SECTION 3

United States Space Systems: Vulnerabilities and Threats

Introduction

We simply cannot afford to defend against all possible threats. We must know accurately where the threat is coming from and concentrate our resources in that direction. Only by doing so can we survive the cold war." [13] - Edwin Land, founder of the Polaroid Corporation and father of U.S. satellite reconnaissance.

Land's prophetic statement quoted above is as valid today as it was during the height of the Cold War nearly five decades ago. The Killian panel established by President Eisenhower in 1954 to assess the Soviet ICBM capabilities, of which Land was a member, warned in its final report: "We must find ways to increase the number of hard facts upon which our intelligence estimates are based, to provide better strategic warning, to minimize surprise in the kind of attack, and to reduce the danger of gross overestimation or gross under estimation of the threat." [14]

With regard to the threats to U.S. space assets, it is crucial to understand both the threats and the ramifications of the proposed counters to the threats. It is just as crucial that the policy debate distinguish between vulnerability and a threat. The latter implies intent to do harm. It is important to recognize that just because satellites are vulnerable to ground-based missiles, laser or radiation from a high-altitude nuclear explosion, it does not necessarily mean that there are credible threats that might exploit those vulnerabilities. But in the future what is a vulnerability and what is a threat could change. For that reason, the Panel addressed these issues looking ahead five years and recommends a reassessment at that time.

The preceding discussion is intended to provide a perspective on how the FAS Panel tried to assess some of the major threats. It made its assessments on the basis of available scientific evidence and at times its own analysis.

Threats with Possible Space Weapons Response

a. Small Satellites

Small, lightweight satellites are making space accessible to an increasingly large number of countries. Generally, this development could be viewed as both stabilizing and desirable. But from the perspective of U.S. national security, expanding international access to space could be viewed as a threat. A number of statements in an Appendix to the report of the Rumsfeld Space Commission suggested such views:

o "Advances in miniaturization and the proliferation of space technologies create opportunities for many countries to enter space with small, lightweight, inexpensive and highly capable systems that can perform a variety of missions."[15]

o "Microsatellites can perform satellite inspection, imaging and other functions and could be adapted as weapons."[16]

o "There are examples of plans to use microsatellite technology to develop and deploy long-duration orbital ASAT interceptors."[17]

o "The Sing Tao newspaper recently quoted Chinese sources as indicating that China is secretly developing a nanosatellite ASAT weapon called "parasitic satellite." The sources claim this ASAT recently completed ground testing and that planning was underway to conduct testing in space. The Chinese ASAT system is covertly deployed and attached to the enemy's satellite. During a conflict, commands are sent to the ASAT that will interfere or destroy the host satellite in less than one minute."[18]

Outside analysts have raised similar concerns:

- o "...stealthy micro-satellites might be used as virtually undetectable active ASATs or passive space mines. . ."[19]
- o "One of the most effective threats is a micro-satellite in the form of a 'space mine.'"[20]

What is a small satellite? And why are they of such concern? A small satellite is generally defined as a satellite with a mass of less than 500 kg (1,100 pounds). Small satellites are further subdivided into mini- (100-500 kg), micro- (10-100 kg), nano- (1-10 kg), and pico-satellites (< 1 kg). To put these masses in perspective, the Hubble Space Telescope has a mass of 11,000 kg.

Since almost any mission that a small satellite could carry out could be accomplished by a larger satellite, why are small satellites a potential security concern? There appear to be three main issues:

(1) Because small satellites are easier and cheaper to build than larger satellites, they could make space accessible to a greater number of countries. In addition, the development of small satellites could be a stepping stone to building larger and more sophisticated satellites.

(2) Small satellites require less capable launch vehicles than larger satellites, and thus could be launched from sites other than those operated by the recognized space-faring nations.

(3) Because of their small size, such satellites may be hard to detect by United States space surveillance systems. Hence, they might be more effectively used in certain roles, such as co-orbital ASATs or space mines.

We briefly consider each of these three issues below and then discuss in more detail two types of small satellites the United States might view as posing a military threat.

The first is the matter of small satellites expanding access to space. Small satellites can be designed and built much more quickly and cheaply than larger, more complex satellites, and their launch costs are lower (but not necessarily low). The number of countries that have launched a small satellite in orbit has increased from about 10 in 1990 to about 30 now, with approximately 400 such satellites having been launched over the last 20 years.[21] While the overall rate of small satellite launches has not increased greatly over this time, the capabilities of small satellites appear to be increasing significantly.

