheaply after being brought "on-line." Hence the use of on-orbit spares would be most attractive if enemy A SAT weapons could be themselves negated soon after space combat begins.

Proliferation—Modularization and Segregation

Another form of proliferation is the partitioning of satellite subsystems into modules which can be segregated and deployed on different satellites. For example, the function of a high-capacity comsat could be performed by several small comsats which pass message "packets" to one another over radio or laser crosslinks.[75] Functions such as stationkeeping might be performed by maneuverable satellite "tenders, each of which could visit one satellite after another, adjusting their positions and velocities as needed. Segregation of subsystems would require forgoing economies of scale in peacetime in order to reduce vulnerability.

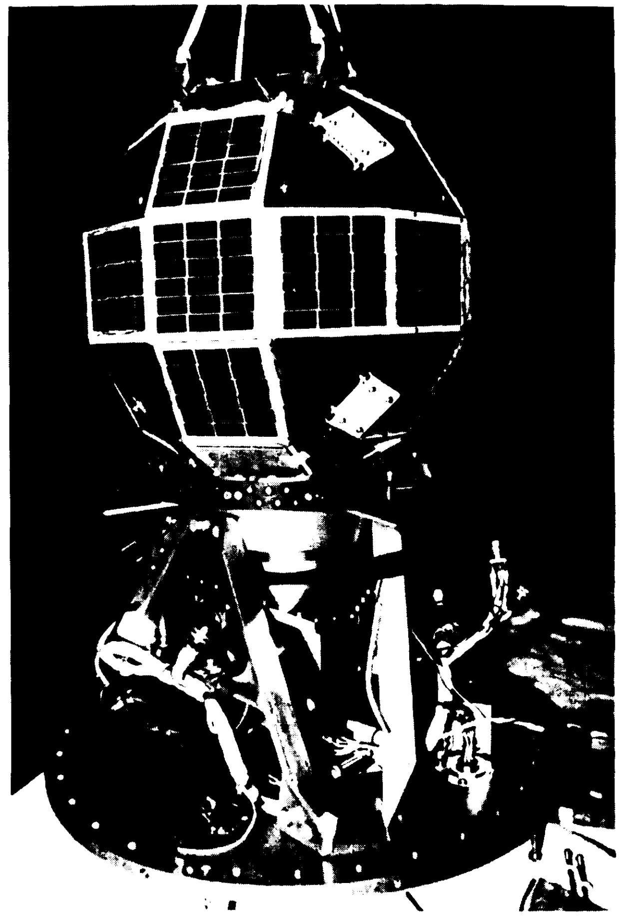
Combined Passive Countermeasures

Passive countermeasures work better in combination than individually. For example, use of decoys for deception would confer little protection against some (e.g., nuclear) A SAT weapons unless maneuver were used to disperse the decoys. It is therefore important to consider the effectiveness of "packages" of passive countermeasures against various ASAT capabilities, which can also supplement and complement one another and which should also be considered packages, or postures,

Active countermeasures could, and probably would, be used to complement passive countermeasures unless prohibited by a comprehensive ban on possession of ASAT weapons. Hence in hypothesizing ASAT threats to be countered by passive measures alone, it is appropriate to consider as threats only those capabilities which are unlikely to be banned or those which might be developed and deployed (or retained) covertly. The former in-

'-'The Defense Advanced Research Projects Agency (DARPA) is investigating the feasibility of a packet-switched network of transponders on low-altitude satellites, or on Earth,

Figure 4-14.— Low-Cost Packet-Switching Communications Satellite



The Global Low-Orbiting Message Relay Satellite (GLOMR), shown here, is designed to receive messages sent to It, store them, and relay them to ground facilities. The GLOMR program of the Defense Advanced Research Projects Agency (DAR PA) is intended to demonstrate that communications satellites operating in this manner can be produced at relatively low cost. If sufficiently Inexpensive, such satellites could be deployed at lower cost than the cost of attacking them with some types of ASAT weapons, and so many could be deployed that other weapons might require a long t!me to destroy most of them

SOURCE U S Department of Defense

elude nondestructive ASAT capabilities (e.g., ECM and E-OCM), and inherent ASAT capabilities of allowed weapons (e.g., ICBMS); the latter include the existing Soviet coorbital interceptor, direct-ascent and coorbital nuclear interceptors, space-based or pop-up X-ray laser weapons, and possibly ground-based lasers. Of these, the nuclear weapons might be based in space disguised as, or aboard, a different type o; satellite, the presence of which would be-observable but the nature of which might be impossible to ascertain except by prolonged close observation or invasive sensing techniques.[74] In general, nonnuclear space-based weapons could not be expected, with confidence, to perform well, unless they had been previously–and observably—tested in space.

