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An Overview of Current Antisatellite Programs (U)*

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~~(S)~~ The current efforts of the United States in developing a antisatellite system were reviewed and are summarized in this paper. The factors that are important to the development of a kinetic energy kill system were identified and five were determined to be critical issues. These are target list, orbit determination, system reaction time, miss distance, and kill criteria. Early attention to these individual problems could reduce the cost and the risk of proposed systems. The systems being contemplated that use high-energy lasers as the kill device are discussed in the light of current and near-term technology levels. The three locations of such systems—ground-based, aircraft-borne, and space-based—are compared, and the attributes peculiar to each are identified.

I. BACKGROUND

~~(S)~~ The Space Defense Program has now achieved a programmatic stability and is expected to proceed in an orderly manner through development, flight test, and deployment. Space Defense is the unclassified title assigned to all U.S. antisatellite (ASAT) efforts. There are no current or planned programs to *defend* space assets. It is expected, however, that if ASAT becomes a subject for SALT negotiation or when a new ASAT hardware contract is let, the Department of Defense will declassify the fact that the United States has been engaged in ASAT activities (both studies and operational hardware) since 1956.

~~(S)~~ The early history of ASAT system studies, technology development, and system operation is summarized in *Space Defense System, Task 1, Historical Summary Report.*(1a) Other volumes of that series (Refs. 1a–1c) discuss threat assessment, conceptual design, and technology assessment, and Ref. 1d is a summary of the three. This series represents the view of the Space and Missile Systems Organization (SAMSO) of the Air Force Systems Command (AFSC). It is one of the few successful treatments of the complex ASAT problem.

~~(S)~~ Figure 1 was freely adapted from Ref. 1e to show the interrelationships in both ideas and concepts among a number of programs that have contributed to the generally known ASAT programs. The Air Force opened discussion on ASAT with SR-143 in 1956, following it with SR-187 and ADO-40—all study programs. In the meantime, the Navy sponsored *Early Spring*, the Navy's first and only foray into the ASAT arena. While this program was only modestly funded ($500,000), it is often remembered as the seed from which many of the current concepts have sprung. Subsequent to *Early Spring*, the Navy has maintained only a low-level interest in ASAT, primarily through nonnuclear warhead and hypervelocity impact testing at the Naval Research Laboratory.

~~(S)~~ The two efforts, ADO-40 and *Early Spring*, gave rise to three distinctly different approaches to the ASAT problem: (*1*) a large-yield nuclear

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*(U) This work was done during 1976–77 for the Assistant Director, Defensive Systems, ODDR&E. During the effort the author worked closely with the Air Staff, the Space and Missile Systems Organization, the Aerospace Corporation, the Vought Corporation, General Dynamics/Pomona, and the Defense Intelligence Agency. The work reported here takes advantage of the concepts, studies, and analyses already developed by them. The author also wishes to acknowledge the able assistance of Dr. Rex Finke, who was invaluable throughout the task.

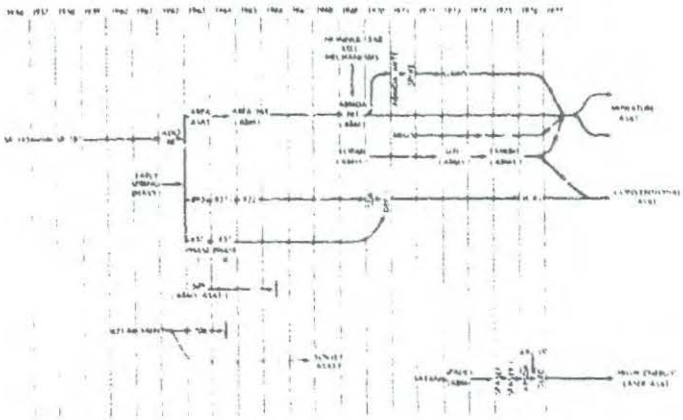

Figure 1. Genealogy of miniature, conventional, and high-energy laser ASAT systems. (Figure classified ~~Secret~~)

weapon and a point-in-space intercept, for example, Program 437; (*2*) a homing guided, large interceptor with a nonnuclear fragment warhead, for example, Program 922; and (*3*) a miniature homing interceptor using the body for kill (the one-eyed goalie), for example, the Army HIT. Figure 1 shows these separate paths, and they are discussed in more detail later.

~~(U)~~ Concurrently with *Early Spring*, the Air Force undertook an ambitious effort toward a satellite interception and inspection system (SAINT). Over a period of 5 years and under three program names, some $60 million were spent. Although the program was terminated in 1962, the Phase 0 study results were not formally published until 1964. The reasons given for termination included lack of development of the predicted Soviet threat, difficulties in developing the technologies thought necessary to implement the system, and cost uncertainties associated with development, deployment, and system operation. The concept of combined inspection and negation has never been revived, and with the advent of sophisticated space object identification (SOI) techniques, it is unlikely that it ever will.

~~(U)~~ The Army, in response to what was then considered an urgent need, developed and deployed in 1963 the first operational U.S. ASAT capability with Program 505. It consisted of a single site at Kwajalein Atoll in the Pacific, from which a modified *Nike-Zeus* missile was launched in a direct-ascent, command-guided trajectory to a point in space. The warhead was nuclear. Program 505 provided the sole ASAT capability until 1964, when the Air Force Program 437 became operational. Program 505 was decommissioned in 1966. The total cost of the Army effort was approximately $11 million. Until recently, there has been no interest on the part of the Army in a return to the ASAT arena. The Ballistic Missile Defense Advanced Technology Center (BMDATC) now has a program* exploring the techniques of intercepting a reentry vehicle during the midcourse portion of its trajectory (near apogee). ASAT is a natural subset of this problem, and as such, it is being examined.

~~(U)~~ Parallel in time to the SAINT program was another program sponsored by the Air Force, the aforementioned Program 437. An outgrowth of the several early study efforts, this program went through both a developmental (Phase I) and an operational (Phase II) sequence. The system consisted of a nuclear warhead delivered to a point in space by a *Thor* booster. The target point in space was defined on the basis of SPACETRACK data. Phase I, which lasted some three years, consisted of development and four flight tests of the system for an investment of about $67 million.

~~(U)~~ In 1964, the system was flight tested by an Air Force crew at Johnston Island. Subsequent to the test, Program 437 was declared operational at that site. Periodic training and evaluation launches were conducted with regular Air Force crews through 1974. When the system was finally decommissioned in that year, the operational aspect had expended about $111 million. The facilities

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* ~~(U)~~ The *Exhibit* program in progress at McDonnell Douglas Corp., Huntington Beach, Calif., sponsored by BMDATC.

at Johnston Island were closed, but were maintained, at least for a while, in a manner that would allow reactivation if the need arose. The facilities were ultimately closed down and the system completely phased out.

(~~S~~) Interest in nonnuclear ASAT has always been present from the time of the early studies, and the Air Force revived nonnuclear ASAT activity through the ADO-40 program, Program 893, Program 437Y, Program 922, and the Special Defense Program. This series of programs (on the same concept as the seminal *Early Spring*), spanning almost 10 years of elapsed time, deals with a rather large interceptor, a homing guidance system, and a fragmentation warhead. The first three programs named were studies, and the last two were for hardware development and tests. The hardware development portion spent over $34 million and required about 5½ years to complete. A single flight test was attempted (during the Special Defense Program in 1970) and it failed, not because the technology being explored was too advanced, but because a leak occurred in the vacuum seal of the sensor cap. Some organizational elements in the Air Force use the Program 922 portion of the series of efforts as a case study in inefficiency resulting from mission redirection and priority reversals.(*) The program was also plagued with rescheduling and stop-work orders, it suffered a change of mission from ASAT to ABM, and it was finally canceled as being an Air Force program in an Army mission area.

(~~S~~) The third focus of attention has been the use of miniature interceptors weighing a few tens of pounds, rather than the few thousands of pounds that are associated with the homing guided, fragmented-warhead schemes. Miniature interceptors were first considered in ballistic missile defense as a counter to indiscriminable decoys. The small interceptors, weighing a pound or so, would be launched by the hundreds into a threatening volume, where they would engage and destroy both decoys and attacking reentry vehicles by body impact—the interceptors would be "intelligent shrapnel." Supported first by DARPA and then by ABMDA, the body fixed seeker version homing interceptor technology (HIT), developed by Vought—was carried through extensive ground and drop tests. A gimbaled spinning sensor implementation was conceived, and a number of tests have been performed by General Dynamics Pomona to investigate the value and applicability of this concept. Other related issues have been the subjects of parallel and subsequent programs, and some of the more important ones are shown in Fig. 1. The Air Force's Miniature Development Program, as it is called today, takes advantage of the DARPA, ABMDA, and Air Force studies and experiments, as well as the sensor technology work sponsored by the BMDATC.

(~~S~~) As soon as it became apparent that high-energy lasers (HEL's) were possible, the Air Force sponsored a study, *Satan*, seeking to exploit the HEL as an ASAT weapon. In a later Air Force study, *Spades*, the laser was thought of as an ABM kill mechanism. The studies *Spaser I* and *Spaser II*, sponsored by DARPA, explored the capability of a space-based laser as a satellite defender and a satellite attacker, respectively. Other DARPA-sponsored work, the Advanced Radiation Space Defense Applications (ARSDA) Study and the Long-Range Optical Systems Study (LROSS), continued the space laser ASAT studies; the Space Laser Experiment Definition (SLED) mapped the path to follow to determine experimentally the capability of a space laser.

(~~S~~) The viable ASAT possibilities, as seen today, fall into three classes:

1. The miniature homing vehicle, whose kill mechanism is direct body impact,
2. A "conventional" fragmentation warhead interceptor, which by definition uses low-risk, proved technology in a sure-kill vehicle that, because of its "conventionality" in heavy warhead and sensor, is expected to weigh about 1,000 lb, and
3. A high-energy laser ASAT that might be space-based but, if required early, might well be deployed atop a high mountain.

Because the HEL ASAT is so far from realization and is considered still in the DARPA class of technology development, it is discussed only briefly in this paper. It is expected, however, that future work will better delineate the role of the HEL against space objects and that ultimately the HEL will replace whatever kinetic-energy kill device is developed.

(U) The current plan for the space defense effort by the Air Force centers on the development of a

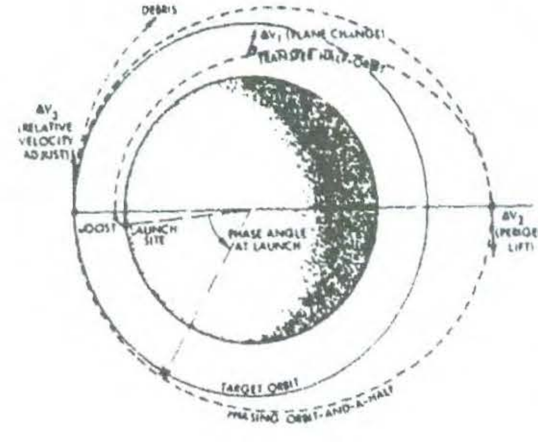

Figure 2. Geometry of Soviet orbital interceptor trajectory. (Figure classified Secret; figure caption classified ~~Confidential)~~

miniature interceptor; a small amount of money is earmarked for conventional-system study and technology development, and some money is earmarked for HEL study. At present, the conventional system is considered only as a backup for the miniature system and no longer as an early-capability system.

II. SOVIET ASAT DESCRIPTION

~~(S)~~ As a matter of general interest and to generate insight by U.S. ASAT designers into some of the interactions among ASAT subsystems a brief description of the Soviet ASAT system as it is perceived is included here. Much of the basic information that follows is from Ref. 2, which can be studied for further details.

~~(S)~~ The technology that supports the Soviet ASAT system is similar to what was assumed in U.S. studies in 1960,(3) when the SAINT program was being pursued. The propulsion and guidance systems were first tested in 1963 and 1964 (*Polyot 1* and *Polyot 2*), but the first interceptor vehicle was not flown until 1967 (*Cosmos 185*). The first intercept tests were made in 1968 with *Cosmos 249* and *Cosmos 252* against an instrumented target vehicle (*Cosmos 248*). These three launches were made with the SL-11 booster, as were all interceptor launches after *Polyot*. Other tests followed, and the original series terminated in 1972, when a target was put into orbit but no interceptor followed. There were 17 launches, 6 targets (of two varieties), and 11 interceptors (with 7 intercept attempts) in the original series, not including the early *Polyot* flights. In 1976, testing was resumed, with three targets and four interceptors launched. All tests in 1971 and thereafter were conducted in orbits inclined 65 deg.

~~(S)~~ The geometry of a typical interception is shown in Fig. 2. After sufficient tracking by *Hen House* space-surveillance radars to establish the ephemeris of the target (over an interval that has been not less than three days), the interceptor is launched when the target is about 60 deg (a few degrees for two of the 1976 tests) before its closest approach to Tyuratam. One quarter of an orbit downrange, the interceptor performs a plane change to get into the plane of the target. The plane change capability may be as much as 8 deg. At the completion of one-half orbit, the interceptor again maneuvers to raise its perigee (or apogee in some cases) to the target altitude. The flight continues for another orbit-and-one-half (half-an-orbit for two of the 1976 tests) for adjustment of phasing with the target, and as the point of closest approach is about to occur, a third burn is made, after which the relative velocity between the vehicles is observed to be 400 m/sec. About 3 min before the point of closest approach is reached, the interceptor begins search, and our observations have shown that acquisition occurs with 70 to 90 sec to go. At this point, the terminal homing maneuver begins, and at about 2 sec to go, a pellet warhead is fired. While there have been failures from time to time in various subsystems, it has been noted that once the seeker has locked on the target the warhead has never failed, and the target has always been observed to react to the impact.

~~(S)~~ Because no ground commands to the interceptor during an engagement had been detected (until 1976), it was assumed that the entire intercept sequence could be preprogrammed. (This was supported by the one-orbit 1976 tests, in which there was no opportunity for ground interaction.) For this reason it was predicted(4) that system operation could be improved to a quarter-orbit (direct-ascent) intercept with the same equipment. Improvement in computational procedures alone (with no change in propulsion capability) would allow a single burn at the quarter-orbit point that would combine the plane change and the closing-velocity adjustment, as shown in Fig. 3. While this mode has not been tested, there is no reason to believe it may not be forthcoming, and if the United States were to plan for the defense of its low-earth-orbit satellites (by evasion or decoying), it should include consideration of this possible capability.

~~(S)~~ The sensor used on the interceptor is assessed to be a monostatic, pulsed radar operating at 938 MHz with a 7.5-deg beamwidth.(5) The unit is estimated to weigh about 125 lb. To scan the uncertainty volume, the entire interceptor has been observed to cone rather than just the antenna;* coning stops, once acquisition is accomplished. Lock-on range is about 15 nmi against a 2-m^2 target.(5)

~~(S)~~ The warhead is estimated t[illegible] the multilayer, explosively driven fragment variety, fixed to the vehicle and fired forward. When the warhead is detonated, the radar ceases to function, indicating either that the explosive destroys the radar or that the pellets tear off the antenna. The estimated warhead weight is 750 lb. The allowable miss distance is estimated at 50 ft and the range-to-go at firing at about 2,000 ft.(5)

~~(S)~~ The vehicle is estimated to be about 14 ft long and 6 ft in diameter. Five orthogonal rocket engines provide axial thrust, as well as the ability to maneuver laterally. The radar and warhead are at the end opposite the axial engine. An artist's concept is shown in Fig. 4. The weight of the interceptor at launch is about 5,500 lb, and the total velocity capability is about 4,000 ft/sec.

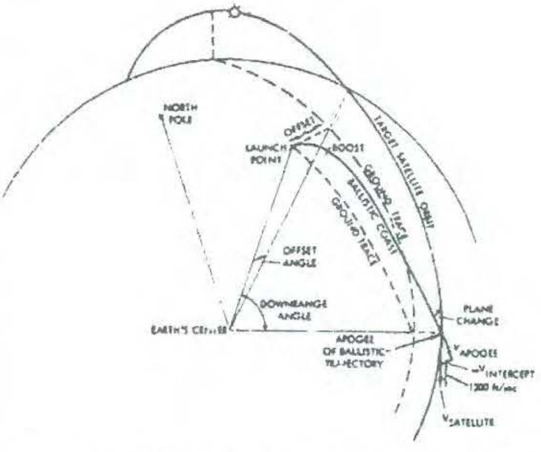

Figure 3. Schematic of direct-ascent intercept mode for the Soviet ASAT system (source: Ref. 5). (Figure and figure caption both classified ~~Secret~~.)