Small spacecraft technology is also rapidly becoming widespread, in part because of deliberate efforts to spread this technology. For example, Surrey Satellite Technology Ltd. (SSTL, a company affiliated with Surrey University in Great Britain) will build micro- or mini-satellites for any country (subject to British export controls).[22] It also has a technology transfer program designed to help countries develop the capability to build their own satellites. So far, participants in this program include Pakistan, South Africa, South Korea, Portugal, Chile, Thailand, Singapore, Malaysia, and China. Recent collaborators include Algeria, Nigeria, and Turkey.

Another example illustrating the increasing availability of access to space is the CubeSat program.[23] Started in 1999 at Stanford University and California Polytechnic State University San Luis Obispo, the project has developed a set of common standards for constructing and deploying a pico-satellite. Each CubeSat is a cube with a 10 cm side and a maximum mass of 1 kg, and typically costs less than $40,000 to build. Several CubeSats have already been launched, and over 50 colleges and universities are currently working on such satellites.

The second concern is that small satellites can reduce launch requirements. Small satellites may enable a country that would otherwise be unable to launch a satellite to do so, because a smaller rocket launcher could be used. However, the significance of this possibility should not be exaggerated. Given that a number of countries are already providing commercial launch services, and the competition among these launch providers, most countries should have little difficulty finding a launcher for any "legitimate" satellite (that is, not an ASAT). This route is likely to be significantly cheaper than developing its own launcher. Thus to the extent that small satellites may make launching satellites easier, it could affect the possible development of ASATs.

The last concern is that small satellites may be difficult to detect. The small size of micro- or smaller satellites may pose a serious problem for U.S. space tracking capabilities. The ability to avoid detection or tracking could significantly increase the effectiveness of a co-orbital ASAT or a space mine. Although the United States has a missile launch detection capability that would almost certainly detect the launch of any rocket capable of placing a satellite in orbit, its capability to detect and track a small satellite released from such a rocket is less robust.

The United States currently employs a range of optical and radar sensors for tracking objects in space. Although the U.S. space surveillance system currently tracks over 8,000 objects in orbit, the lower limit on the size of objects it can detect is frequently described as being about 10 centimeters and it is "currently limited in its ability to detect and track objects smaller than 30 centimeters." [24] Thus some small satellites may be able to avoid detection and tracking-particularly if they have been intentionally designed to have reduced radar and optical signatures.

Moreover, countering potential co-orbital ASATs would require detection and tracking to occur very shortly after launch. A solution to this problem,-to the extent it is a problem,-may require a system that could track a satellite as soon as it is released from its rocket booster. A space-based tracking system, such as the proposed SBIRS-Low missile defense system, might be capable of carrying out this mission. However, even in this case, small satellites could be secretly launched from larger satellites. This capability has already been demonstrated by the Orbiting Picosatellite Automatic Launcher (OPAL) program, developed by Stanford University. It consisted of a "mothership" satellite that housed and successfully launched six "daughtership" satellites that each weighed a kilogram or less[25] . The design is similar to the one reported by a Chinese news agency and cited in the Rumsfeld report as a "parasitic satellite" ASAT system.

Small satellites may be used as vehicles for developing and testing the technologies needed to build an ASAT. An ASAT might need a number of capabilities, such as sufficient in-orbit propulsion to close rapidly on its target, a sensor capable of detecting and discriminating the target, stealth techniques, guidance and control for homing on the target, and a kill mechanism, that would not commonly be found on a small satellite, much less combined on a single satellite.

One type of small satellite that might raise concerns is one that "inspects" other satellites. Such "inspector" satellites would rendezvous with another satellite to carry out a visual or other type of inspection. Such satellites have been proposed to determine if a repair mission for a damaged satellite makes sense (insurance companies are reported to be interested in this),for refueling/resupply/upgrading missions, or for verification purposes. There have already been three experiments.

The first two, Inspector (Germany, 72 kg, 1997) and SNAP (Great Britain, 6.5 kg, 2000), attempted to examine either their host satellite or a satellite launched on the same booster, and both failed. In January 2003, the U.S. Air Force's 31 kg XSS-10 micro-satellite successfully observed the second stage of its own rocket, several times approaching within about 100 feet of it.[26]

Such small satellites could also be adapted for use as space mines, satellites that maintain their orbital position in the vicinity of their target satellite, ready to launch an attack on essentially zero notice. Such space mines could use explosives or other means to destroy their target satellite or could be used to jam communications or otherwise obstruct the operation of the satellite. As with ASATs, such small space mines would most likely require a combination of technologies that would not normally be associated with a small satellite.