Active Measures

Passive countermeasures against ASAT attacks may be supplemented by active measures intended to deter ASAT attack or to defend satellites if deterrence should fail. Active measures can therefore be used for either defensive or retaliatory purposes. Defensive active measures are *active countermeasures* against ASAT attacks. Retaliatory active measures do not counter ASAT attacks but instead fulfill explicit or implied threats of retaliation which were intended to deter ASAT attacks. Active measures used for either purpose can be either nondestructive (e.g., electronic countermeasures and electro-optical countermeasures) or destructive (e.g., shoot-back), as shown in table 4-5.

Defensive Countermeasures

Shoot-Back.–" Shoot-back" usually refers to counter-attacking spacebased ASAT weapons, but can also denote counter-attacks against the ground segment of A SAT weapon systems (e.g., satellite control facilities). Many weapons capable of shoot-back would themselves be subject to shoot-back, making the effectiveness of shoot-back highly dependent on the types and numbers of ASAT and other weapons deployed and on the incentives for preemptive attack which ASAT weapon vulnerabilities, if any, could create. Analysis of the effectiveness of shoot-back is therefore very complicated in general, although simple in certain important cases.

For example, shoot-back would be ineffective against expendable, single-shot space mines employing kinetic-energy, directed-energy, or nuclear destructive mechanisms. Such weapons would damage their targets almost instantly, if at all, and destroy themselves in the process, leaving nothing of value to shoot back at. Moreover, shoot-back using sequential-fire weapons which are vulnerable to attack by expendable, single-shot weapons would be ineffective, because they could be damaged by single shot weapons after attacking only one target. However, space-based single-shot ASAT weapons would themselves be subject to preemptive attack—i.e., "shoot-first" instead of "shoot-back." If such weapons were mutually deployed in space, if each such weapon could instantly destroy several similar weapons and if such weapons were not salvage-fused to fire if disturbed, the resulting preemptive advantage could cause a condition of "crisis instability, " in which each nation, desiring peace but fearing (perhaps mistakenly) an imminent attack by the other, would have reason to initiate hostilities.[75]

However, it is conceivable that even if such incentives should induce escalation from peace or low-level conflict to war in space, the preemptive ASAT attack which would begin such a war might reduce incentives for further escalation, either "vertically" (to higher levels of conflict) or horizontally (to other theaters of conflict, e.g., Earth). For example, if the United States and the U.S.S.R. continue to possess strategic offensive missile forces of considerable counterforce capability, and if each were to deploy a large BMD system

Table 4.5.—Active Measures Against ASAT Attack

Defensive measures:
Nondestructive
e.g., jamming
Destructive
shoot-back
attack on ground-based ASAT command and control facilities
Retaliatory measures:
ASAT counterattack (retaliation in kind)
Horizontal escalation (to terrestrial theaters)

[74] E. g., see U.S. Patent 4,320,298.

[75] See M.B. Callaham and F.M. Scibilia, *Proceedings of the Society of Photo-Optical Instrumentation Engineers,* vol. 474, 1984, pp. 107-114.

which relied on vulnerable space-based components, then each nation might fear that the other nation (also fearing a preemptive attack) might attack these BMD components preemptively with some confidence that its BMD system could limit damage from a retaliatory missile attack, if any. Each nation would therefore have an incentive to attack the other's space based BMD components preemptively. However, after having done so, the attacker would have no motive to launch a preemptive, damage-limiting missile attack, because it could assume that the other nation—now highly vulnerable to retaliation-would not seriously consider such an option. Hence, under these assumptions, escalation instability would exist during crises in peacetime (thus "crisis instability' but not at the level of war confined to space.