~~(S)~~ A number of observations that can be made from the above description should aid U.S. designers in pursuing their ASAT program. The principal limiting factor in the system is the sensor. Considering the time period of development, a radar was in order, but because radars are severely range-limited (because of radiated-power constraints), serious compromises are placed on system operation. In addition to the radar, another limiting factor is the propulsion. The

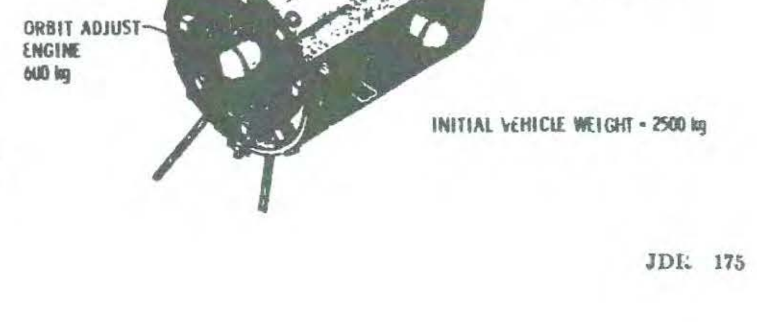

Figure 4. Soviet satellite interceptor configuration (source: Ref. 6). (Figure classified ~~Secret~~.)

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*~~(S)~~ Tests in 1976 may have introduced an articulated antenna or feed.

Soviet designers chose to use four fixed-thrust transverse engines to close the initial lateral error and final miss distance. The final miss distance is strongly dependent on engine thrust,[7,8] and the thrust was therefore probably chosen to be sufficient to get the interceptor within the desired miss distance (which had been assessed as about 50 ft).

~~(S)~~ The lateral maneuver capability of the system required for operation within the combined errors generated by the target-ephemeris measuring system and by the ASAT booster guidance is essentially the lateral velocity (that can be added) times the time to go. This lateral velocity increment capability was probably set by the miss-distance consideration, so the only free parameter is the time to go. The time to go is the acquisition range (set by the radar) divided by closing velocity. To have the lateral range sufficient to close out the errors mentioned above (about 10 km), the Soviet design adopted a very low value of the relative velocity (the observed 100 m/sec) for the end game. The chief consequence of this small closing velocity is that orbital-injection capability is required of the booster—and hence, the use of the large SL-11 (modified SS-9 ICBM) booster.

~~(S)~~ What have been described above are the principal interactions among the several parameters that control the system design. The prudent U.S. designer will choose a sensor with as long a detection range as possible and a rocket motor (or set of motors) whose thrust vector and impulse have a large controlled variability. If those selections can be made without undue penalty in complexity, the need for precise ephemeris data will be reduced, a lower cost booster guidance system can be used, and short-time-of-engagement geometry (such as direct ascent) can be chosen for the intercept.

~~(S)~~ It was surprising that, after the 4- to 5-year standdown, the new series of Soviet tests did not include new components (besides articulated antennas) that would relax some of the constricting parameters described above. If no new tests are conducted with major upgrading of the limiting subsystems, we can expect that the Soviet system will remain very limited in altitude reach and inclination coverage, will therefore place only a limited number of U.S. satellites at risk, and will be replaced eventually by an all-new system.* Thus far, there have been no observations or indications of follow-on Soviet ASAT activity.

III. KEY ISSUES IN KINETIC-ENERGY KILL SYSTEMS

~~(S)~~ A number of issues must be successfully addressed if the United States is to continue the development of an ASAT system that uses a kinetic-energy kill mechanism. These issues are discussed in the sequence one might follow in an operational consideration. Those issues that are considered as key considerations are then identified, summarized, and ordered as to their relative importance.

A. TARGET LIST

~~(S)~~ The list of targets that can be negated by the ASAT system is important in several ways. The functions of the targets and their usefulness to the Soviets determine the vigor with which we must pursue their destruction and the timeliness required of the intercept trajectory. The altitude, the inclination, and the apparent size of the satellite determine the performance requirements of the interceptor system.

~~(S)~~ In Ref. 9, which is a 1976 revised version of the required operational capability (ROC) for a space defense system, the Aerospace Defense Command (ADCOM) has taken a more relaxed position than it took in an earlier document[10] with regard to the number of Soviet satellites that need negation and the urgency of their negation. Although ADCOM, in Ref. 9, still projects for the 1982 time frame a large number of satellites that it asserts the United States must be capable of negating, estimates that were current in 1976 and near-term projections† indicate that only 10 to 15 interceptions would negate all the Soviet tactical and strategic-support satellites. It is expected that ADCOM will continue to scrutinize the Soviet satellite force and alter the ROC as the perceived threat changes.

~~(S)~~ A slightly different criterion can be used to decide what satellites must be negated. It is that

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*~~(S)~~ Note that Soviet troubles with ASAT reliability have not been discussed here.

†(U) On the basis of the *Defense Intelligence Projections for Planning*.[11]

the United States must be able to negate Soviet satellites (or satellites from any other country) whose existence poses a threat to U.S. forces or to the security of the United States. Here, it is important that the potential enemy be denied the use of space to gain a military advantage he would not have in any other way. As the satellites listed by ADCOM as requiring negation are discussed below, this criterion will be applied.

(U) Table 1, taken from Ref. 9, is shown here as the focal point of the discussion. Satellite descriptions and performances are taken from Refs. 6 and 12.

1. Photoreconnaissance Satellites

~~(S)~~ The photoreconnaissance satellites currently in use are a low-resolution photo/elint and a high-resolution photo. They both use modified *Vostok* vehicles and operate at a few hundred kilometers altitude. Inclinations of 52. 65, 72, and 81 deg are used, and the satellites are launched from Tyuratam Missile Test Center and Plesetsk Missile and Space Center by SL-4 boosters. The low-resolution satellites are launched at the rate of about 10 per year and the high-resolution satellites at the rate of about 20 per year. There is usually only one of each operating at any one time.

~~(S)~~ Both systems use film, which is recovered after landing, and both satellites have useful lives of 12 or 13 days, which limits the use of such a system to long-term intelligence and verification. Unless the design and operation of these vehicles are changed, they will have little value in a real-time situation. Therefore, from a view of what is "at risk," there is little incentive to intercept them.

~~(S)~~ A new-generation photoreconnaissance satellite system, operating at a 67-deg inclination with a spacecraft lifetime up to 40 days and film-capsule recovery, began tests in September 1975. With this system, the converse of the above problem is the case. This photoreconnaissance satellite system is of a technological level that it would be possible to make the first orbit a data-gathering orbit, if it were in an inclination to overfly interesting areas. Therefore, it would be possible to launch the photoreconnaissance satellite, take the desired photographs, and drop the film capsule on the first orbit, well before an ASAT system could even establish the ephemeris of the orbit. While the new photoreconnaissance satellite may be a desirable target, it is also well beyond the capability of currently projected orbit determination systems, at least for the first few orbits.

TABLE 1. *Soviet military satellites projected for 1982. (Table and table caption both classified ~~Secret.~~)*

Low Altitude (below 1000 nmi)	Elliptic	High Altitude (above 1000 nmi)
2 Photorecon	4 MOLNIYA	4 Meteorology
4 ELINT	3 Missile Surv.	3 STATSIONAR
4 Meteorology		3 SIGINT
5 Ocean Surv		18 Navigation
5 Air Surv.		2 Missile Surv.
32 Comm Repeat		

2. Elint Satellites

~~(C)~~ A dedicated elint system operation was initiated by the Soviets in 1968 with the so-called second-generation system, the first-generation system being an add-on package to photoreconnaissance satellites. It appears that this second-generation system, cylindrical in shape, 1 meter in diameter, and 2 meters long, continues to be launched in spite of the existence of a third-generation system that was first launched at the end of 1970. The third-generation system uses a vehicle substantially larger than the second-generation system, but of the same general configuration. These third-generation satellites operate at about 600-km altitude at an inclination of 81 deg. They are normally programmed once per day, and play back their output during a single pass over Moscow, but there is no reason to believe that this procedure will remain static. The elint program appears to be very active and one should not ignore a possible real-time, local readout mode with local tasking of the satellite as part of the growth of the system. If this happens, the elint system could in a time of crisis become a serious threat, one whose existence places a number of our assets such as command posts or radar sites at risk. The elint satellite therefore should be considered as a target for a U.S. antisatellite or some growth version thereof.

3. Meteorological Satellites

~~(S)~~ The Soviets have upgraded their meteorological satellite program with a new *Meteor-2*, first launched in mid-1975. It has the same basic configuration as *Meteor–1* and is in the same orbit inclination, 81 deg. Both *Meteors* are launched from Plesetsk on SL–3 boosters to an altitude of 870 km. It is expected that the number in operation at any one time will be nine to twelve, with three to five launches per year. The operational lifetime is about 24 months.

~~(S)~~ The prime sensor for *Meteor* is vidicon television, scanning and nonscanning infrared systems are secondary. Both systems can be operated in real time or in store-and-dump modes. The automatic picture transmission capability that was developed on *Meteor–1* is a standard feature. There are three known civil recipients of *Meteor* data, and it is believed that there is a network of ground stations serving the military forces.

~~(S)~~ The *Meteor* system provides repetitive coverage of a given area every 4 to 6 hr, which, coupled with the real-time readout, could provide the Soviet forces with tactical weather situation and prediction information to support their ICBM strategic strike forces and their tactical aircraft used for theater operation. The operation of the satellite places our forces and our nation at a higher level of risk than would exist without the satellite. Hence, *Meteor* should be a target for any U.S. antisatellite.

4. Ocean Reconnaissance Satellites

~~(S)~~ The ocean reconnaissance satellites come in two versions, radar and elint. The development of the radar version (RORSAT) was started in 1965, and a prototype was launched in 1967 (*Cosmos 198*). All of the satellites are launched from Tyuratam aboard an SL–11. This booster (a slightly modified SS–9) uses storable fuel in both stages and, thus, could be deployed on short notice in time of crisis. The operating altitude is 270 km at an inclination of 65 deg. The operational system is expected to consist of two satellites, separated in phase by about 25 min. The system is currently assessed as having achieved initial operational capability, and the tests (in pairs) during 1974 and 1975 were thought to confirm overall system performance. The life of the system is about 2.5 months, after which the satellite separates and one piece transfers to a circular orbit at an altitude of about 980 km. A thermal-balance analysis of this higher altitude section, together with the expected decay time (250 years) from that altitude, suggests a nuclear-reactor power supply.

~~(S)~~ The data acquired can be played back in real time or in a store-and-dump mode. Operating in pairs, this system poses a real threat to naval forces and has been observed to be used in tracking U.S. aircraft carriers. Other RORSAT activities include operations at the same time as Soviet and U.S. fleet operations. The expected RORSAT launch rate is two per year. RORSAT is an obvious target candidate.

~~(S)~~ The elint ocean reconnaissance satellite (EORSAT) is a new addition to this series, having first been launched in December 1974 (*Cosmos 699*). It, too, comes from Tyuratam aboard an SL–11 booster. The operating altitude is 435 km[*] at an inclination of 65 deg. It is similar to the RORSAT, in that it uses the same command system and a similar data format. Data are read out in a store-and-dump mode over Moscow and in real time to other sites in the USSR and to Soviet fleet elements. It appeared to be operational after only two launches, suggesting a high reliance on proved RORSAT technology. The expected EORSAT launch rate is one per year. The elint ocean reconnaissance satellite is an ASAT target candidate.

5. Air Surveillance Satellites

~~(S)~~ Air surveillance satellites are projected for 1982. It is difficult at this time to anticipate the details of the technology and the system operation that would make these satellites a threat. However, it is understood that the projection was made with good foundation, and one should properly expect its appearance. If an air surveillance satellite system appears and becomes operational, one should consider the system able to support tactical operations in Europe, as well as to detect and track strategic bombers. At this time, one should consider an air surveillance satellite as a potential target and expect a U.S. ASAT to either intercept it or be able to grow in capability so that it could negate the low-altitude air surveillance function.

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[*] ~~(S)~~ It is noted that, of the four EORSAT satellites that been launched, *Cosmos 699*, *Cosmos 777*, *Cosmos 838*, and *Cosmos 868*, the precision in-orbital altitude has been ±1 km. Since no other Soviet system has this precision, it is suggested that this might be an EORSAT system requirement.

6. Communication Repeater Satellites

~~(S)~~ Communication repeater satellites, as presently deployed at low altitude, are of two varieties: (*1*) small satellites that are launched in groups of eight (hence the nickname, "eight balls") from Plesetsk by an SL-8 and are randomly injected at an altitude of about 1,500 km at an inclination of 74 deg, and (*2*) larger single satellites at about 800-km altitude at the same inclination, also originating at Plesetsk and boosted by an SL-8. They both appear to be store-and-dump communications repeaters with little capability to support a tactical situation. As such, they should not be on a target list. In any event, it would be very difficult to attack a set of eight-ball satellites with a kinetic-energy interceptor because the satellites are many and are physically small.*

7. Molniya Satellites

~~(S)~~ The *Molniya* family of satellites was launched in three models, starting in 1965 with *Molniya 1*. The announced function of the program was to serve as a domestic communications system, but the capability for a global military communications application is obvious. The succeeding models *Molniya 2* and *Molniya 3* are very similar, the only apparent changes being in frequency, antenna configuration, and power supply. The launch vehicle is the SL-6, and the launch site is now Plesetsk.

~~(S)~~ *Molniya 1* appears to have become of primary service to the Soviet military forces. It is assessed as being capable of relaying voice or telegraphy only. The orbit is highly elliptical (with apogee at its greatest northern latitude) and harmonic (two orbits per day). The apogee is about 39,800 km, the perigee is about 500 km, the inclination is 63 deg, and the period is 12 hr. The expected lifetime is about 2 years, and the launch rate has been three per year.

~~(S)~~ *Molniya 2*, first launched in 1971, is similar in deployment to *Molniya 1* and has television repeating capability as well as telephone or facsimile. The operational lifetime is expected to be a bit shorter than that of *Molniya 1*, and the launch rate has been as high as three per year. The use is primarily commercial.

~~(S)~~ *Molniya 3* was first launched in 1974 and is expected to be only a modest improvement over *Molniya 2*. The orbital elements are the same. It is expected that *Molniya 3* will be a component of the Washington–Moscow hot line.

~~(S)~~ A single launch, in July 1974, of a *Molniya 1S* to synchronous orbit aroused great interest. It was stabilized at longitude 85° E., operated for about 5 months, and has been silent since. It appears to have been a development satellite in the *Statsionar* program (Section IIIA10).

~~(C)~~ The *Molniya* family of satellites in elliptical orbit appears to be a part of a concerted effort by the Soviets to deploy a worldwide communication system to serve both their military and civil needs. There is a plethora of ground stations in the Soviet Union, and there are a number in countries friendly to the USSR and on several Soviet ships.

~~(S)~~ It is not clear that *Molniya* is a desirable target. With the exception of *Molniya 1*, the system appears to be civil oriented. Soviet military satellite communication traffic, while heavy, is paralleled by other military systems that are not satellite related. In addition, one must consider the practical aspect of interception. The satellite, while large in size, is virtually out of range of our Northern-Hemisphere-based tracking stations when overhead (apogee) and out of sight of our tracking stations when at perigee (midocean in the Southern Hemisphere). In addition, when the satellite is at its lowest altitude, its velocity is about 8,000 ft/sec faster than satellites in circular orbit at that altitude. One would have to make a substantial cost/benefit argument that the continued existence of the *Molniya* system places our forces or our national security at a unique risk before committing oneself to an ASAT capability to engage this difficult target.

8. Missile Surveillance Satellites

~~(S)~~ A series of missile surveillance satellite experiments was initiated in September 1972 with the launch of *Cosmos 520* from Plesetsk on an SL-6 into a highly elliptical orbit. There is

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*~~(S)~~ Should it be necessary to depend solely upon space for communications, one technique that would have a high chance of surviving a limited conflict involves the proliferation of very-small-cross-section repeaters with long-life power supplies.

Refer to USD (R&E)

some difference of opinion as to the satellites' shapes and sizes, but not as to their function. A total of five launches have taken place, injecting the payload into *Molniya*-like orbits. The coverage of the broad ocean areas in the Northern Hemisphere was almost continuous, with lesser coverage of the *Minuteman* sites, the Western Test Range, and the Eastern Test Range.