Small satellites with meaningful military capabilities (such as ASATs) would not be easy to build for a nation not already possessing advanced space capabilities. Moreover, some of the reported small satellite threats may be greatly overstated. For example, the Chinese "parasite" satellite threat described above appears to be based solely on a single story in a Chinese or Hong Kong newspaper, a story whose credibility is called into question by its assertion that the satellite is "nanometer-sized" and contains "nanometer-sized components: solar panels, batteries, computers...." (Note that one nanometer is less than 1/10,000 the thickness of a human hair).[27] Perhaps the most significant security issue associated with small satellites is that they might not be easily detectable by U.S. space surveillance systems, a situation that could be at least partially countered by quite feasible improvements in these surveillance capabilities.

It will be critical to periodically assess U.S. surveillance capabilities and the capabilities adversaries have for fielding stealthy satellites. Within the next five years, however, it appears unlikely that an adversary could field a non-detectable space mine.

The Panel concludes that the best way to counter the threat posed by space mines is not, as some have suggested, to field armed sentinel satellites in space, but rather to continue to improve space situational awareness and enhance the maneuverability of critical satellites in the event that evasive action needs to be taken.

b. Ground Based Anti-Satellite Weapons

Attacks on satellites with Scud-like ballistic missiles that do not have homing capabilities would have low probability of success, and would be limited to only the lowest altitude satellites.[28] Such an attack with a conventional warhead containing shrapnel would need to place the debris cloud in the direct path of the satellite. This would require fairly precise tracking-a capability available only to highly sophisticated militaries.

Satellites in low earth orbit (LEO) are also vulnerable to laser illumination that could potentially cause loss of power due to solar cell degradation as discussed in Dr. Geoffrey Forden's article "Anti-Satellite Weapons" found in Appendix B. Even low power lasers can cause permanent damage to satellites with large optics, typical of many reconnaissance satellites. A U.S. experiment in 1997 demonstrated that even a low power laser with output much lower than a megawatt-class laser could saturate an infrared detector whose wavelength was in-band with the laser.

To attack satellites in geo-synchronous orbits, interceptors cannot be fired directly from the earth; they would need to be fired from low earth orbits (LEO). The closing velocities at semi and geosynchronous orbits are about 1.4 kilometers per second, making homing followed by a direct impact or fragmentation warhead feasible. Homing could be achieved using optical systems that function at visible wavelengths. Such optical sensors are commercially available and do not require cooling. Since satellites are almost always illuminated by the sun, the use of such sensors should not create severe operational constraints. In addition, the small velocities required for transfer from low to high-earth orbits means that anti-satellite vehicles launched into low-earth orbit could be relatively light. This type of technology is not now available to countries such as North Korea, Iran, or Libya.

Figure 1 shows the transfer orbits that would be necessary to attack satellites in higher orbits. Figure 2 shows the estimated capabilities of North Korean missiles in reaching targets in low earth orbits, more specifically, the estimated near-vertical trajectories of North Korean Scud-C and Nodong missiles. It can be seen that the Scud-C is only capable of reaching an altitude of about 300 kilometers with a payload of 250 kilograms while the Nodong can potentially carry 1000 kilograms to about 500 kilometers altitude.

Fig. 1: Low to High Altitude Transfer Orbits that Could be Used for Anti-Satellite Attacks