It might be supposed that the crisis instability which would accompany mutual deployment of such weapons could be eliminated by salvage-fusing them to fire if disturbed in certain ways (presumably indicative of an attack). If salvage-fusing were feasible and actually used (or believed to be used), there might be little incentive to fire first even if an attack were expected. However, salvage-fusing some types of weapons against some other types may be inordinately difficult or infeasible. Moreover, even though an "intelligent" salvage-fusing system might be able to distinguish among different types of disturbances, it could not be made completely reliable or infallible in discrimination, so there would be a risk that some natural disturbance (e.g., a meteoroid impact) might trigger such a weapon to fire, possibly at several similar enemy weapons, possibly triggering them to fire, etc. Similar consequences could follow an accidental attack or a "catalytic" attack by a third party. Moreover, if salvage-fused spacebased weapons only held an enemy's spacebased assets at risk, the prospect of losing such assets in retaliation for an attack might be considered an acceptable or favorable trade by a nation less dependent on space assets.

Regardless of whether salvage-fusing were employed, mutual deployment of singlepulse weapons would not be expected to create strong proliferation incentives: with mutual salvage-fusing each side could plausibly lose all its important space assets in such an exchange regardless of whether it had many such weapons or only a few deployed; it would therefore have no incentive to deploy more weapons than would be required to negate all threatening satellites *except* single-pulse ASAT weapons, against which neither preemptive attack nor shoot-back would be effective. Without salvage-fusing, the side which failed to preempt could plausibly lose all its important space assets in such an exchange regardless of whether it had many such weapons or only a few deployed, and would therefore gain nothing by deploying many weapons.

Electronic Countermeasures and Electro-Optical Countermeasures.–Active electronic and electro-optical countermeasures (jamming, blinding, and spoofing) could be used against some near-term ASAT command uplink systems, KEW homing systems, and DEW acquisition, tracking, and pointing systems which have inadequate counter-countermeasures.

Attack on Ground-Based ASAT Weapons or Support Systems.—At present there appear to be only two launch pads for Soviet coorbital interceptors, both at Tyuratam, and only two Soviet ground-based lasers of significant ASAT capability, both at Sary Shagan. Hence attacking such ground-based facilities with conventional or nuclear weapons could be very effective, especially if preemptive, but would be viewed by some in the United States as escalator with respect to attacking or defending satellites using nonnuclear weapons.

Retaliatory Measures

The ability to respond to ASAT attack by active measures could be maintained and publicized in an attempt to deter such an attack in the first place. Postures and policies intended to enhance deterrence could act as adjuncts to or substitutes for active and passive countermeasures. Even in the event of deployment of advanced ASAT weapons such as expendable single-pulse lasers against which "shoot-back' and passive measures might be ineffective, postures and policies intended to enhance deterrence could enhance security, although they cannot guarantee security.

In pursuing security through deterrence, it is appropriate to develop retaliatory capabilities which place at risk targets of sufficient value to deter attack and which do not exacerbate crisis instability. The first of these considerations implies that to deter ASAT attack, retaliation need not necessarily be "in kind"—i.e., against satellites. In fact, an ability to retaliate in kind, however thoroughly or swiftly, would be inadequate to deter an ASAT attack if the attacking nation valued destruction of enemy satellites more than survival of its own. For example, if the U.S.S.R. developed a capability to quickly destroy all on-orbit U.S. satellites, then even if the United States could destroy all on-orbit Soviet satellites in retaliation, the U.S. capability to mount such a retaliatory response —although valuable in the event—might not deter a Soviet first use of ASAT weapons. Soviet leaders might judge the continued deployment of U.S. MILSATS to be more detrimental to Soviet interests than survival of Soviet MILSATS is valuable to Soviet interests. If this were the case, an ability to retaliate against [more valuable] terrestrial assets would be required to successfully deter an ASAT attack. Such retaliatory capabilities might be provided by terrestrial or space based weapons. [A separate, classified appendix to this report (Appendix D) contains a more detailed discussion of the utility of military satellites to the United States and to the U. S. S. R.]

The second consideration—avoidance of crisis instability—precludes reliance on destabilizing weapons to provide retaliatory capabilities. Space-based ASAT weapons capable of instantly destroying several satellites, including similar ASAT weapons, would be most destabilizing unless salvage-fused but would be prone to accidental firing if salvage-fused. By comparison, an ideal weapon for deterring ASAT attack would be nonnuclear and hence usable at all levels of conflict without escalating the level of conflict. It could survive a preemptive attack and destroy enemy assets of sufficient value to deter an attack while causing little collateral damage.

Diplomatic Measures

In addition to the military measures discussed above, diplomatic measures such as arms control initiatives and negotiation of "rules of the road" for space operations could be useful responses to foreign development of threatening ASAT capabilities. The variety of possible measures is great, and assessment of their advantages is complicated; this topic is discussed in detail in chapter 6.