~~(S)~~ The satellites described above as being in highly elliptical orbits were followed by *Cosmos 775*, which was launched to synchronous orbit in October 1975. Whereas the earlier satellites were launched from Plesetsk on an SL-6, *Cosmos 775* came out of Tyuratam on an SL-12. There is a difference of opinion as to the configuration of the launch-detection satellites. Some hold that they are variations on the *Molniya* spacecraft, while others regard them as new configurations. *Cosmos 775* is stationed at about longitude 24° W. and inclined at about 0.1 deg.

~~(S)~~ One should consider the value and risk associated with the interdiction of these missile surveillance satellites. In times of tension, there may be value in the enemy's knowing that the United States has not launched a massive ICBM or SLBM attack. The value of destroying the Soviet launch surveillance system would come only if a U.S. attack were launched and only if the satellite had some capability to estimate trajectory and time of arrival and to alert the Soviet defense. It is argued, however, that the interception of this type of satellite would prematurely alert the Soviets to a U.S. intention to launch a ballistic missile attack. Serious consideration should be given to these factors before the United States undertakes the design of an ASAT for this capability.

9. High-Altitude Meteorological Satellite

~~(S)~~ No Soviet meteorological satellites have been observed to be launched for high altitudes. *Meteor 1* and *Meteor 2* represent the total Soviet meteorological satellite capability, but the Soviets have announced that they intend to place a weather satellite in geostationary orbit. If it comes, it will be a candidate, albeit a difficult one, for interception by a growth ASAT.

10. Statsionar

~~(S)~~ The Soviets announced plans to establish a network of geostationary communication satellites named *Statsionar*; it would duplicate coverage of the *Intelsat* system. *Cosmos 637* was the first Soviet satellite launched to a synchronous equatorial position in March 1974, but it remained inactive. A second synchronous equatorial satellite was launched in July 1974, but it was designated *Molniya 1S* (mentioned earlier) and operated, as expected, on *Molniya 1* frequencies. After two announcements in June and September 1975, *Statsionar T* (*Raduga 1*) was launched on an SL-12 on Dec. 22, 1975 and inserted into geostationary orbit at longitude 90° E. The satellites have a television relay function rather than the announced general communications function announced for *Statsionar 1*. The plans for a ten-satellite system appear to have slipped in time, but are expected to be implemented in the near future. *Raduga 2* was launched in September 1976, and a geostationary satellite designated *Ekran* was launched in October 1976. *Statsionar 4*, expected in the 1978–79 period, would be placed off the west coast of Africa over the Atlantic. *Statsionar 5* and *Stationar 6* would be placed over the Indian Ocean, whereas *Statsionar 7* would be placed over the Pacific Ocean. About 1980, *Statsionar 8* would also be placed over the Atlantic. Two more *Statsionars* in that period would be positioned over the Indian Ocean and the Pacific.(13)

TABLE 2. *Revised target list.* (*Table classified ~~Secret.~~*)

Targets Perceived Today

Radar Ocean Reconnaissance Satellite (RORSAT)
ELINT Ocean Reconnaissance Satellite (EORSAT)
ELINT Satellite
Meteorological Satellite (METSAT)

Possible Targets

Air Surveillance Satellite*
Precision Navigational Satellite*
High-Altitude Meteorological Satellite*
New-Generation Photoreconnaissance Satellite
MOLNIYA 1

Improbable Targets

Communication Repeater Satellite
MOLNIYA 2 and MOLNIYA 3
Missile Surveillance Satellites (Elliptical and High-Altitude)
STATSIONAR

* Foreseen but not yet in orbit

~~(S)~~ As far as is known, no military functions are currently associated with these geostationary satellites. They are parallel to other Soviet communication links, and therefore they do not present a high-value target to a U.S. ASAT unless,

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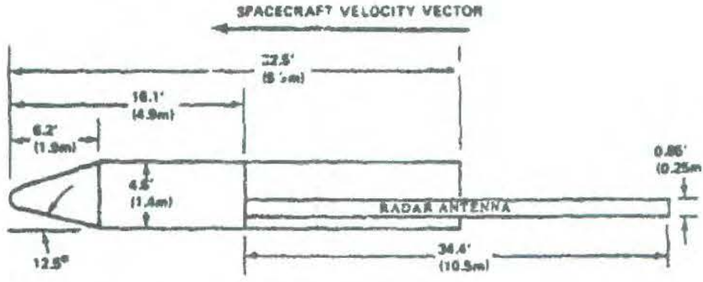

Figure 5. Composite image of radar ocean reconnaissance satellite (RORSAT) (source: Ref. 12). (Figure and figure caption both classified ~~Secret~~.)

of course, it becomes necessary (and possible) to interrupt the entire Soviet communications system.

11. Sigint Satellites

~~(S)~~ No Soviet satellites are currently identified with the role of sigint, although they are projected for the 1982 era. It is not clear how this function differs from the elint function. Should the sigint satellite system be capable of more than long-term intelligence gathering, it should be reexamined as a potential target. Until then, the physical characteristics and the location remain as nebulous as the function and need not be considered as distinct from elint satellites in the current concerns over the configuration of a U.S. antisatellite system.

12. Precision Navigation Satellites

~~(S)~~ Precision navigation satellites are projected to appear in the early 1980's. It is not clear which military role will be assigned to this new capability. The Soviets can achieve satisfactory soft-target accuracy for their SLBM and ICBM force with their current technology. Should they find it advantageous to use a navigation satellite to improve the accuracy of their tactical ballistic missiles, the existence of the satellites would place our troops at risk and the satellites would become attractive targets. It is not likely, however, that an ASAT could be made effective in such a time-demanding role when the flight time to high altitude is so long (2 to 5 hr). Another role for the navigation satellite would be to give the Soviet SLBM force a real capability against our hard targets without the need for significant improvement in the inertial guidance equipment on the submarines or in the SLBM's themselves. Should this role come about or appear imminent, the navigation satellites would indeed be a serious threat to our forces.

~~(S)~~ In summary of the above discussion, we have a revised target list, as shown in Table 2. Here, the list from Table 1 has been partitioned, for the reasons stated above, i. [redacted] ve groupings: target satellites today, satellite become attractive (necessary) targets, es that are not now and are likely neve: nwhile targets. The basis for the choice of the first group is, of course, that the continued existence of a particular satellite or set of satellites places U.S. forces or assets at a significantly higher level of risk. The second group, possible targets, consists of three satellites whose existence is foreseen but has not yet materialized, a military communication satellite, and a new-generation photoreconnaissance satellite. It should be recalled that *Molniya 1* is a valid target only if all other parallel communication links are also attacked. The last group poses no threat to the United States in their present employment. Should their roles be changed, these satellites should be reconsidered as possible targets. It is unreasonable to categorize these satellites as targets just because they might possibly be used in a limited military way.

~~(S)~~ The satellites that are perceived to be targets for an early U.S. ASAT system are shown in Figs. 5 through 8.(12)

B. ORBIT PREDICTION

~~(S)~~ Once the satellite target list has been established, it is important to determine the accuracy to which the orbital parameters of those satellites can be measured. The prediction error (volume of uncertainty) contributes to the maneuver radius required of the kinetic energy interceptor.

~~(S)~~ At the present time there are a number of ground tracking stations that provide data on which the ephemerides of satellites are based. The space detection and tracking system,

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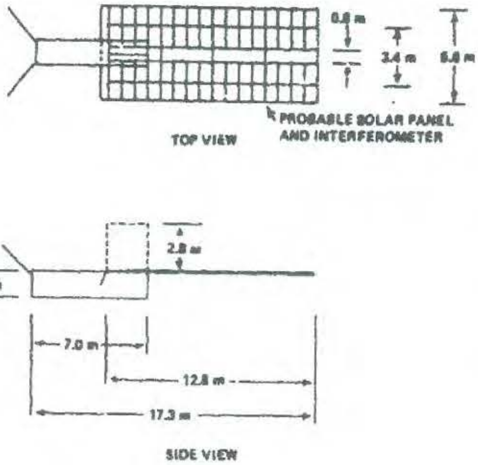

Figure 6. Elint ocean reconnaissance satellite (EORSAT). (Figure and figure caption both classified ~~Secret.~~)

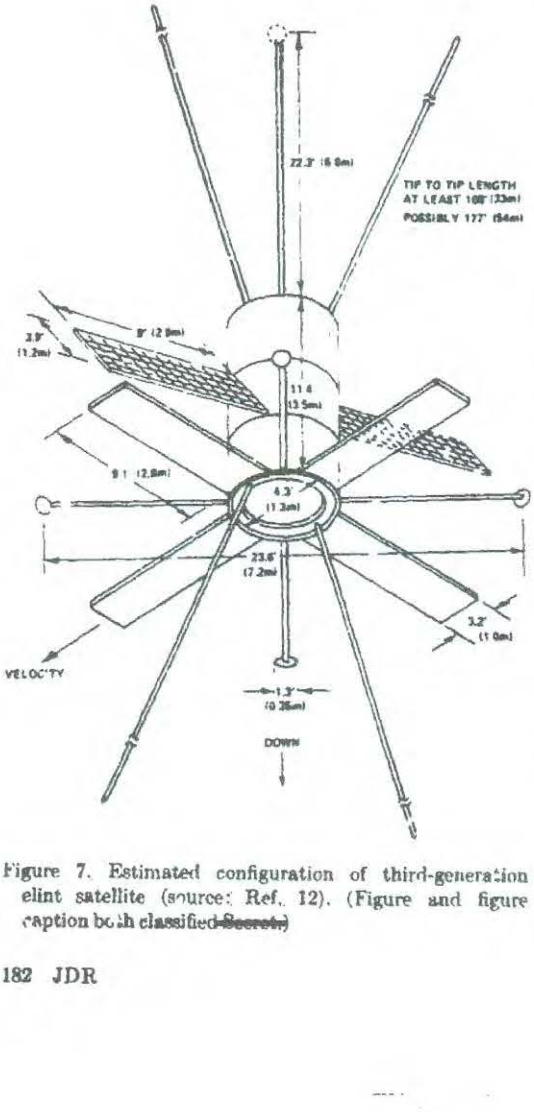

Figure 7. Estimated configuration of third-generation elint satellite (source: Ref. 12). (Figure and figure caption both classified ~~Secret.~~)

SPADATS,(14) has two primary operating sensors: (*1*) the tracking and detection radars at Diyarbakir, Turkey, which are now at least temporarily inoperative and (*2*) the tracking and detection radars at Shemya, Alaska, which are to be replaced by a phased-array radar in the near future. In addition, there are a number of contributing sensors whose secondary mission is satellite tracking and that respond when available to requests from SPADATS. These sensors include: the three ballistic missile early warning system (BMEWS) detection and tracking radars at Thule, Greenland, at Clear, Alaska, and at Fylingdales, England; the FPS-85 radar at Eglin Air Force Base, Fla., the Air Force tracking radars at Ascension and Antigua Islands; the Lincoln Laboratory Millstone Hill radar; and the Navy-operated space surveillance system (SPASUR) radiometric interferometer.

~~(S)~~ Part-time contributors include the Air Force Satellite Control Facility, the perimeter acquisition radar (PAR), the Kwajalein Missile Range Radar, NASA tracking and detection sensors, and selected intelligence sensors. Baker-Nunn cameras are not considered here, because of their long response time.

~~(S)~~ When both the NAVSPASUR and the FPS-85 are available, they complement each other. The SPASUR notes that an object has penetrated a "detection fence," alerts the FPS-85, and furnishes it with "look angles." The FPS-85 is then able to operate much more efficiently because, without this alerting, the FPS-85 would spend about half its power in search.(15) Figure 9 illustrates the locations of some of the sensors that can be used as part of the SPADATS system and shows their visibility circles.

~~(S)~~ A study is now in being to investigate the capability of the SPADATS system as it is presently constituted and to recommend the quality and location of additional or alternate sensors that might be used to upgrade the system if need be. The study, tentatively titled "Space System Network Evaluation/Optimization," is sponsored by SAMSO and is being performed by the Aerospace Corp. The results, when published, will provide a valuable insight into the system. The last general study of the SPADATS, published in 1965,(15) was performed by an ad hoc working group reporting to ODDR&E.

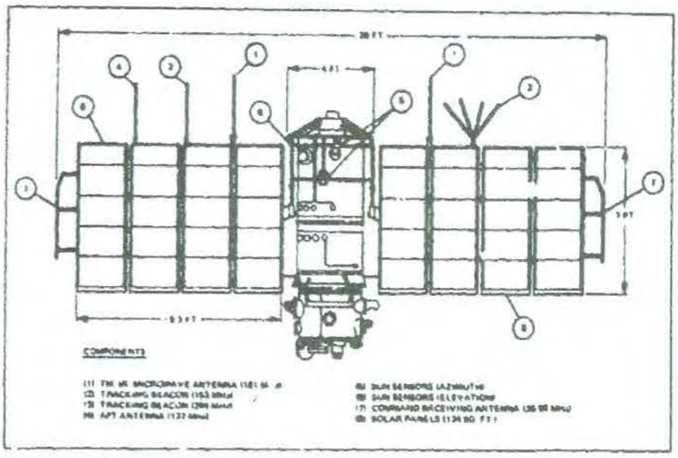

Figure 8. Front view of Soviet meteorological satellite (source: Ref. 12). (Figure classified ~~Secret~~)

~~(S)~~ In its analysis in support of the Air Force Miniature Development Program, the Air Force SPADATS says it expects to be able by 1980 to predict satellite location 24 hr ahead with an "equivalent spherical error" of 3 nmi for low-orbit earth satellites.* To do this, it would use the current sensor array and special computer programs. For satellites at higher altitudes, where the sensor angular error gives greater position uncertainty, the "equivalent spherical error" is expected to be 10 nmi. Highly elliptical orbits such as that of *Molniya* are not discussed, but when a sensor is available for tasking, one would expect an error of about 10 nmi, considering the sensor location.

~~(S)~~ Of course, the error of location of a low-orbit satellite is not a sphere but an ellipsoid having its long axis along track, because of uncertainty in the drag. For these orbits, the drag magnitude is

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*~~(S)~~ Today, for 90 percent of the low-altitude "satellites," the best position determination at the latest routine measurement is stated in Ref. 14 to be 12 km, or about 6 nmi.

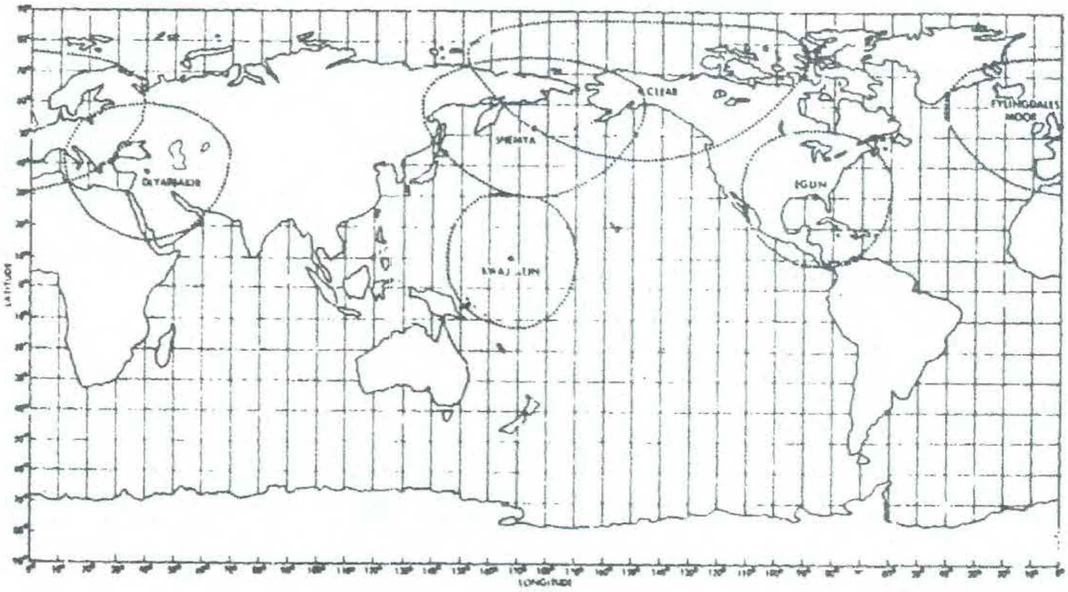

Figure 9. Visibility circles (2-deg horizon) for sensors used as part of SPADATS. (Figure classified ~~Secret~~)

uncertain enough to generate errors in this dimension from 10 to 20 times that of the cross-track or radial errors. As the altitude increases, the drag and the along-track uncertainty decrease. The measurement error finally dominates, the error volume assuming a spherical shape. Above 1,000 nmi, the constant angular error leads to a linearly increasing error volume dimension with increased altitude, and not a constant 10 nmi as is being considered in current ASAT studies.