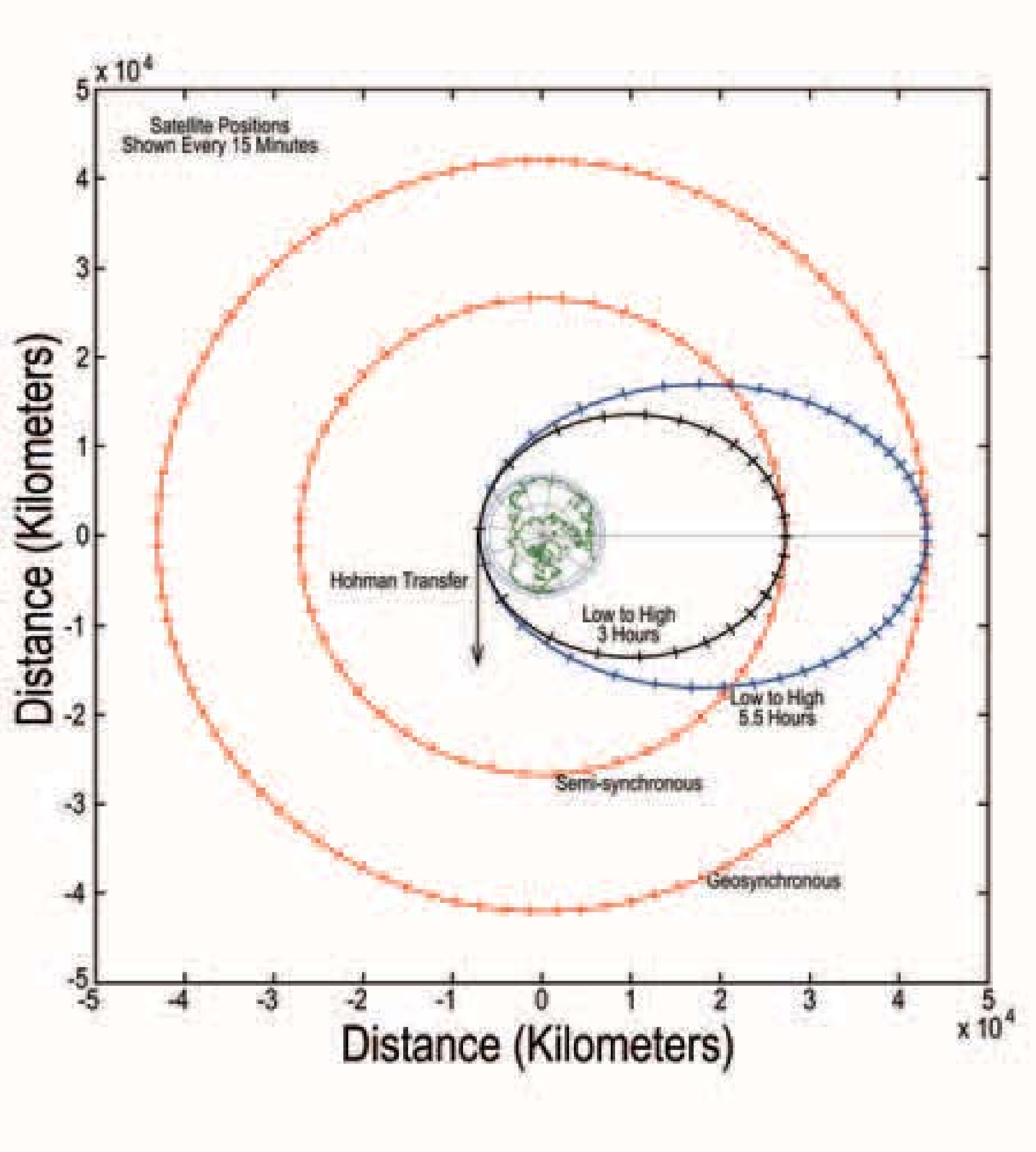
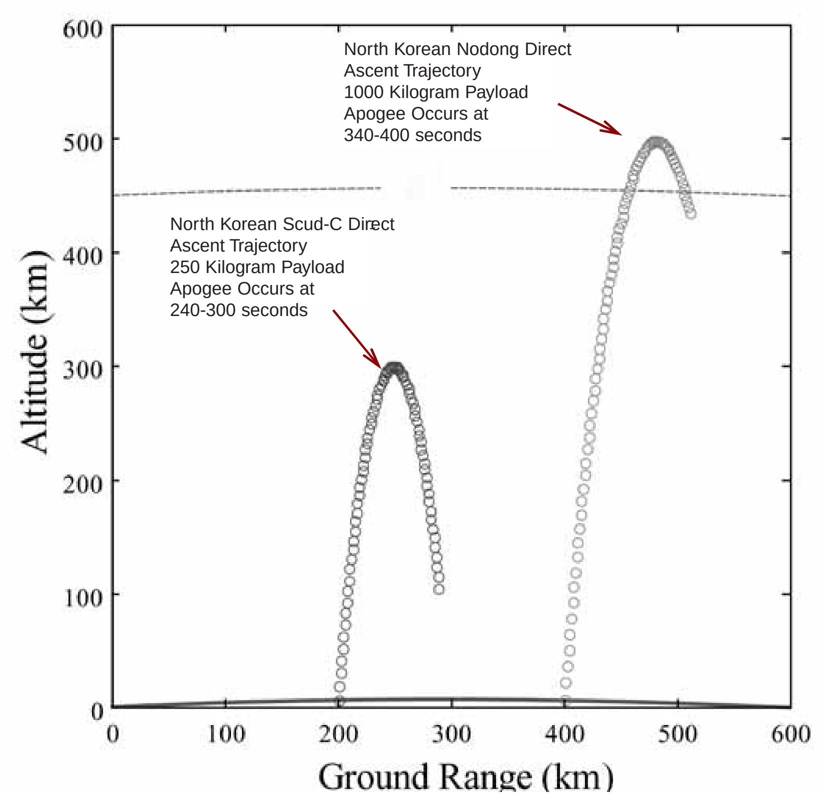