SUMMARY OF FINDINGS REGARDING ASAT CAPABILITIES AND COUNTERMEASURES

The most important conclusions which may be drawn from the preceding discussion of ASAT capabilities and countermeasures are:

1. Nonnuclear ASAT weapons which are now deployed or being tested by the United States and the U.S.S.R. are limited in altitude capability and responsiveness and can attack only a subset of currently deployed opposing MILSATS, although this subset includes important MILSATS.
2. The inherent A SAT capabilities of existing nuclear weapons such as U.S. and Soviet ICBMS and Soviet ABM interceptor missiles are substantial. Such weapons could pose a threat even to satellites in synchronous orbit, but are useful only at the highest levels of conflict.
3. Technologies applicable to future ASAT weapons are so varied, and many so promising, that future ASAT weapons, if developed, would be able to attack and dis-

able virtually all MILSATS of current types as currently deployed. Hence to maintain the survivability of constellations of future MILSATS, it will be necessary that the development and deployment of such weapons be constrained by arms control or that future satellites be protected from them by passive or active countermeasures, or that a combination of these approaches be pursued.

4. Of individual passive countermeasures which might be used against advanced ASAT weapons, only deception (use of de coys) is likely to be effective against all types of ASAT weapons, and deception is likely to be economical (relative to the offense) only if the decoys, and the satellites they mimic, are lightweight and inexpensive. Use of deception in combination with maneuver, hardening, and proliferation might offer economical protection for lightweight satellites.
5 Active countermeasures—electronic countermeasures, electro-optical countermeasures, and shoot-back—would be ineffective against an aggressive or preemptive surprise attack using expendable, single-shot ASAT weapons (e.g., kinetic-energy, directed-energy, and nuclear "space mines"). Actively defending keep-out zones around critical satellites might be able to protect such satellites against emplacement of short-range space mines but not against advanced, long-range space mines.
6. Of future ASAT weapons now foreseeable, those which would be most effective if used in a preemptive or aggressive surprise attack—i.e., expendable, single-shot ASAT weapons–would be space-based and therefore subject to such attacks by similar weapons. The cost of protecting them from such attacks—which must necessarily be by passive means—would exceed the cost of attacking them. Such weapons, if mutually deployed, would pro vide or increase incentives to attack preemptively in crises in which similar attacks are anticipated. Salvage-fusing such weapons to fire if disturbed would reduce but not necessarily eliminate incentives to preempt but would increase risks of accidental attack.
7. A capability to confirm the occurrence and identify the perpetrator of an A SAT attack and to retaliate in proportion, but not necessarily in kind, might deter ASAT attacks. A capability to retaliate in kind—i.e., against the attacker's satellites-could contribute to deterrence, if this capability were survivable, but if this capability were vulnerable to ASAT attack, it could undermine deterrence by posing an opponent an incentive to attack preemptively. However, a capability to retaliate in kind would be inadequate to deter an ASAT attack by an adversary nation which values destruction of U.S. satellites more highly than survival of its own.
8. Strict arms control measures could not be expected to eliminate the inherent ASAT capabilities of weapons such as ICBMS nor provide complete confidence that no ASAT weapons have been developed and deployed covertly. In an arms control regime which bans ASAT weapons, use of passive countermeasures would be required to reduce the residual risk posed by weapons such as ICBMS. However, prohibiting the testing of A SAT capabilities of weapons would preclude the attainment of confidence that certain types of advanced, nonnuclear ASAT weapons would perform reliably if used and would therefore also reduce incentives to develop such weapons or to attempt to deploy them covertly. A ban on testing would also render more difficult, costly, and risky any attempt to attain confidence, by covert testing, that other types of advanced, nonnuclear ASAT weapons (e.g., ground-based lasers) would perform reliably if used and would therefore also reduce incentives to develop such weapons or to attempt to deploy them covertly.

Prohibiting the basing in space of weapons with ASAT capabilities, to the extent that compliance with such a ban could be verified, would forestall the creation of strong incentives to attack such weapons preemptively when a similar attack is feared. Even in the absence of such strict restraints, if ASAT weapons are based in space, an agreement banning unauthorized close approach to foreign spacecraft could reduce the ambiguity of such provocative acts and thereby reduce the risk of ASAT attack resulting from misunderstanding, while providing a legal basis for anticipatory self-defense against ASAT weapons of short effective range.