~~(S)~~ A recent ADCOM technical note(16) includes several sets of tracking data and predictions made from them, as well as an analysis of the error in the prediction. While these data do not constitute a sufficiently large base on which one could predict future capability with any real assurance, some understanding of orbit-prediction limitations can be obtained. The radial and out-of-plane errors for resident satellites are indeed small and are nearly equal over a 24-hr-ahead prediction interval. Values of these errors of less than 0.2 nmi are typical with dedicated tracking. The typical values of along-track error are large compared to the other two, sometimes as much as 20 times. From these data and further discussions with the AD COM Chief of Astrodynamics Application(17) it was asserted that one can expect accuracies (predicted ahead for 24 hr) of 0.3 nmi (3σ) in the out-of-plane and radial directions and 3 nmi (3σ) in the along-track direction for satellites below 1,000 nmi. This expectation assumes no new sensor, no curtailment of existing facilities, no traffic overload problems, tracker tasking dedicated to the designated few satellites, and the routine use of what are now special perturbation algorithms in the data reduction. These accuracies do not apply to newly launched satellites or to orbital altitudes above 1,000 nmi.

~~(S)~~ While the required accuracies to meet these antisatellite capabilities are expected and freely predicted by the Aerospace Defense Command and the Fourteenth Aerospace Force, there are still several areas of serious concern. An analysis memorandum of the Fourteenth Aerospace Force titled *SPADATS Orbit Prediction Capabilities*(18) states that: *(1)* to meet the space defense capability required by ADCOM, an abnormally high-level dedicated tasking for satellite tracking is required of the prime sensors (two of which are no longer operational); *(2)* there is no currently available analytical method for selecting an orbit determination interval (observation period prior to the prediction interval); and *(3)* actual (a posteriori) observed values of the solar radiation parameters during the prediction interval were used. (Knowledge of these solar parameters is not an operational capability; and if it is ever achievable, it will not be available for at least 10 years.) These are rather serious deficiencies for a system expected to provide accurate orbital parameters on a routine basis. A detailed out-of-house study is needed to examine the capability of the current and future SPADATS, either to confirm the capability of existing sensors and data reduction facilities to meet the Air Force requirement or to identify revisions in the tracking and computational system that will provide the prediction capability necessary for an ASAT.

~~(S)~~ Another principal area of concern is the suggestion that SPADATS become a key element in a weapon system* rather than just cataloging space objects. Currently, SPADATS operates in a rather leisurely, non-realtime mode and, to become part of a real-time weapon system, it will require a significant change in operating procedures.

~~(S)~~ It is not obvious that SPADATS (as currently constituted) can ever become such a highly time-critical, key element in the system. It might be better to create a new organization that would perform in the manner required than to task an existing organization unreasonably beyond its operating capability.

C. ENGAGEMENT GEOMETRY AND SYSTEM REACTION TIME

~~(S)~~ The engagement geometry involves parameters that have a substantial effect on the performance requirements of an ASAT system. Of particular interest are the advantages and penalties associated with a quasi-coorbital approach trajectory, in that this trajectory is what is being used in the only existing ASAT today, and it is what was strongly suggested by ODDR&L in late 1976 as the approach to be followed for the so-called "conventional" ASAT. Elements of the engagement geometry that have a strong interaction

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*~~(S)~~ As part of the current Miniature Development Program, the possible involvement of SPADATS in a mission control subsystem is being examined.

include the previously discussed SPADATS error, the interceptor position and velocity errors at the beginning of the engagement, and the relative velocity between the two objects. Driving the design of the system, of course, is the range at which the target can be detected, as was true of the Soviet system design. While detection range is not discussed in detail in this section, its importance must be borne in mind.

~~(S)~~ Consider the quasi-coorbital approach geometry used by the Soviets in their ASAT tests. Having the ASAT in almost the same orbit as the target satellite makes the relative velocity between the ASAT and the target very small. By careful application of thrust, the attacker can extend the engagement time to last as long as is desired. For example, one could implement an inspection system for use prior to the interception and destruction of the target satellite, as was considered in the SAINT program.

~~(C)~~ Further advantages of a low relative velocity between the two objects, and therefore a long time of engagement (for a given acquisition range), include the provision of sufficient time to point a directional warhead (discussed later) and a relaxation of the rather serious requirements on fuze timing.

~~(S)~~ The prices one pays for these advantages are large ones:

- The interceptor must be boosted to orbital rather than suborbital velocities.
- The time of interception cannot be severely urgent, because it may take several orbits to achieve interception.
- The propulsion system may require dual thrusters per axis—large engines to obtain the lateral reach needed and small engines to obtain the precise control needed to effect terminal homing interception.
- Finally, the kinetic energy delivered to the target must be produced almost entirely from the explosive in the warhead that drives the pellets, rather than being generated mostly from the relative velocity between the ASAT interceptor and the target satellite.

~~(S)~~ Since it is highly unlikely that the orbit plane of the target satellite will pass through the ASAT interceptor launch site at the precise time required for a launch into an intercept trajectory, there will be the necessity for a plane change at least as great as the offset angle at launch. The optimum (minimum-intersection-angle) point at which to change planes in the interceptor trajectory is one-quarter orbit downrange (or any incremental half-orbit later), and therefore the interceptor should be launched into the inclination that provides an intersection one-quarter orbit from launch. The velocity added at this point for low earth orbits is about 450 ft/sec per degree of plane change desired. The minimum step-over distance (between subsequent orbital ground tracks) for a low-orbit satellite is about 22° of longitude. Therefore, a satellite must always come within 11° of longitude of the ASAT interceptor launch site. The requirement is then set by virtue of having, in this illustration, a single fixed launch site (that is, Tyuratam) at about latitude 45° N. to provide the ASAT interceptor system with at least 3,500 ft/sec of velocity for the sole purpose of plane changes.*

~~(S)~~ Another requirement for the ASAT system is becoming apparent—that of the field of fire available to the launch site. If it is desirable to use the quasi-coorbital approach and there is but one launch site available, it will be necessary to have the freedom to launch almost directly into the inclination of the satellite to be attacked. Launch would take place when the phase angle were correct for the orbital passage nearest the launch site.

~~(S)~~ The would-be ASAT system synthesizer should now begin to appreciate the strong interactions among the engagement geometry, the number, location and restrictions on the launch site, and finally the system reaction time that is required of the ASAT in response to an order to destroy a specific satellite (or satellite set).

~~(S)~~ If multiple launch sites were possible—two, for example—they should be separated by 11 deg or 33 deg or 55 deg, etc., so as to require that a satellite pass within 5.5 deg of one of them and thus achieve the greatest reduction in the propulsion required to perform a plane change. The location of the launch sites relative to the

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*~~(C)~~ It is recognized that this could be reduced in effect by combining this maneuver with others, if others of equivalent magnitude are required.

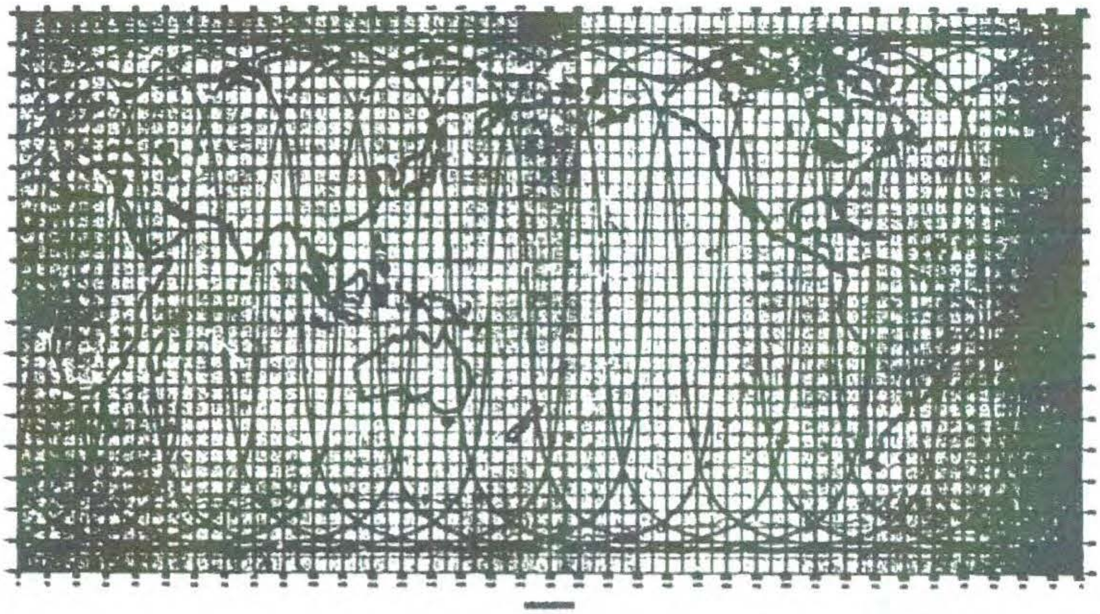

Figure 10. Typical orbits of a satellite in an 83-deg inclined orbit counting from a southern pass near Hawaii and first encountering the field of fire available from Vandenberg Air Force Base for a quasi-coorbital intercept. (Figure unclassified.)

position of the satellite in its orbit when the order to attack is issued is important, because it is necessary to wait until the satellite orbit nears the launch site in order to attack using the previously described mode of operation. For example, if a satellite were in an 83-deg inclined orbit and passing Hawaii on its way south when the order to attack were given, the first opportunity to ground-launch a U.S. ASAT out of Vandenberg Air Force Base would not occur for at least 21 hr. Figure 10 shows the ground track of such a satellite. One can see that the first time the satellite passes near Vandenberg going in such a direction that a quasi-coorbital engagement geometry can be enforced is on the 14th orbit after the order is given.

~~(C)~~ If system reaction time were essential, a number of options would be open, but not all might be acceptable for one reason or another. The options are discussed below.

~~(S)~~ One could launch into a retrograde orbit out of Vandenberg Air Force Base into the plane of the target and perform the intercept where the relative velocity between the ASAT interceptor and the target satellite (the sum of the actual velocities) is on the order of several tens of thousands of feet per second, rather than a few thousand (the difference in velocity). While such a geometric arrangement can be entirely feasible, for typical radar sensor detection ranges it does result in a total engagement time of a few seconds. Longer range sensors, such as passive long-wave infrared, would extend the time to a few tens of seconds—still not a practical solution in view of the state of the supporting propulsion and guidance technologies.

~~(C)~~ The range safety limits of the Vandenberg launch site could conceptually be altered so as to allow a launch in the example 83-deg orbit in a northeasterly direction, reducing the time to initiate the engagement to less than 12 hr. However, such action would risk the lives and property of people along the boost trajectories.

~~(S)~~ A number of launch sites could be built, preferably on islands where there may be a nearly all-azimuth field of fire available. This is a direct, but expensive, solution to the problem, and its implementation would depend upon the perception of national need relative to the competition for the funds available to defense.

~~(S)~~ Mobile launch platforms have been considered from time to time as having application, not only to the launch-site selection problem, but also to the potentiality of a covert launch as a counter-countermeasure. Although a surface ship would be an ideal platform, it would be unreasonably expensive to dedicate a vessel large enough to be practical to this mission. A missile-launching submarine would be well suited to take on this additional mission, but the current view of the role of missile-launching submarines is that of offense against ground targets, and it would take a strong hand at the helm to alter that view, even though the principal U.S. assets at risk from current Soviet operational weapon-associated satellites are capital ships of the Navy.

~~(S)~~ An air launch of an ASAT is not unreasonable. Current efforts of SAMSO are to develop a miniature interceptor that can be boosted to an apogee at satellite altitudes using vehicles such as modified short-range attack missiles (SRAM's) launched from F–15 aircraft. Recent demonstrations have shown that boosters as large as *Minuteman I* can be air-dropped and fired from C–5A aircraft. In-house studies by Lockheed Georgia show the feasibility of using other boosters and other aircraft, such as the C–141.

~~(S)~~ An airmobile booster has several advantages and disadvantages that are summarized here. Potentially, a jet cargo aircraft or an extended-range fighter could, in time of need, be diverted to a site in the far northern latitudes and be fitted with an already checked out and prepared module (or modules) containing the complete ASAT system hardware. The aircraft could then fly (with a much shorter transit time than a ship) to its first possible encounter orbit and (perhaps have the range-safety freedom to) launch the ASAT on its mission. If the payload were sufficiently small and light (implying the success of the current miniature ASAT program), the aircraft could salvo against high-priority targets, proceed to the next possible encounter point, and refire in case of failure of the first launch or proceed to engage a second satellite.

~~(C)~~ The arguments against such a scheme include the availability of suitably modified aircraft with trained crews in geographic locations from which such an operation could be carried out. Modification kits, while not complex, could be expensive. Availability of aircraft at times of high national readiness would be questionable. Crew training would be both expensive and time consuming. (Similar arguments apply to ship basing.)

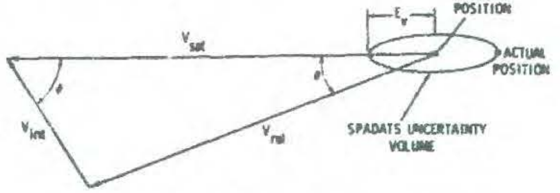

Figure 11. Satellite intercept geometry.
(Figure unclassified.)

~~(C)~~ Since fixing the position of the launch point at the time of launch is as important as predicting the position of the satellite at the time of intercept, these aircraft would have to be equipped with navigation devices possibly of a quality higher than their usual operational needs. Adding these devices might represent a nontrivial cost consideration.

~~(S)~~ Another candidate mode of operation that would be responsive to the requirement for an intercept in the shortest possible time after the decision to intercept were made is to launch the ASAT interceptor on a direct-ascent, but suborbital, trajectory such that it crosses the orbit plane of the satellite at the time the satellite is there, not waiting for the orbit of closest approach. Although time responsive, this scheme is not conservative of energy and may induce severe technological problems.

~~(S)~~ Depending on the field-of-fire limitations of the launch site, the engagement could take place within a few hours of the decision to launch. The engagement would begin with the velocity vector of the satellite substantially different in direction from the velocity vector of the interceptor. Figure 11 shows a representation of a typical encounter geometry, and the additional propulsion requirements to perform in the crossing-course mode are calculated below.

~~(S)~~ As was described earlier, the shape of the volume of uncertainty for low-earth-orbit satellites for the SPADATS is an ellipsoid with the longest dimension along track. Collinear intercept schemes using on-board homing sensors view this uncertainty essentially from along the satellite track.

Some schemes allow the satellite to catch up to the interceptor, whereas others give the interceptor the velocity advantage. Under these conditions, the along-track component of error, E_v, does not enter into the computation of propulsion requirements. However, if there is a substantial angle, shown as ψ in Fig. 11, between the velocity vector of the satellite, V_{sat}, and the velocity vector of the interceptor, V_{int}, and if V_{int} is not small compared to V_{sat}, then the on-board sensor will see a component of E_v.

(S) If, as shown in the figure, the actual position of the satellite is behind the expected position, the interceptor must have a lower velocity in order to make the intercept. The adjustment of the velocity is independent of any other corrections that must be made to take out the radial or cross-track errors from SPADATS.

(S) The velocity required normal to V_{rel} and normal to the line of sight is

$$\Delta V_{req} = \frac{E_v \sin\theta}{T_{ot}}$$

where T_{ot} is the time of flight to the intercept point. Since

$$T_{ot} = \frac{V_{rel}}{R_D}$$

where R_D is the range at which the interceptor can begin to make corrections based on sensor-acquired data, then

$$\Delta V_{req} = \frac{E_v \sin\theta V_{rel}}{R_D}$$

But, by the law of sines, we have

$$\frac{\sin\theta}{V_{int}} = \frac{\sin\psi}{V_{rel}}$$

and then

$$\Delta V_{req} = \frac{E_v V_{int} \sin\psi}{R_D}$$

(S) Thus, it is seen that the additional velocity required solely to take out that component of SPADATS error along track is proportional to the magnitude of the error, to the sine of the angle between the velocity vectors, and to the magnitude of the interceptor velocity. It is inversely proportional to the range at which the engagement is initiated.