Fig. 2: Maximum Altitudes and Time-to-Apogee for North Korean Direct Ascent Anti-Satellite Attacks with Scud-C and Nodong Ballistic Missiles



Since residual atmospheric drag is significant at 300 kilometer altitude, photo-reconnaissance satellites would probably operate at altitudes higher than 300 kilometers. North Korea could therefore only reach satellite operational altitudes with a Scud in the event that a photo-reconnaissance satellite was in an orbit lower than 300 km. A Nodong would have to be used if they were to attempt to attack a reconnaissance satellite stationed above 300 km. The locations of both the Scud-C and Nodong are shown at 5-second intervals. It takes the Scud-C about four to five minutes (240 to 300 seconds) to reach apogee while the Nodong takes some six to seven minutes (360 to 420 seconds) to apogee. This time to apogee is long enough that even a very minor maneuver of the reconnaissance satellite (one to two meters per second) after the launch of a Nodong will greatly reduce the chances of the Nodong doing any damage to the satellite in an attack.

It would be quite straightforward for the US to detect launches at engine ignition, which would then make it possible to issue maneuver orders to an approaching reconnaissance satellite minutes before the Nodong could reach the satellite's orbital altitude.

Capabilities of North Korean missiles are further analyzed in David Wright's article in the Appendix F of this report.

The Panel concludes that the threat posed by ground-based ASATs is best countered by ensuring redundancy of critical systems, developing quick launch capabilities to field replacements, using conventional forces to destroy enemy launch sites, and, *if proven effective*, utilizing land- and sea-based missile defenses.

c. High Altitude Nuclear Explosion

A much-discussed threat is that of a high altitude nuclear explosion to knock out virtually all satellites in low earth orbit. The threat arises from the so-called "Christofilos Effect," named after the physicist Nicholas Christofilos, who worked at what is now the Lawrence Livermore National Laboratory in California. He theorized that high-altitude nuclear explosions (HANE) might create artificial radiation belts around the earth, which might supercharge the Van Allen belts.[29]

A HANE also produces an electromagnetic pulse (EMP) whose existence has been known since the 1950s when nuclear weapons were being developed and tested in the atmosphere. EMP effects are primarily a concern for ground systems such as electrical power and communications networks. EMP is primarily a “line of sight” effect, and consequently the dominant cause of damage to satellites near a HANE would be prompt nuclear radiation from the blast. The dominant cause of wide-spread damage to space systems is due to the “pumping” of the Van Allen radiation belts.

To test Christofilos's theory, the United States conducted a set of atmospheric tests in 1958 called Argus, in which three modest warheads were exploded at altitudes of 100, 182, and 466 miles. An additional test called Starfish exploded a 1.4 megaton warhead at an altitude of 300 miles near the equator in the middle of the Pacific Ocean. The explosion supercharged the Van Allen belt and created artificial belts 100 to 1000 times stronger than normal space radiation belts.