(S) An extreme case exists in which there is a large crossing course and a high interceptor velocity, such as might occur when a time-urgent intercept is necessary and the satellite under fire is several orbits away from the ASAT interceptor launch site. If one assumes $\psi = 45$ deg and a satellite ephemeris error of 3 nmi along track, with a sensor capability allowing the engagement to start at a range of 50 nmi, then the additional propulsion required to correct for the along-track error amounts to 42 ft/sec per 1,000 ft/sec of interceptor velocity.

(S) From these calculations, it is easy to see what price in additional propulsion must be paid for timeliness of intercept obtained via a crossing-course, direct-ascent intercept geometry. Further, it also points up the relief that might be obtained through better satellite ephemeris prediction techniques and sensors having longer (effective) range. A large propulsion unit sized to deal with the large velocity increments brought about by the pressure of early negation may well be too large to be effective in the end game, where the interceptor must reduce the miss distance in a precise manner to within the lethal range of the warhead.

(U) It has been seen in the above discussion that timeliness of response can have a large leverage—either on the basing required to support an intercept a short time after the order is issued or on the performance of the ASAT interceptor subsystems.

(S) While the required operational capability document[9,10] discusses the need to negate newly launched satellites within two revolutions (720 deg) in their orbits and to negate the long-term resident satellites within 24 hr, there is little support in that document for either requirement.

(S) Let us consider the requirement to negate a newly launched satellite before it has completed 720-deg central angle from launch. Plesetsk is the launch site most often used for reconnaissance, data gathering, and surveillance satellite launches, although the RORSAT and EORSAT come out of Tyuratam. Figure 12 shows the ground track of satellites launched from Plesetsk to a 100-nmi circular orbit for their first two revolutions, 720-deg central angle, using the range of inclinations

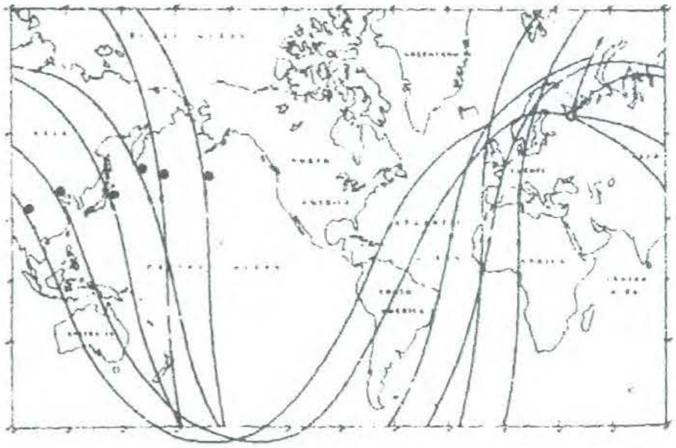

Figure 12. Ground track of first two orbits, 100-nmi circular inclinations of 63, 73, and 83 deg. (Figure unclassified.)

(63, 73, and 83 deg) normally associated with those satellites. During the first two orbits, satellites with these orbital inclinations view little that is of strategic importance to the United States. Indeed, there might be some coverage of South America and considerable coverage of Western Europe, but there is little of strategic importance there.* If one were to make the argument on a tactical operations basis, there would be more ground; but if so, the question of when the data are acquired and retrieved becomes paramount. First is the question of the quality of early ephemeris data. So little is known of the SPADATS capability (*1*) to detect the launch of a Soviet satellite and (*2*) to calculate the ephemeris based on whatever SPADATS sensors are available and with the possible assistance of other non-SPADATS sensors that might be available at times of high stress, that it would be difficult to predict how one would operate with potentially degraded ephemeris data. An alternative—even less attractive—is to make the intercept after the reconnaissance data are acquired but before they are dumped. Unless the United States could establish a base from which it could carry out its ASAT mission during that short time between the satellite's data acquisition over the Mediterranean Sea, for example, and the possible dump of its data a few tens of minutes later over its homeland, the United States would be hard put to enforce this requirement.

~~(S)~~ A question of operational checkout should also be raised. It appears that it would be possible to make the first orbit of a photoreconnaissance satellite a data-gathering orbit, if useful information could be obtained on that orbit. The technology is well known, and the terrain background (for location determination) is fixed and easily identified. As one goes to elint or ocean reconnaissance satellites, the problem changes because of the lack of a fixed grid system to make location positive. Until the ephemeris of a newly launched satellite is known and the errors in the satellite's attitude control system are compensated, the data derived from it might not prove useful. Our own experience with this type of equipment suggests that the several weeks now required could be compressed to several days, but not to less than 3 hr (two orbits).

~~(S)~~ Clearly, the quick-reaction requirement should be reevaluated in the light of the above discussion and other considerations.

~~(S)~~ Alternatively, the Air Force should reconsider the arbitrary statement regarding the 24 hr allowed for the negation of the satellites in residence that the Air Force considers threatening. As was discussed in an earlier section, some satellites are more threatening than others. Of those that are threatening, the level of threat is highly dependent upon the perceived capability of the satellite and its location. For example, at a time when international tension is high, negotiations have broken down and ceased, troops have been alerted, and a pair of ocean reconnaissance satellites, a

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*~~(S)~~ Worldwide, useful photoreconnaissance data could be obtained in the first few orbits only if the Soviets broke their long-established practice of launching into only these stereotyped inclinations.

RORSAT and a EORSAT, are only two orbits from the American fleet, one would look upon these satellites as candidates for interception in much less than 24 hr. In like manner, in a similar high-tension situation, a real-time meteorological satellite (METSAT) or elint satellite about to make a pass over West Germany should be a candidate for immediate interception.

~~(S)~~ It would appear that those who periodically revise the required operational capabilities documents could well give more serious thought to the nature and location of threatening satellites and how these would affect a U.S. ASAT system. The definition of system reaction time alone could alter the future of the U.S. system that is now in the embryonic stage.

~~(S)~~ There are substantial interactions among the location, number, and possible mobility of launch sites, the order and timeliness of negation, the accuracy of SPADATS, the range capability of the sensor, and the resulting propulsion requirements on the interceptor system. Thus far in this analysis, a question of technical feasibility does not appear—only one of practicality and cost.

~~(S)~~ For the interceptor, the most benign and least energy-demanding engagement situation is a nearly in-plane (orbit of closest approach to the launch site), suborbital, apogee geometry. Deviations from this standard raise the cost of the system. Payment can be made in the form of delay in operation, multiple launch sites, mobile launch sites, or improved propulsion and/or on-board sensor.

~~(S)~~ If a system can be made small, it will probably cost less. In the ASAT systems studied to date, the booster and related operation and maintenance costs dominated the system. Therefore, a lightweight terminal stage, no matter how costly, will permit a lower overall cost system.

~~(S)~~ It appears that there may be targets that will require negation within a short time of the decision that they must be destroyed. Under these rules and with the desire to keep the system costs low, one must reexamine the roles and missions assigned to be satisfied that ADCOM is the appropriate ASAT user. In addition, a cost/benefit analysis must be performed to consider single, multiple, and mobile launch sites without the constraints of current military structure. For example, ADCOM could not seriously consider the use of a large booster air-dropped from a cargo aircraft flying from an overseas site.

~~(S)~~ There are no critical issues, per se, with regard to engagement geometry; that is, there are no serious singularities upon which the success of an ASAT depends. There is, however, a substantial, though subtle, interaction among a number of parameters which, if not properly addressed, may make the developed ASAT far more complicated and costly than it needs to be. The system reaction time, for example, does involve issues critical to successful design of the ASAT system.

D. MISS DISTANCE

~~(S)~~ It is not the purpose of this section to demonstrate that a specific miss distance can be achieved with a certain system against a certain class of targets. The intent is, however, to discuss the major factors contributing to miss distance in sufficient depth that we can be assured that the problem of achieving an acceptably small miss distance has a satisfactory solution. The miss distance that can be achieved is a key factor in the several ASAT mechanizations that are being considered for U.S. development, and it is therefore of serious interest here.

~~(S)~~ The Miniature Development Program (MDP) sponsored by the Space and Missile Systems Organization, AFSC (SAMSO) has been under way for several years at Vought and also at General Dynamics/Pomona. These are the current efforts on the Miniature ASAT, and the heritage can be traced in Fig. 1. In this concept it is expected that the vehicle itself can be made to collide with the satellite. Each contractor has a slightly different technique as to how this will be accomplished from a mechanization view, but the end result is the same—body impact. While one thinks of zero miss distance in this situation, in actuality the miss distance is the distance between the center of the interceptor and the centroid of radiation of the target. For targets with large vulnerable areas, there is less of a problem than for small targets, but while the concept of body hit to kill is not new (it was explored rather thoroughly in analysis and flight test during the ARPAT Program),(19) the success of MDP depends on the miss distance being made acceptably small (less than the sum of the radii of the interceptor and of the target's vulnerable area), and this is properly classified as a high-risk area.

~~(S)~~ A more conservative approach is being taken in an Air Force study program under the "Conventional ASAT" title. Here, it is assumed that the miss distance is not sufficiently small to ensure body impact, but an explosive-dispersed pellet pattern must be used to make up for the error. A significant weight penalty (with explosive/pellet warhead) must be paid for the inability to obtain body-hit kill. Warheads presently being considered weigh several hundred pounds, which, when added to the other components used to maintain a low-risk, conservative approach, raise the total interceptor weight to the order of 1,000 lb. This gross weight should be compared with a few tens of pounds for the minature vehicle.

~~(C)~~ The payoff for small miss distance is great. Dispensing with the warhead (and utilizing a lightweight sensor) can reduce the interceptor weight to a value that can be launched to the altitudes of the satellites on the near-term target list by a vehicle costing much less than *Minuteman III*. This cascading effect is of sufficient attractiveness to make the Air Force willing to direct its primary effort toward the miniature approach and to leave the conventional ASAT as a backup.

~~(C)~~ Miss distance is most strongly influenced by three inputs; (*1*) the accuracy with which the sensor can make angular rate (or angular position as a function of time) measurements, (*2*) the precision to which the thrust of the propulsion system can be controlled, and (*3*) the time that has elapsed from the first perception of the need for an incremental maneuver until a substantial fraction of the incremental maneuver impulse has been applied. More succinctly, sensor accuracy, thrust control, and system response time are the principal factors in determining miss distance.

~~(C)~~ That is, if one can make an angular rate (or position) measurement without error, generate exactly the required amount of thrust, and do both without any delay in time, then the miss distance of the system approaches zero. A number of simulations of the kinematics of an angle-only-measurement (as a function of time) homing system have been developed and exercised. For example, in support of the work being done for ODDR&E on the Space Defense Program, the Institute for Defense Analyses has developed a simplistic, transparent simulation of the end-game encounter between a miniature-type ASAT and a satellite. In this simulation, it was possible to vary the parameters of interest (that is, angle accuracy, propulsion granularity, and system response time) and ascertain their effect on the miss distance. The results indicated that, with reasonable choices of the values of these parameters, the miss distance could be made acceptably small.

~~(U)~~ The most extensive simulation of this kind known to us was developed by Vought to explore the interactions among the specifications for the various components and subsystems in the HIT interceptor, as well as to determine the ultimate effect on miss distance from the variations. Currently, this simulation is being modified slightly to model the engagement between the Vought mechanization of the MDP and a satellite; the previous model was for an engagement between HIT and a reentry vehicle.

~~(S)~~ General Dynamics/Pomona has a simulation that models the General Dynamics mechanization of the MDP engaging a satellite, and the results are substantially the same; that is, by proper balance among the important parameters, a near-zero miss distance (less than a foot) can be achieved for cases where there are reasonable component specifications.

~~(U)~~ In support of their work on the midcourse interception of reentry vehicles by homing interceptors, several contractors have modeled the engagement.([illegible]) Here the interceptor was of a more "conventional" design, as opposed to the MDP. The sensor was large and gimbaled, the thrust was controlled in magnitude and direction, the warhead required fuzing, and realistic time delays for the various subsystems were modeled. Again, the results showed that for very small sensor errors, fine thrust control, and little time delay the miss distance approached zero. Realistic values of the performance parameters of the "conventional" components and subsystems drove the miss distance up to the order of 10 ft, illustrating the fact that larger systems are harder to control accurately because of their larger inertias.

Refer to USD (R&E)

TABLE 3. *Qualitative comparison of sensors. (Table classified ~~Secret~~.)*

Sensor	Weight	Size	Range	Angle Error	Available Signal From Typical Targets	Risk	Remarks
Radar	High	Large	Short (power-limited)	Medium	Active sensor, therefore limited by radiated power	Low	Range data also available
LWIR	Low	Small	Long	Small	Moderate	High	Requires cooling
SWIR	Very low (hot targets)	Very small	Long (hot targets only)	Very small	Very little	Moderate	Best operation against hot targets
Visible	Low	Very small	Moderate	Very small	Moderate (function of size)	Moderate	Has basing and/or response time limits

~~(S)~~ From these studies and observations it is concluded that the prediction of miss distance between an ASAT interceptor and a point target is well understood. The mechanizations that have been constructed are realistic and produce miss-distance values near 10 ft for the large vehicles and near zero (less than 1 ft) for the miniature ASAT version.

~~(S)~~ The effect on miss distance of a distributed, rather than point, target is of some concern. One can easily make the argument that a reentry vehicle approximates a point target, but it is impossible to represent large satellites of the RORSAT or EORSAT class as point targets. Investigations are under way not only at the MDP contractors, but elsewhere, to attempt to ascertain the effect of nonpoint targets and to develop a sensor/data processing technique that will in effect reduce a distributed target to a point source of energy.

~~(C)~~ Other efforts to deal with the potentially disruptive effect on miss distance due to a distributed-radiance target include kill-enhancement devices such as very-small-pellet warheads, rod warheads, net warheads, and sheet warheads. These are intended to be deployed just prior to the point of closest approach at a signal from a suitable sensor (in this case, a fuze). It appears that this approach is merely a different version of the fuze/warhead problem and that it should be considered in that light.

E. SENSOR SELECTION

~~(C)~~ Sensor accuracy has long been an area in which significant improvements are continually being made. The early radar trackers, where the angular error was measured in degrees, have given way to the more precise, high-frequency, fire-control radars, where the error is measured in mils. Long-wavelength infrared (LWIR) trackers have a significant advantage in wavelength over radar in defining angular error, but they still fall short of the short-wavelength infrared (SWIR).

~~(C)~~ In addition to the inherent capability of a sensor to measure angle, given a sufficiently high signal level, two additional desirable characteristics of a sensor should be considered: (*1*) the generation of a high internal signal-to-noise ratio and (*2*) the incidental ability to measure range. Range measurement is a useful, but not a necessary, source of guidance data. If available, it would be used, but comparably accurate guidance commands can be generated without range data. Range measurements are of great value for fuzing, which will be discussed later. A qualitative view of the four distinct sensor types is given in Table 3.

~~(S)~~ In an assessment of the characteristics of the sensors listed for a possible role as a guidance component, it is immediately seen that a SWIR device would give accurate angle track data against a hot target and be small, light, and at low risk. Unfortunately, satellites generally have low temperature, so SWIR has little value. Radar (here assumed to be microwave), while large and heavy, is low-risk and does provide range data. The angular accuracy possible is coarse when compared to IR and visible, but it could be used (it is used by the Soviets) for an ASAT sensor. The principal shortcoming is that of limited range—limited primarily by the weight necessary to generate the power to travel both ways and still provide a signal-to-noise ratio high enough

Refer to USD (R&E)

to be useful. LWIR has its greatest sensitivity, and therefore its greatest capability, against warm targets, typified by satellites. The sensor size can be much smaller than radar, but not quite as small as SWIR might be. Cooling is a serious problem, and its seriousness (in terms of weight and power to produce lower temperatures) is a function of the sensitivity desired. Few LWIR sensors have been built at all, and fewer yet have been built specifically for space object detection. Current efforts are expected to bring to test designs that are suitable for ASAT systems in the next few years; hence, LWIR sensors are still considered high-risk items of technology.

~~(S)~~ Visible-light sensors have been considered for an early-capability miniature ASAT using the Army's HIT vehicle,([illegible]) and these were given some serious thought during and after the Air Force-sponsored ICAS study.([illegible]) Visible-light sensors do exist that could be modified for use in an ASAT, but the use of visible light requires that the engagement take place in sunlight and with the sun-target-sensor geometry such that sufficient light is reflected from the target to allow the interceptor to begin track at a useful range.

~~(U)~~ Selection of a sensor suitable for the ASAT mission is not, in this case, based on the ability to measure an angle precisely. The four sensors listed in Table 3 will qualify. SWIR cannot be considered, because of the very small signal available at short-wavelength IR from a satellite. The choice is among visible light, radar, and LWIR, and the basis of selection is really one of evaluating tradeoffs such as time and risk versus size and cost versus operational difficulty. That is, an LWIR sensor, if it can be developed (risk), will take several years (time); or a radar sensor for an adequate range capability will be heavy, necessitating a large booster (cost). Our perception of the Soviet design experience has shown that being range-limited has serious consequences: Very demanding performance requirements are levied on other components, a compromised system performance may result, or both. However, if there is a demanding requirement that an ASAT capability be fielded as soon as possible against the threats that are considered here, with little or no regard to cost or to growth capability, one should give serious consideration to a radar sensor.

~~(U)~~ The advantages of small size and early capability can be captured if a visible-sensor path is followed, but the operational problems could be overwhelming. Should there be a desire for an early limited-capability (but not minimal-time) system that can grow to full capability, the Air Force should undertake a study to explore and quantify the limits of a system using a visible light sensor and, on the basis of this study, perhaps assess this as the preferred route to follow.

~~(U)~~ The LWIR sensor is high risk, in that none has yet been built for the ASAT purpose; but when it is realized, it will provide full capability at small size and, therefore, low system cost. With the present situation of a rather leisurely development cycle for the ASAT, this is almost certainly the route to follow, since the real element in risk here is one of time of development and not one of requiring an invention or a better understanding of the physics.

F. PROPULSION REQUIREMENTS

~~(U)~~ The propulsion system on the interceptor can be considered as performing two functions: (*1*) that of moving the interceptor on a coarse normal to the line of sight to the target (lateral range) and (*2*) that of providing thrust of the precise magnitude and timing to ensure intercept. For the first requirement, a large-thrust engine is usually indicated in order to displace the interceptor in the time between target acquisition and interception, so as to cover completely the volume of uncertainty that surrounds the satellite's predicted location. A large engine can also make up for a range-limited sensor, a poor booster guidance system, a poor satellite ephemeris-measurement system, or some combination of these.

~~(U)~~ Before considering the miss-distance contribution of the propulsion, let us first examine a few practical aspects. Large rocket motors often generate vibration of sufficient magnitude to inhibit a sensor from making measurements. Thus, in some mechanizations one sees restartable (liquid) rocket motors or multiple (solid) rocket motors. Liquid-motor technology has been predominantly limited to large spacecraft, where the tankage, plumbing, and motor inert weights are not significant, and few are seen in a size similar to the miniature ASAT. The two mechanizations of the miniature ASAT use multiple, very small, solid rocket motors fired sequentially on demand. The technology tradeoff between liquid motors from the well-understood space applications and newly developed restartable motors is not clear at this time; no preference can be stated.

~~(C)~~ To correct a sensed miss distance, it is necessary to provide exactly the right amount of thrust normal to the line of sight to the target at exactly the right time. Because the thrust-time history of large motors is difficult to predict with precision and because practical throttling ratios (maximum to minimum thrust) for controllable-thrust motors seldom exceed 15, the designer with the end game in mind usually strives either for small values of thrust with throttle-susceptible or restartable liquids or for multiple solid rockets.

~~(C)~~ The end product is of course a compromise. Some designs use large engines for maneuver and small engines for end game. If the engine is small enough, it need not be off when the sensor is taking measurements. In some designs, the engine is throttled to its minimum thrust as the intercept approaches and the requirement for propulsion diminishes. In other designs, the constant-thrust engine is oriented away from the normal to the line of sight, so that only the desired component of the thrust vector is in a direction normal to the line of sight and the remainder is expended along the line of sight, where it has no effect on miss distance. In this way, the difficulty in providing a large throttling ratio is traded for additional computation and a precision attitude-control system.

~~(C)~~ There appears to be a large variety of solutions to the propulsion problem. The current state of technology is broad enough to allow the interceptor designer to choose a solution that will not tax the rocket industry. In view of the many improvements in propulsion in recent years, there does not appear to be a key issue here.

G. RESPONSE TIME

~~(C)~~ The final important contribution to miss distance to be discussed is response time, here defined as the time lapse between the instant that there is a sufficiently large error for the sensor to detect and the time that the interceptor has achieved a large portion of the response necessary to eliminate the error, a portion usually defined as 90 percent of the impulse required to overcome the error. System response time is the sum of the individual component or subsystem response times. The principal components of the response time in a typical ASAT system are the sensor response time, the data-processing delay, time to rotate the interceptor (or some portion of it) to point the thrust in the proper direction, and the delay entailed in overcoming the inertia of the interceptor and changing its velocity (a function of thrust-to-weight ratio). Optical sensors and modern computer technology can make the sensor response time and data-processing delay small. The rotation time can be made small only through clever design, and as was discussed earlier, the inertial delay is a compromise in the rocket engine size selection.

~~(C)~~ Of the many designs that have been considered, great care has been taken to control response time and hold it to a value at which small variations have little effect on the miss distance.

~~(S)~~ In summary, the three most important contributors to miss distance are sensor accuracy, thrust-control accuracy, and system response time. Investigations of these, as applied to the ASAT problem, have shown that the miss distance against a point target can be made satisfactorily small with current technology and design tools. Selection of a sensor will be made on factors other than miss distance—primarily system cost and risk (length of development time). The current efforts to understand the effect of a distributed target must yield a satisfactory solution if the miniature ASAT concept is to prevail.

H. WARHEAD

~~(S)~~ The miniature ASAT concept calls for a final miss distance so small that body impact should occur, and no warhead would be needed. For the conventional ASAT concept, however, the miss distance is assumed to be small, but not zero, necessitating a warhead to distribute sufficient energy to kill over the area whose radius is the miss distance.

~~(C)~~ A number of warheads have been developed over the years whose designs could be slightly altered to provide adequate capability for a conventional ASAT. A few are described here to assure ourselves that, while important to the concept, the warhead involves no critical issues. It is considered a straightforward engineering problem.

~~(C)~~ Surface-to-air and air-to-air missile systems have long depended on kinetic-energy transmission devices such as rods, pellets, or fragments to destroy targets of interest, which are usually aircraft or missiles. In general, the warhead designs consist of a mass of projectiles surrounding an explosive charge. At the proper time, the charge is detonated and the projectiles are driven in a pattern that expands radially outward from the flight path of the interceptor while maintaining uniform density. The principal difficulty with this type of warhead stems primarily from a lack of ability to predict the time history of the end game with sufficient accuracy. The design of the warhead requires prior knowledge of the expected maximum final miss distance, the relative velocity between the interceptor and the target, and the projectile weight and spatial density required to ensure that the target is destroyed. Coupling this knowledge with the principle of operation of the fuze, the warhead designer can specify the fuzing distance, the projectile design, the explosive charge, and the other requisite design characteristics that will at the right instant produce a distribution of projectiles that is suitably uniform over the miss-distance disk.

~~(S)~~ Secondary design issues for atmospheric applications deal with the effects of the angle of attack of the interceptor, the ballistic coefficient of the projectiles, and the desire to have the effectiveness degrade gracefully from the design operating conditions and, thus, give the warhead the greatest latitude possible for employment. The energy delivered to the target usually comes from the relative velocity between the interceptor and the target. Should the relative velocity be inadequate—and it is inadequate in the design of the Soviet ASAT—it will be necessary to add velocity to the projectiles in a direction along the line of sight to the target in addition to directions normal to it (radial). Now the projectile distribution assumes the form of a frustum of a cone, rather than a flat plate. Angle-of-attack effects become more critical in this case. In the space encounter, the angle of attack can be equated to the angle between the body (or warhead) axis and the line of sight to the target. There is no sensible atmosphere, of course, so there is no true angle of attack or any slowdown effect of ballistic coefficient.

~~(C)~~ Now there arises a competition between the warhead and the sensor for the favorable location at the front of the interceptor. The sensor should be in front to maintain an unobstructed view of the target, and the warhead should be in front to make possible an unobstructed distribution of projectiles toward the target. As the relative velocity between the target and the interceptor becomes smaller and smaller, the cone angle of the warhead shrinks until the warhead pattern resembles that of a shotgun, and the projectiles do not suffer serious interference from an antenna mount that shares the favored forward surface. But then warhead pointing becomes critical.

~~(S)~~ In the configuration of the Soviet ASAT interceptor vehicle, it is deduced that both the warhead and the radar sensor are on one end of the structure, with the warhead perhaps slightly behind. It is observed that when the warhead is detonated, the radar becomes inoperative. This indicates that the radar was destroyed by the detonation of the high explosive driving the projectiles or by the projectiles themselves when they passed through critical radar components.

~~(S)~~ The energy required in a projectile is a function of the target being attacked. In the case of a compact and structurally rigid target such as a reentry vehicle, the required energy per projectile is high, and the number of impacts to destroy the target is seldom more than one. For a large, lightweight structure such as a satellite, the required energy per projectile is low, but because the shock of impact does not propagate as well as it does in a rigid structure, the number required is often stated as being more than one.

~~(C)~~ The ABM community has spent considerable effort in the design of projectiles that are very effective against the very dense reentry-vehicle targets they seek to destroy. These optimized designs, generally rods oriented in the direction of impact, deliver the most energy per frontal area, but they are not required for satellite targets. The orientation of the rods at impact is critical, and the difficulty of orienting the rods is great; the payoff against light structures is negligible.

~~(C)~~ Although the warhead may seem complex in detail, its designer really has a fairly straightforward engineering task. For low closing velocities, the mass-to-charge (mass of projectiles to weight of explosive) ratio must be low in order to deliver the necessary energy to the target. The projectiles will generally be pellets whose radial velocity component is adequate to cover the miss distance in the time allowed. The warhead industry is mature, and it needs little or no prompting to make its technology available to the ASAT community.

I. LETHALITY

~~(S)~~ An area of serious concern in the development of an ASAT system is the effect of the impact of a projectile on a satellite. A great number of studies and experiments have dealt with the impact on proof plates of pellets of different shapes and of various materials, weighing different amounts, traveling at different velocities, and arriving at various angles of incidence; but there has been little, if any, attempt to correlate these data with regard to their individual or cumulative effects on a satellite structure. There are still two diametrically opposed points of view on hypervelocity impact damage to a satellite, both widely held in the community. One asserts that the hypervelocity impact of a pellet anywhere on a satellite will send through the structure a shock wave that will arrive at a vulnerable component with sufficient amplitude to render the satellite inoperative. The other asserts that a light, compliant structure such as a satellite will not support the propagation of a shock and that, while the pellet will undoubtedly destroy the component it strikes and in most cases will pass through it, damage will be confined to the local area. While we hold the latter view, we do recognize that it is no better supported on an analytical or experimental basis than the other view. Clearly, more work needs to be done in this area in both analysis and experimentation. The ultimate experiment will be to impact a full-scale satellite-like structure with a hypervelocity pellet (or pellets) in a vacuum environment and to measure the damage.*

(S) There have been a number of studies and experiments on the effect of projectiles on U.S. reentry vehicles. Some of this work led to the design of the so-called spinning rod warhead for Program 922. That warhead consisted of two bundles of rods strapped together to form two cylinders in tandem. The reason for having two was to increase the density of the rod pattern. The cylinders were spun about their axis of symmetry, and at the proper instant the straps were removed. The centrifugal force caused the rods to spread radially outward, keeping their individual spin axes pointed at the reentry vehicle. The intent was that the rod density would be sufficient to ensure that at least one of the rods would impale and penetrate the reentry vehicle. Experimental evidence that this impact would provide a high-confidence kill of a reentry vehicle was never obtained, nor was there any assurance that a Soviet reentry vehicle or its payload would be structured in the same manner as the U.S. ones.

~~(S)~~ The studies of the lethality of a pellet or pellets against a satellite are even less satisfying. Again, data on pellets launched by a light-gas gun against a proof plate are cited, but they have even less relevance here than they did in the case of a reentry vehicle.

~~(S)~~ A number of tests of subscale model projectiles of the two (Vought and General Dynamics/Pomona) configurations of the Air Force MDP were made. The models were driven at hypervelocity speeds by a light-gas gun against a proof plate. Little useful information was gained. In general, the model projectiles broke up either in the barrel or in flight, and the data obtained from the few that did strike the proof plate could not confidently be scaled in size, velocity, or material. While the tests were expensive and impressive, they provided little gain in confidence over the analyses that support the earlier lethality studies for the MDP program.(25)

~~(S)~~ Several uncertainties need to be resolved, including (*1*) the vulnerable area of the target satellites, (*2*) the energy required to be delivered to that area for assured disablement, (*3*) the need for that energy to be delivered directly by the pellet or by propagation through the structure, (*4*) the benefits, if any, of impact at hypervelocity speeds, and (*5*) the need to define the failure mode(s) (including ECM and sensor-binding) to disable the target satellites.

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*~~(S)~~ Of course, asymmetric impact of pellets on a satellite can cause tumbling, but the magnitude of this effect is not predictable.

(S) Our lack of knowledge of the above factors may constitute the most serious deficiency in the current ASAT program. Once this knowledge is obtained, the argument between the proponents of a single impact of MDP and the proponents of the many pellets of the "conventional" ASAT can be resolved and a warhead can be designed.

(C) The cost of the system is almost entirely governed by the weight of the interceptor, which in turn is a very strong function of the weight of the warhead. This amplification from warhead weight to system cost is what establishes the criticality of the lethality question.

3. FUZING

(S) The function of a fuze is to provide a firing signal to the warhead at the precise time that maximizes the effectiveness of that warhead. The fuzing problem exists only in ASAT systems where the miss distance is large enough to preclude body impact or where the probability of negating the effectiveness of a satellite with a single (MDP) object is unsatisfactory. The fundamental uncertainty in a fuze system is the time until the point of closest approach ("time to go"). For ASAT systems with low closing velocities and small miss distances, sensitivity to errors in this predicted time is low. For systems where the relative velocities are above 10,000 ft/sec and the expected miss distance is in tens of feet, there are no fuzes in being, in design, or contemplated.

(S) One of the principal driving reasons for the initiation of the HIT program in 1963 by DARPA was to bypass the fuzing problem against reentry vehicles. It was thought that it would be easier to drive the miss distance of a small, agile interceptor to zero than to develop a fuze that would provide a timely firing signal to detonate a pellet warhead. Other ABM midcourse intercept systems have avoided the timing uncertainty in a fuze by incorporating a nuclear warhead, for which there is virtually no timing problem. Further, ABM systems do not have the advantage of reducing the relative velocities between the objects by launching in the same direction. Because ABM interceptors are required to operate at much higher relative velocities (ranging from 25,000 to 50,000 ft/sec), the time of engagement is much shorter and the fuze timing is much more critical than in satellite engagements.

(S) Design techniques used by surface-to-air and air-to-air interceptor systems have been considered for use in ASAT systems. In general, a (radar) sensor locates the target and, after making suitable range and angle measurements, calculates the time of closest approach. If there is sufficient time, the calculation is repeated and the predicted time is updated. Systems so designed are generally limited by radar power (and thus, by range-of-operation restrictions), as well as the high angular rates and accelerations imposed upon the angle tracker. Variations on this technique substitute laser radar for microwave and/or electronic scanning for mechanical trackers. Some innovative designs have been proposed that would generate three or more cone-shaped beams fixed at specific angles relative to the interceptor to detect the passage of the target through them. With three or more beams, the time of closest approach can be calculated from the time of penetration of the beams and used to detonate the warhead.(26)

(S) These systems appear to have merit, and if the conventional ASAT program is to be pursued beyond the system-design stage, it would be worthwhile to evaluate the several fuzing concepts that have been proposed and to fund the most promising through advanced design. Although appearing to involve a straightforward engineering design, these fuzes have never been built and their limits have never been fully explored.

(S) Other innovative techniques have been proposed that do not require a separate sensor or range data; they operate on information that is available from an angle-only sensor. They both take advantage of microelectronics and Kalman filter techniques. They are treated here separately from the above grouping because not only do they apply to the conventional ASAT out, because they have such little weight and volume, they could also be considered as an adjunct to the MDP interceptors, should it be determined that a single impact of the body upon the satellite would be insufficient to negate the satellite's effectiveness and that some form of kill enhancement should be provided.