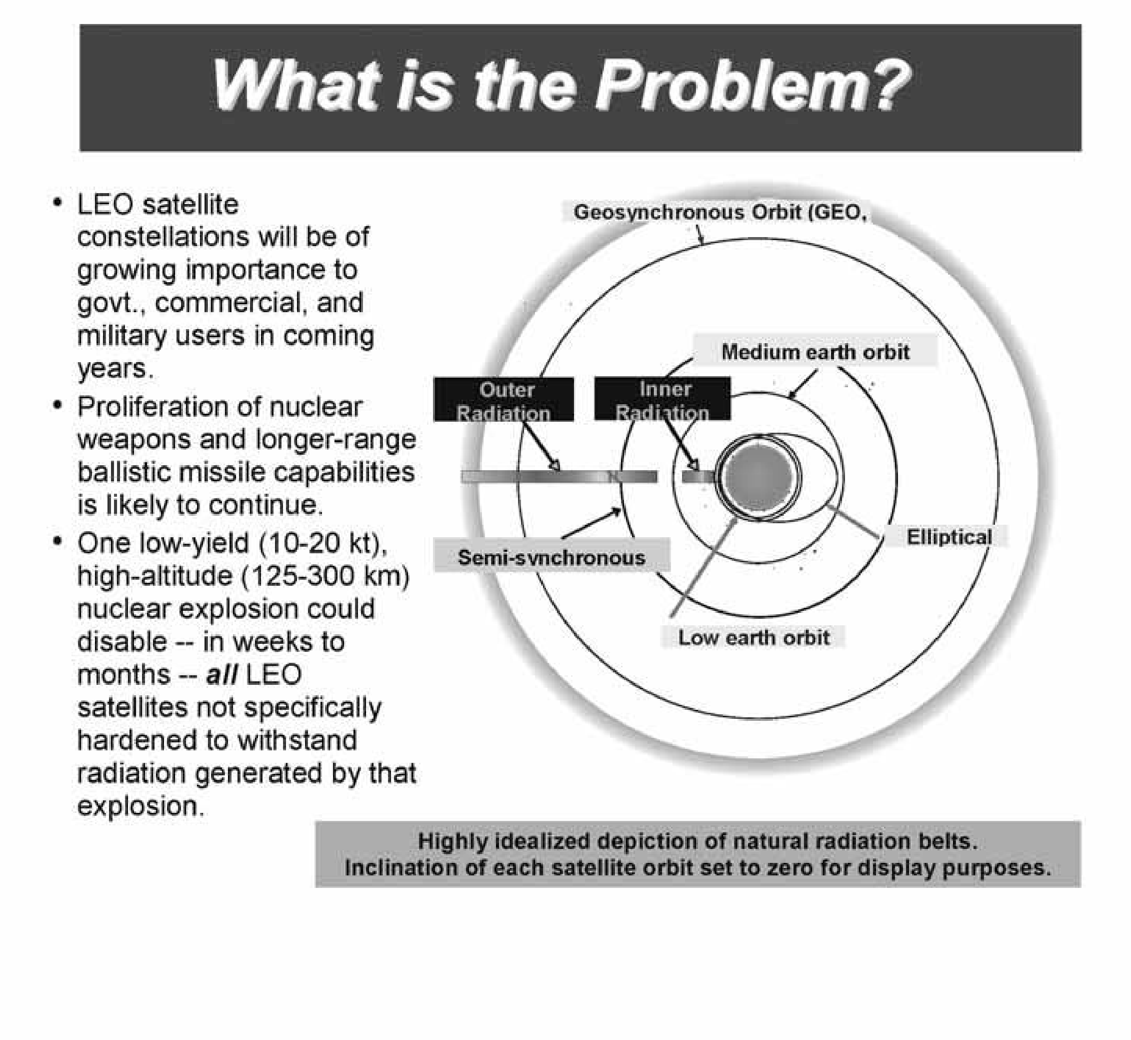
The high energy electrons damaged the solar arrays of several satellites and caused three of them to fail. The electromagnetic pulse generated by the test led to power surges in electrical cables in Hawaii, blowing fuses, streetlights, and circuit breakers. *Residual radiation from the experiment lingered in the magnetosphere for nearly seven years."*[30]

What happened was that the high-energy charged particles, electrons, protons, and heavier ions from the blasts were injected into the Van Allen radiation belts that surround the earth and were trapped by the earth's magnetic field. The lifetime of these particles can be long, on the order of months, if not years. Satellites in low earth orbits that are bombarded by these particles could accumulate doses of radiation in excess of their design limits within a short period of time.

Dennis Papadopoulos of the University of Maryland, a recognized expert on the HANE threat, briefed the panel on July 10, 2003. (See Appendix C.) According to Papadopoulos, at least seven satellites were temporarily disabled within a few months of the Starfish test.[31] He also stated that the "pumped" belts lasted until the early 1970's. Dr. Hans Mark, a well-known physicist and a former Deputy Administrator of NASA, in his article cited earlier, said that Starfish put a number of satellites only temporarily out of commission.[32]

In 2001, the Defense Threat Reduction Agency (DTRA) conducted a study called HALEOS to assess the HANE threat. (See figure from the report below.) The study concluded that "one low-yield (10-20 kt), high-altitude (125-300 km) nuclear explosion could disable–in weeks to months–***all*** LEO satellites not specifically hardened to withstand radiation generated by that explosion."[33]

Fig. 3: Depiction of Natural Radiation Belts, with Defense Threat Reduction Agency Conclusions. (For the Panel's assessment, see text.)



What is the Problem?

- LEO satellite constellations will be of growing importance to govt., commercial, and military users in coming years.
- Proliferation of nuclear weapons and longer-range ballistic missile capabilities is likely to continue.
- One low-yield (10-20 kt), high-altitude (125-300 km) nuclear explosion could disable -- in weeks to months -- ***all*** LEO satellites not specifically hardened to withstand radiation generated by that explosion.

Highly idealized depiction of natural radiation belts.
Inclination of each satellite orbit set to zero for display purposes.

While perhaps there is agreement in the scientific community on the phenomenology of "pumping" of the radiation belts, there is disagreement about the accuracy of the computer models that predict the radiation levels. The authors of the HALEOS report admit that predictions from models have significant uncertainties. The report states that indeed they are "based on limited high-altitude testing" and have an uncertainty in the computation of post-explosion radiation density at any point in LEO space by a factor of 4 to 10. However, the report says that the uncertainty in the total amount of absorbed dose is reduced by "orbital averaging" over time as satellites pass repetitively through the "hot" bands over days, weeks, and months.[34]

But others familiar with the codes believe that the projected flux levels could be off by an order of magnitude or higher.

The FAS Panel reviewed this report and found further uncertainty in how the model computes the total radiation dose. The HANE-produced total dose accumulation comes from two sources: the prompt radiation of the nuclear explosion and the subsequent pumping of the radiation belts. However, the prompt radiation affects only the small fraction of the LEO satellite fleet that would be in the line of sight of the weapon, whereas the other LEO satellites will be affected only by the charged particles entering the Van Allen belt. It is not clear whether this difference is taken into account in calculating the total accumulated dose for these satellites.

The other crucial factor in the HALEOS's study prediction that all LEO satellites will fail is its assumption about their level of hardening. The HALEOS study assumed that satellites were designed to withstand two times the natural background flux. If the cumulative dose due to HANE exceeded this limit, it assumed the satellites would be destroyed.

However, the simple fact that most satellites have weathered the vagaries of natural space radiation so well over time indicates their normal design hardening is better than assumed. Military satellites in LEO are much more hardened, whereas the hardness of commercial platforms may vary. It is noteworthy that natural background radiation does vary significantly over time and yet not many satellites are known to have failed due to this variability.

For example, under natural background radiation conditions in LEO, the peak flux for electrons with energy greater than 1 MeV ranges from 10^4 for the outer radiation belt to 10^6 for the inner. Enhanced solar flux is said to have resulted in >1 MeV electron flux to reach 10^8 particles/sq cm sec. Coincidentally, this is the same magnitude that is computed by the model due to a high-altitude nuclear explosion one day after the burst over Korea.[35]

A few years ago, damage due to solar flux to a commercial satellite was reported, which resulted in a loss of all pager signals for several hours on the West Coast. Papadopoulos says that according to the office of the U.S. National Security Space Architect, in 16 years as many as "13 satellites have been lost that can be clearly attributed to natural enhancement (flux of 108 particles/sq cm sec) of MeV electrons."[36] In fact, Baker et al. in 1998, cited also by Papadopoulos, merely said that three spacecraft were damaged between 1994 and 1998 by the enhanced solar flux. The Panel requested a briefing from DTRA to confirm some of these data, but could not locate a presenter who could receive permission to talk to the Panel.

In a written answer to questions from the Panel, Papadopoulos said that he believed that a fully shielded GPS satellite had a lifetime of 120 to 180 months. Citing the DTRA's HALEOS study, he noted that a nuclear explosion would cause the flux level at to go up 100 times from 106 electrons/sq. cm./sec to 108 electrons/sq. cm./sec. From this he predicted by linear extrapolation that a LEO satellite with an equivalent shielding of a GPS satellite would last only 1.2 to 1.8 months, concluding that shielding was not a solution. This is in contrast to the finding of the DTRA study, which states that the cost of hardening LEO satellites to withstand the enhanced radiation would be about 2-3% of the cost of a satellite.