(S) A technique suggested by Kearfott-Singer(27) requires that a precise maneuver be made early in the end game and that the effect of that maneuver upon angle and angle rate measurements be

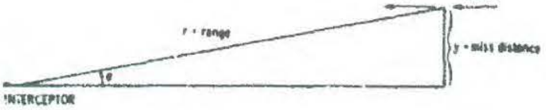

Figure 13. Geometry of intercept end game for fuzing. (Figure unclassified.)

coupled with the (approximate) data already known in the engagement to predict the time of closest approach. The analysis was briefly reviewed, and it appears sound.

~~(S)~~ Another approach suggested by McDonnell Douglas West(²²) requires that a seven-state Kalman filter be preloaded with the initial conditions of encounter such as range, range rate, and time to go and that then one of the outputs of the filter can be the time to go to an accuracy of 0.001 sec. Evaluation of this technique is being carried out by the Ballistic Missile Defense Advanced Technology Center, and their preliminary estimate is that it is valid for the ASAT application.

~~(S)~~ If angle measurements can be made precisely enough, the time to go can be calculated directly from the variation of the line-of-sight angle with time. In the coordinates of the diagram in Fig. 13, the angular rate is given by

$$\dot{\theta}=\frac{yV_{rel}}{r^2}$$

(where θ is small enough that sin $\theta \approx \theta$ and cos $\theta \approx 1$). The range to go is given directly from the above relation by

$$r=\sqrt{\frac{yV_{rel}}{\dot{\theta}}}$$

Differentiating, we have

$$\dot{r}=\sqrt{yV_{rel}}\left(-\frac{1}{2}\dot{\theta}^{-3/2}\ddot{\theta}\right)$$
$$=r\left(-\frac{1}{2}\frac{\ddot{\theta}}{\dot{\theta}}\right)$$

(making use of the first relation above to simplify). But $\dot{r}=V_{rel}$ and the time to go is approximately r/V_{rel}, so the time to go is given by a relation that involves angle measurements only:

$$t=\frac{2\dot{\theta}}{\ddot{\theta}}$$

The raw line-of-sight-rate data are generally too noisy to differentiate directly to give a clean value of the angular acceleration, but smoothing techniques such as the Kalman filter are said to be able to produce values clean enough to give the aforementioned accuracy for the time to go.

~~(S)~~ Of course, a value of the angular acceleration can be obtained simply from the overshoot in angular rate during the response time of the interceptor (for each impulsive motor firing). A firing signal is sent to the motor each time the angular rate exceeds a prespecified threshold. If the angular rate exceeds a second (higher) precalculated threshold before the motor can drive the angular rate back down, a signal can be sent to fire the warhead. The drawback of this technique is that the sampling interval is no finer than the motor-firing interval, given by $\Delta t=\Delta V/(2\dot{\theta}_T V_{rel})$, where ΔV is the impulse from a motor firing and $\dot{\theta}_T$ is the angular-rate threshold for a motor firing.

~~(S)~~ Thus, it appears that there may be a number of potentially useful approaches to fuzing an ASAT from an angle-only tracking sensor, either by separate means of generating additional data on which to fuze or by using tracking sensor data directly. The latter is probably more conservative of weight, volume, and power, but it requires analysis and verification before it can be implemented in an ASAT.

K. NECESSARY AREAS OF CONCERN, BUT NOT DRIVING ISSUES

~~(S)~~ A number of areas have been of concern to the ASAT community for some time that do not require serious study or expenditure of money, but are of sufficient importance to be discussed here, if only to ensure that they are not ignored in any U.S. ASAT development program.

1. Damage Assessment

~~(S)~~ There is always the problem of assessing damage to a satellite target. This is done to determine whether or not the assets being defended from the satellite are safe and whether or not the ASAT system should be refired to complete an initiated, but failed, negation. The need for rapid damage assessment is largely a function of the target being attacked and the urgency with which the negation is required. A number of techniques can be considered. A photoreconnaissance, elint, meteorological, or communication satellite typical of today's Soviet technology has a pressurized power-conditioning chamber,(18) the puncture of which will negate the satellite's mission. There is no necessity for the Soviets to remain with this design philosophy, particularly in the face of a possible U.S. Asat, so one would not want to depend upon mere assurance of rupturing the pressurized compartment for kill. In like manner, some satellites have known transmission patterns, and should these terminate or change after impact, it could mean that the function of the target satellite is substantially limited or negated. Again, we have no assurance that there is no prearranged second mode of operation ("peace–war switch") to be used only after an attack we have never observed and that we are therefore not prepared to evaluate.

~~(S)~~ A more nearly certain damage assessment is to observe the impact and to attempt, by use of sensors, to measure the energy release, which would also be a measure of damage. The same or other sensors might be used also to count the number of objects after interception and compare this to the number before, or to observe the operation of the attitude control system on the target satellite. By and large, the Soviet satellites are attitude controlled, and a simple means of determining that the useful life of a satellite is over has been to watch it tumble. A tumbling satellite would be considered completely negated.

~~(S)~~ The sensor for observing and assessing the damage could well be a current space object identification (soi) sensor, but soi sensors are few in number and are not located at the expected intercept points. Nonetheless, they represent the most reliable technique currently available. A proposed scheme for damage assessment, should such a scheme become of sufficient importance to pursue, is to equip the last stage of the interceptor booster with a sensor whose only function is to observe the intercept and report back. A variation on this scheme, if the interceptors are small enough, is to disperse interceptors sequentially and to use the second to observe the first and, if the first fails, to report back and then undertake to engage the target. The third interceptor watches the second and repeats the operation. Clearly, this is an area for innovation and invention.

2. Booster

~~(S)~~ Although the cost of the booster and its support constitute the bulk of the cost of the Asat system, there appears to be little cost reduction to be gained through innovation in propulsion. Early studies by the Aerospace Corp.(16) and the more recent ICAS study(24) support the argument that a payload approaching the weight of 100 lb could still be air-launched from a fighter or fighter-bomber aircraft and perform the low-earth-orbit mission in a direct ascent mode. Should the payload (interceptor) weight be between 100 and 1,000 lb, the booster requirements increase from an augmented sram (or an Alcor/Star motor) to a *Scout* or a *Minuteman*. In general, one would consider these vehicles as being ground-launched, although they could be air-dropped if it were very advantageous to the mission. Beyond a payload weight of 1,000 lb, the booster required is of the *Thor–Delta* class. It is difficult to conceive of an operational weapon system built around a *Thor–Delta*, in view of the operation and maintenance requirements, the large launch crew required, and the long turnaround time . refurbishing the launch site to fire a second round. There is clearly great incentive to keep the interceptor launch weight below 1,000 lb.

~~(S)~~ Not only would the booster used drive the cost of the system, but it could have an impact with regard to the SALT agreement limiting the number of icbm launchers. If a *Minuteman* were chosen for the Asat booster, would it be counted as an icbm? The answer is not clear. While there is a certain correspondence between Soviet weapon-system boosters and the Soviet space-launch booster and while the United States can normally discern the difference, would the USSR accept U.S. space boosters derived from icbm's as willingly? It has been suggested that the proper definition of an icbm launcher is one from which an icbm is expected to be fired. In this country, the launchers are hardened underground concrete structures, they have removable hardened doors, and they are loaded with a known icbm. Since the Asat mission is quite different in operation, there is no need to use the same silo design or to protect the vehicle from more than the natural environment. Therefore, we might expect that a *Minuteman* on an above-ground open launch pad or in a shelter would not be regarded as an icbm.

~~(S)~~ The questions of what booster to use and whether or not it would be counted as an ICBM launcher are straightforward problems to be solved—critical, but solvable, and not key issues.

(U) Not considered here, of course, is the arms-control impact of ASAT's—the unknowable limitations that may be applied by SALT to ASAT systems.

3. Operations

~~(S)~~ There appear to be a few minor organizational problems with the operation of a U.S. ASAT system and only one of major concern. Should it be determined that the appropriate launch vehicle (whether an aircraft-launched SRAM or a ground-launched *Minuteman*, as typical examples) is neither now nor ever was expected to be in the ADCOM inventory, action must be taken to allow for its inclusion in the scope of ADCOM operations. This is largely a political problem internal to the Air Force.

~~(S)~~ In like manner, if the appropriate bases from which to launch the ASAT to ensure a timely intercept at lowest possible cost are not now ADCOM bases, it will be necessary to reconfigure the basing structure of ADCOM.

~~(S)~~ A principal operational concern is how SPADATS can become an integral part of a weapons system. At the present time, SPADATS has the task of maintaining a catalog of space objects. To do this, SPADATS attempts to establish the ephemeris of a newly launched object as soon as is practical and to predict the position of that and every space object 24 hr ahead, so that the tracking sensor, wherever it is, can easily reacquire the target and update the ephemeris. To do this in an orderly way, the Air Force has organized a group of sensors, some dedicated, but most of them shared with early warning systems operated and staffed by various organizations, some military and some civilian. What is not clear, and is therefore of great concern, is how this rather loosely knit group could function as a critical part of a real-time weapon system at times of high international tension, when many other demands might be made upon it.

~~(S)~~ The most serious and interesting problem with regard to operational capability will be to determine the number, location, performance requirements, and dedication of facilities necessary to support the planned ASAT system. Integration, coordination, and command and control of these facilities are critical factors for the successful operation of this real-time weapon system and are yet to be worked out.

4. Countermeasures

~~(S)~~ In designing any weapon system, one should always determine the susceptibility of the system to countermeasures and design into the system whatever safeguards are cost effective. The ASAT designer should consider the steps the satellite designer could take to protect his satellite from negation by the ASAT. The obvious choices are interference with the acquisition process by using decoys or jamming, avoidance of acquisition by jinking, or attack on the ASAT directly.

~~(S)~~ Using the Soviet ASAT as an example, one can examine the several tactics the United States could employ to avoid intercept. Since the Soviet system uses a rather simple radar to provide signals to the guidance system, only a simple jammer would be required to deny those data. The Soviet ASAT radar-tracker system is well characterized and it operates over a short and critical time span, and a jammer aboard the targeted satellite has the power advantage. The jammer could be turned on through detection by the target of the radar-tracker search signal.

~~(S)~~ Since it is known from what launch site (Tyuratam) the Soviet interceptor has always been launched (and current assessments indicate it will continue to be launched from there) and since the mode of operation of the Soviet system is expected to be well established (although at this writing it appears that the Soviets may be changing from a two-orbit intercept to a single-orbit intercept), when the launch of a Soviet ASAT occurs, the target for that ASAT can be determined by the United States to be within a small uncertainty volume. Since our DSP satellite can observe the ASAT launch and our SPADATS keeps constant predictions on our satellites' positions, should a launch occur when one of our satellites is vulnerable, there would be 1.5 hr (in the case of the single-orbit intercept) or 3 hr (in the case of the two-orbit intercept) during which attack assessment and evasive action might be accomplished.

~~(S)~~ The evasive action might be a modest maneuver to remove our satellite from the acquisition zone of the Soviet interceptor, or it might be the deployment of a group of decoys that would either confuse the acquisition process or perhaps present what appears to be a much stronger target than the ASAT. Detecting the radar emissions long before the ASAT can sense a return, the satellite could also trigger deployment of interceptors of the MDP class to directly attack the Soviet ASAT before it could attack our satellite.

~~(S)~~ The above examples serve to illustrate several features of an ASAT that could make it less susceptible to countermeasures; these are direct trajectory, antijam capability, maneuverability (lateral reach), large acquisition zone (angle and/or range), and target discrimination capability. Key factors in the above example of avoidance of intercept included a known ASAT launch site, a quasi-coorbital trajectory for the ASAT, and a well-understood radar tracker. If the trajectory of the ASAT were direct, then the time from launch to intercept could be on the order of 10 min, which would severely limit a reactive system for the satellite. If the launch were made from an aircraft or a submarine, it is not likely that a targeted satellite could be warned in time to react, even if there existed a Soviet launch-detection satellite analogous to our DSP. If the tracking signal were based on passive radiance or reradiance rather than reflection of an active signal from the target satellite, jamming or decoy dispersal would be complicated because of the time uncertainty of the attack due to lack of early detection of a radar emission.

~~(S)~~ Of the systems being considered by the United States for development, the miniature ASAT launched from an aircraft using an LWIR sensor has a clear edge over the others in providing the above counter-countermeasure characteristics. The same system, but with a sensor in the visible wavelengths, might be just as good; but since intercept would be limited to sunlit areas, this potential illumination weakness might be exploited. A ground-launched miniature ASAT system could of necessity deliver multiple interceptors to partition the volume of uncertainty generated by a jinking maneuver and be able to intercept every object, whether decoy or satellite. A ground-launched conventional interceptor with an LWIR sensor needs to have the lateral range to cover the uncertainty generated by jinking and the ability (discrimination) to identify the target in the presence of decoys.

~~(S)~~ Thus, from the expectation that Soviet countermeasures might be employed against a U.S. ASAT, it will be advantageous for the U.S. ASAT designer to strive for a long-range sensor with the possibility of discrimination and small size with the possibility for proliferation. If he is successful, he not only has in principle an effective ASAT (in early expected encounters) but an anti-ASAT (for the current Soviet ASAT).

L. KINETIC ENERGY KILL SYSTEMS SUMMARY

~~(S)~~ Of those issues addressed, five can be identified as key issues which, if unresolved, can have a deleterious effect on the U.S. antisatellite program. The five key issues are: (*1*) the target list, (*2*) the orbit determination system, (*3*) the system reaction time, (*4*) the miss distance that can be enforced, and (*5*) the lethality criteria on which satellite negation is based. Other issues, while contributing more or less to the difficulty of the ASAT task, have much less effect on the outcome of the development and are thought to be amenable to good engineering judgment.

IV. HIGH-ENERGY LASER OR BEAM WEAPONS

A. INTRODUCTION

~~(S)~~ Significantly beyond the technology described above are high-energy lasers and particle beam weapons suitable for use in an antisatellite system. Since lasers are considered a substantial advance in the state of the art, less attention is given them here than was given kinetic energy devices. Because particle beam weapons are even further future developments, they are only referred to, not described. The ground-based high-energy laser ASAT is thought to be the earliest achievable weapon of this class, and it is described in more detail in another paper in this series.

B. BACKGROUND

~~(S)~~ A "beam of energy" has long been the dream of the scientist as well as the science fiction writer. In 1898, H. G. Wells wrote

> It is still a matter of wonder how the Martians

> are able to slay men so swiftly and so silently. Many think that in some way they are able to generate an intense heat in a chamber of practically absolute nonconductivity. This intense heat they project in a parallel beam against any object they choose by means of a polished parabolic mirror of unknown composition, much as the parabolic mirror of a lighthouse projects a beam of light. But no one has absolutely proved these details. However it is done, it is certain that a beam of heat is the essence of the matter. Heat, and invisible, instead of visible light. Whatever is combustible flashes into flame at its touch, lead runs like water, it softens iron, cracks and melts glass, and when it falls upon water, incontinently that explodes into steam.(29)

It is interesting to note that he discussed the beam pointing by means of a parabolic mirror, the wavelength as not being visible, and the kill mechanism being that of a high heat load. Later in the same text he notes that the device gave off a "greenish gas." The description is a more-or-less accurate description of the HF or DF laser that is being exploited as the most practical (at this time) source of laser energy. Most of the weapons systems studies being conducted now or in recent years attempt to take advantage of the high efficiencies associated with chemical lasers coupled with their short wavelengths that allow relatively small mirrors to focus the energy on a small spot at a rather large distance. Prior to discussing the application of a laser to the ASAT problem, a brief review of laser technology is in order. A more thorough coverage, but still a primer on the subject, is contained in Ref. 30.

~~(C)~~ HF and DF lasers are chemical combustion-driven devices that lase in the 2.7- and 3.8-micron wavelengths, respectively. Some devices use either medium interchangeably, with the slightly different generation and transmission efficiencies associated with each.

~~(S)~~ The dry weight of the laser is about 0.5 to 0.3 lb/kw of useful laser energy generated, and it expends on the order of one pound of working fluid for every 200 or so kilojoules of energy. The weight of the tankage to store the working fluids, as well as the structure to support the laser, largely depends upon the proposed application and total beam-on time required before refurbishment.

~~(S)~~ At this writing, there are numerous HF/DF lasers operating in the 10-kw region and two larger lasers built by ganging a series of the smaller units. The baseline demonstration laser nominally operates at 100 kw, while the Navy–DARPA chemical laser operates at between 400 and 500 kw. Other larger lasers of the few megawatt class are in development and the optimistic system designer works with values in the tens of megawatts.

~~(S)~~ Mirror technology has progressed rapidly in recent years, being driven in part by the space astronomers and partly by the high-energy laser weapon advocates. A 2.4-meter-diameter mirror, diffraction-limited at visible wavelengths and suitable for space operation, is available today. Techniques for building larger mirrors, either monolithic or segmented, are being explored and DARPA has in development mirrors that can be folded for launch and then erected for space operation. Their goal is to demonstrate diffraction-limited optics tens of meters in diameter.

~~(C)~~ For high-energy laser operation, the reflectance of a mirror must be very high, or else there will be a severe penalty in cooling weight or in permitted operating time. While 0.99 was highly acclaimed in the past, 0.999 is currently available and 0.9999 is foreseen.

~~(C)~~ Active compensation for nonplanar illumination and/or turbulent atmosphere is also under development. These techniques, called adaptive optics, seek to compensate for the error by purposely deforming a small segment of the optics so that the beam is diffraction-limited when it arrives at the intended target. Active deformation in real time for a transient phenomenon, such as atmospheric turbulence, is no small accomplishment. There has been much success in this area, and it is promised that more is in store.

~~(S)~~ Of primary concern to the high-energy laser weapon system designer is the inability to isolate the laser beam from vibration brought about by bearing friction in the gimbals, unstable combustion in the laser, or vehicle motion. Jitter causes a smearing of the damage spot and, unless it is kept to a small fraction of the spot size, the penalties in power become great. Current demonstrated capabilities are at least an order of magnitude short of that which is desired.

C. LOCATION

~~(C)~~ The three approaches that have most often been considered for high-energy laser ASAT have dealt with ground-based, aircraft-based, and space-based weapons. Each has its advantages and disadvantages from an operational point of view, but more importantly, the technology requirements for each are quite different and therefore the question of immediacy is raised. Each is discussed in turn in an attempt to point out its salient features, but because laser weapon system technology is so new and so little is known of laser weapon effects, the details are limited when compared to kinetic energy kill interceptors.

D. GROUND-BASED LASER ASAT

~~(C)~~ The ground-based laser can be of almost unlimited size and weight, and efficiency is not a serious problem such as is seen for the mobile systems. The designer has an interesting set of parameters among which he must trade in order to achieve an effective system. Ideally, the weapon system site would be located as high as possible, atop an easily accessible mountain, perhaps, to minimize the thickness of atmosphere through which the laser beam must penetrate. A dry environment would also relieve the attenuation of the beam through the atmosphere.

~~(S)~~ With a single fixed installation, the array of satellites that can successfully be engaged is reduced. Because of thermal blooming and attenuation, there is a range beyond which sufficient energy to destroy a satellite cannot be delivered. A brief discussion of this phenomenon is contained in Ref. 31. Therefore, the ground-based system can only attack low-altitude satellites that pass near the laser site. Although the target list discussed earlier set the highest priorities on these very satellites and no others, it is seen that, while a ground-based system might be very effective in the near term, it has little growth potential. (This is not meant as a disparaging remark. The ground-based system could provide an effective ASAT during the interim period while the Soviets developed newer high-altitude satellites and we were developing other means to combat them.) As the altitude is raised, so is the period of the orbit lengthened, increasing the step-over distance of the satellite track on the ground. Therefore, not only are higher altitude satellites farther removed in vertical range, but they can be farther away because of the lateral offset between the site and the ground track of closest approach.

~~(C)~~ The most serious problem with the ground-based system is that of reaction time between the order to destroy a particular satellite and the satellite's destruction. The time lapse could be as much as 12 hr between the order to fire and its execution. However, if one assumes that a number of sites are built to solve the lateral offset problem, then proper choice of ground site would allow the ASAT system to attack a particular satellite with less delay. The locations of these sites are important to providing this timeliness, which then raises the problem of overseas bases at which to locate weapon sites. This problem is yet to be addressed.

~~(S)~~ The orbit-determination system, which was so important in the direct-attack, kinetic-energy-kill ASAT systems discussed earlier has far less demanding performance requirements in this application. Knowledge that a launch occurred (DSP) would alert the usual tracking stations, and a rough ephermeris could be established early in the satellite orbit. Since the microwave radars have the capability to search a large volume very rapidly and can easily detect the presence of an orbiting satellite when the satellite is still several orbits from the orbit of closest approach, it appears that a reasonably large microwave radar located near the laser site (or coupled to it through a parallax correction) would be a necessary adjunct to the system.

~~(S)~~ Given the orbital parameters, perhaps as crude as from DSP, a radar could search, acquire, and track the potential target satellite well before the laser system needs to be alerted. The tracking accuracy needs to be sufficiently precise only to minimize the efforts of the low-power laser tracker that would be an integral part of the laser ASAT system. Using either the same or auxiliary optics, the laser tracker would provide data to predict the orbit precisely for the attack, characterize the atmospheric parameters (moisture, turbulence, dust, etc.), and transfer the tracking parameters to the laser weapon system.

~~(S)~~ The wavelength chosen for the weapon would result from an evaluation of several parameters, the most important of which are interaction of that wavelength with the atmosphere (attenuation and blooming), efficiency with which the energy could be produced and directed, and the effect of that wavelength at that power level on the target satellite. The attenuation is less for 3.8 microns than for 2.7 microns, but the efficiency of generation is better at 2.7 microns and the mirror for that wavelength can be smaller for a given kill spot size, although the precision to which that mirror must be ground is greater.

~~(S)~~ Jitter is a less serious problem for a fixed ground-based system than for a mobile unit. The sheer massiveness that is possible in a fixed installation precludes significant motion of the components. It is expected that wavefront jitter and vibration from even the large bearings in the mirror gimbals can be compensated through the adaptive optics. However, the primary reason for the adaptive optics is to compensate for atmospheric turbulence.

~~(S)~~ As for lethality, the same problem exists as with the kinetic energy ASAT. The speculations that exist at this time require thorough analysis and experimental demonstration that a particular power level over a period of time will produce a satisfactory probability of kill. The current estimates of the energy required to kill a satellite range from 1 kJ/cm² to 10 kJ/cm², but it is generally agreed that for current Soviet satellites the centroid of the satellite is the center of the vulnerable area.

~~(S)~~ Assessment of kill also remains a serious problem. The techniques discussed earlier in this paper apply to the laser system as well, but here, since the kill mechanism is essentially one of heating and melting, it is possible that a spectrometer would be useful in measuring the energy deposition on the target and estimating kill on that basis. Other techniques using a spectrometer include the detection of materials known, a priori, to be within the vulnerable volume.

~~(S)~~ Should the kill dose be marginal, the prudent system designer would develop the capability for reengaging the target in a minimal time after kill assessment. This task is dependent upon the speed with which kill assessment can be accomplished, the available geography over which the repeat attack can take place, and the funds available for a backup laser site. A careful systems analysis will show whether the more economical approach is to reengage a target that was not destroyed in the first attack or to use the resources that would support the reengagement site to ensure that the first attack was of sufficient certainty to preclude the requirement for reengagement.

(U) Countermeasures is an area that requires considerable thought, especially at this time. The prudent system designer will incorporate the first-generation counter-countermeasure into his design to be assured of some finite life and, therefore, value to his system.

~~(S)~~ The obvious countermeasure for a ground-based laser ASAT is to rotate the satellite into the minimal cross section relative to the laser and to have a highly reflective surface covering that cross section. Since the satellite has knowledge of the location of the ground base, it would be a simple matter to interrupt the mission of the satellite during the time it can be attacked, protect itself in the above manner, and reinstate the mission when the danger area has been passed. The satellite operator must then determine if the mission can be aborted while over that area, which then establishes for the ASAT operator the need to locate the ASAT near the area where the satellite focuses its primary mission.

E. AIRCRAFT-BASED LASER ASAT

~~(S)~~ The next consideration in laser location is to utilize a large aircraft, a C–5A or wide-body jet, to carry the weapon system to a relatively high altitude to avoid as much of the atmosphere as possible and, perhaps more importantly, to give the ASAT system a capability to destroy an enemy satellite wherever and whenever it is important to do so. The price that one has to pay for this capability is not small, and several hitherto less important issues with regard to technology will be raised.

~~(C)~~ The target list will not be substantially changed, in that while the altitude is raised, thus reducing the effects of the atmosphere, there is a limit placed upon the size (weight) of the laser and its fuel supply. At this writing, there has not yet been published any tradeoff between the two driving parameters, and thus, it is not known whether the list is longer or shorter.

~~(S)~~ The more important issue is the unpredictable (by the satellite operators) location of the aircraft-based ASAT. If one assumes that the number of satellites that can be attacked is the same, then the requirement for the satellite to come to the ASAT is eliminated and the entire array of satellites is at risk. The satellite operator cannot count on being secure from attack, except during the rather short times of overflight of his own country. With the potential use of airfields the world over, the United States could have an ASAT that could respond very rapidly to an alarm and not have to deal with the countermeasure discussed earlier.

~~(S)~~ Another capability that could be associated with the aircraft-carried ASAT is the ability to carry out an attack and a reattack without the problems associated with fixed ground bases. An ASAT aircraft operating in the high northern (or southern) latitudes could attack a satellite and, if the attack were judged unsuccessful, could fly to the ground track of the next orbit and reattack. Note that with sufficient warning the aircraft can always proceed to a point directly beneath the satellite and attack without any degradation due to lateral offset range.

~~(S)~~ This capability does not come easily. Requiring that the laser and its fuel supply be transported in an aircraft imposes the consideration of specific power of the laser device, mass flow efficiency of the working fluids, and the design of a lightweight fluid supply and structural-support system. No longer would the system designer enjoy the luxury of being able to use virtually unlimited weight, volume, and coolant. Recalling the years of effort that have gone into the Airborne Laser Laboratory, one can hope that the system designer can and will take advantage of the many solutions to problems of aircraft-located high-energy lasers that were discovered there.

~~(S)~~ The requirements on the orbit-determination system are also greater than for the ground-based system. No longer can a large microwave radar be used as an adjunct to the laser device, in that the aircraft will already be crowded with the laser system components, and we cannot depend on operating near a ground radar that can support the ASAT mission. Thus, the orbit of the satellite to be attacked must be described with sufficient accuracy that a radar (microwave or laser) of the size that can be carried on board the aircraft can search, acquire, track and hand over the target to the laser weapon system early enough to effect a successful intercept.

~~(S)~~ Jitter is expected to be a serious problem in aircraft operation. For ranges of operation on the order of several hundreds of miles, it is desirable to have jitter down to a few tenths of a microradian. To date, the operation on a large (KC-135) aircraft attempting to track a target with a 0.6-meter mirror has experienced jitter on the order of a few microradians without a high-powered laser on board. Thus, it is seen that an order-of-magnitude improvement, plus whatever else is needed to compensate for the laser itself, is required.

(U) The wavelength chosen is now (in the aircraft-borne case) less dependent upon the atmospheric absorption and more dependent on the efficiency of generating a plane wave with little inherent jitter. Again, the tradeoff study to support this choice is yet to be made.

~~(S)~~ Kill and kill-assessment considerations are similar to those previously discussed, although it is doubted that a kill-assessment system could be implemented within the confines of the aircraft, and thus, refire would depend upon the availability of space object identification sensors to determine if kill was indeed accomplished.

~~(S)~~ Countermeasures for an aircraft-borne laser ASAT are more difficult to conceive than for the ground laser site. The form of the solution, however, should take into consideration the problems peculiar to aircraft-carried lasers. Limited weight and, hence, limited power could be exploited as well as the generally expected higher (than ground-based) jitter that would result from aircraft vibration and buffeting.

F. SPACE-BASED LASER ASAT

~~(S)~~ Space-based laser ASAT was the subject of a DARPA-sponsored study at LMSC, and this is reported in detail in Ref. 32. The scenario used by the investigators involved the requirement to negate a large number of satellites (about 75) in a short period of time. The periods studied were both 1 and 7 days. The currency of value in the study was the number of SPASER (for SPAce laSER) attack satellites of a given technological level to destroy the target array in a given length of time. A summary of the results is shown in Table 4. Here, it is seen that increases in technological capability have an immediate payoff, but

TABLE 4. *Spaser II performance summary.*[a] (*Table classified ~~Secret~~.*)

(kW)	Mirror Dia (m)	Beam Quality	Pointing Stability (µrad)	Number of Interceptors Required: Non-Maneuvering, 1 Day	Non-Maneuvering, 7 Days	Maneuvering, 1 Day	Maneuvering, 7 Days
"Low" Technological Risk							
100	2.0	1.3	2	57	36	9	4
250	2.0	1.1	2	45	21	8	4
500	2.0	1.1	2	34	15	7	3
1,000	2.0	1.4	2	28	11	6	3
"Moderate" Technological Risk							
100	3.5	[illegible]	1	39	17	9	3
250	3.0	1.1	1	26	11	6	3
500	3.0	1.2	1	20	8	6	2
1,000	[illegible]	1.2	1	[illegible]	5	6	2
"High" Technological Risk							
1,000	4.5	1.1	[illegible]	10	3	3	2
2,000	4.5	[illegible]	0.5	8	2	2	1
5,000	4.5	1.2	0.5	5	2	2	1
10,000	4.5	1.3	0.5	4	1	(4)[b]	1

[a] Source: Lockheed Missiles and Space Company, Inc.

[b] The 10-MW high-technological-risk system required more maneuvering propellant than can be lifted by the Space Shuttle. Therefore, it is treated as a nonmaneuverer and is shown in parentheses.

that the real payoff comes from the ability of the SPASER to maneuver.

~~(S)~~ In the operational modes selected by Lockheed, the SPASERS were located at altitudes between those occupied by the target satellites, and the targets were attacked as they neared their point of closest approach. A limited maneuver capability on the part of the SPASER allowed a phase change in the orbit and greatly speeded up the opportunities for intercept over the opportunities that would be afforded if the SPASER maintained a fixed orbit. The kill dose used was 1.6 kJ/cm^2, and the kill times were up to 100 sec.

~~(S)~~ Subsequent studies, also sponsored by DARPA, entitled "Advanced Radiation Space Defense Applications"([33]) and "Long Range Optical System Study,"([34]) explored the use of space-based high-energy lasers as ASAT systems, but with little improvement in the state of knowledge of requirement for such systems.

~~(S)~~ What has been missing from these and other system studies of space-based lasers is the exploitation of the characteristics that are peculiar to a laser. The above studies treated a laser as if it were a gun, caused the ASAT to approach the target, and then fired the laser gun. A laser has a number of peculiar properties that can easily be exploited by the clever designer. A laser has variable power, instantaneous (almost) time of flight over a fairly large distance, and a very rapid retargeting capability. Now, consider utilizing such capability against an advanced Soviet satellite that has planned certain countermeasures such as maneuvers or decoys. If the U.S. ASAT proceeded to what was expected to be a point from which to attack and was faced with a target that was widely displaced because of an unexpected maneuver, then the laser would have the range to make up for that maneuver and could carry out the mission as planned. A more complete exploitation of laser capability is seen if the target expecting an attack should deploy replica decoys. In this case, the laser ASAT could reduce the energy in a pulse and rapidly fire at each target with a quantity of energy sufficient only to destroy a decoy. With the retargeting and target-recognition capabilities that can be built into the ASAT, all the decoys would be recognizably destroyed and the target remaining would be the satellite, which could then be destroyed with a lethal dose, as planned. A space-based laser ASAT is valuable, not because it can do the same job as a kinetic energy interceptor, but because it can negate an array of first-order countermeasures with which other systems have greater difficulties or require higher costs.

~~(S)~~ A shortcoming of the space-based laser ASAT system is its very presence. To be effective, the ASAT force must be on station at all times, ready to act, because it would require a significant amount of money to maintain a force ready to launch and a rather large (compared to the desired reaction time) time to put the force on station. Such an array would appear provocative and could easily incite an attack on it. While this is not a technological problem, it is nonetheless real and must be considered in the planning for a space-based laser ASAT force.

G. LASER ASAT SUMMARY

~~(S)~~ In summary, regarding laser ASAT systems, it appears that ground-based lasers have the earliest potential for operation because of their lesser requirement for lightweight advanced technology. They also have limited growth, but they might well constitute a useful learning tool for ground-based laser phenomenology while giving some capability for ASAT. The aircraft-based system has many virtues. Among them are the covertness that can allow an attack virtually anywhere and anytime. The price is the high development cost of lightweight components and the very high operational and training cost associated with man-operated equipment. A space-based system features the rapidity-of-attack capability, but not the covert operation, associated with the aircraft-borne laser. The cost of developing lightweight components is necessary here, but experience with nonmanned space systems indicates an expected low operational and maintenance cost.

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