The Panel concludes that radiation hardening against both immediate radiation and against cumulative doses from the radiation belts is a reasonable option. However, there are always tradeoffs between the degree of shielding and associated cost on the one hand and added weight and loss of payload on the other. Many factors influence the radiation hardness of a satellite. In some cases, minor design changes from parts selection to component shielding can affect the radiation tolerance. In other cases, there may not be any practical amount of shielding that will do the job.

To account for the uncertainties in the model, the DTRA's HALEOS report included this cautionary note: LEO satellites may be damaged by HANE "if the models are *right*." The report also considered the radiation dose for one-fourth the rate of accumulation to reflect the lower end of the uncertainty and stated that, if the model is off by that much, *"HANE may not have much impact on LEO satellite lifetimes."*[38]

Given that the finding of the DTRA report suggests a modest 2%-3% increase in satellite cost could harden the satellites to withstand the increased flux levels, the Panel suggests implementing this shielding as a prudent precaution. In light of the disagreement about the effectiveness of the shielding, however, the panel recommends a study to improve existing models of a HANE and determine the risk to radiation hardened satellites.

The FAS Panel is aware that some U.S. military satellites are being hardened adequately and recommends that hardening of individual military and commercial satellites, especially commercial satellites used by the military, be taken into account before the government puts them to any critical use. It is important to note that the GPS satellites, which are at 20,000-km altitude, are designed to survive a million-rad dose of total radiation over a 10-year lifetime. Moreover, the cost of shielding GPS satellites is reported to be 1% of the program cost.[37]

The GPS constellation consists of 24 satellites, which are spread over different orbital planes at an altitude of 20,000 kilometers. To substantially degrade the GPS, the satellites have to be attacked individually, which is difficult to do. The satellites are also hardened against nuclear effects and have on-orbit spares.

The robustness of the GPS constellation has been analyzed by Geoffrey Forden and is reported in Appendix D. The analysis shows that the GPS constellation is robust to the extent that it can lose up to four satellites and yet only suffer from periodic loss of function at any place. As stated earlier, this robustness makes the vulnerability of the GPS constellation to ASAT-type attacks rather small.

The Panel concludes that the best way to counter the near-term threat posed by a rogue state such as North Korea detonating a nuclear weapon in space is not to deploy space-based missile defenses, but rather to ensure that critical space satellites in LEO are radiation hardened to appropriate levels, to destroy missile launch sites in the event of war, and, *if proven effective,* to deploy ground- and sea-based missile defenses.

Threats Which Cannot be Addressed by Space Weapons

a. Jamming of Satellite Links Including GPS Signals

The U.S. military is responding to GPS jamming vulnerability by developing upgraded capabilities to the GPS signal, new bands, and increased signal strength. In addition, GPS-dependent military systems are adding anti-jamming capability as well as back-up terminal guidance.

The U.S. military, as well as the entire world economy, makes extensive use of commercial satellite communications, which are essentially all based in geostationary earth orbits (GEO). While such distant orbits make these satellites relatively immune from the physical threats lower earth orbit (LEO) satellites might face, their distance-coupled with the economic factors that drive the industry-actually make them more susceptible to electronic jamming. Instead of jamming the receiver on the ground, as a radio jammer would attempt when trying to block a ground-based transmitter, the satellite-signal jammer attacks by trying to overwhelm the signal sent to the satellite, which then rebroadcasts that jammed signal back to earth. The recent jamming from Cuba of National Iranian TV (NITV), a station operated by an Iranian dissident group based in Los Angles, demonstrates the viability of such a threat.

A further analysis of these issues is included in Appendix D in an article by Geoffrey Forden.

b. Control of High-Resolution Imagery

The resolution of commercially available satellite imagery is improving rapidly. One- or two-meter resolution imagery is available from the Ikonos satellite operated by the

U.S. company Imaging Sciences, Inc., as well as from the Russian SPIN-21 and the Israeli EROS-1A. Another U.S. company, Digital Globe, Inc., launched in 2001 the QuickBird Imaging satellite, which is reportedly capable of acquiring panchromatic (black and white) images with 61-cm. resolution and multi-spectral images with 2.44 meter resolution.[1] Space Imaging is planning to launch a panchromatic sensor with 50 cm resolution in 2004.[2]

The proliferation of high-resolution imagery presents opportunities for adversaries to target U.S. forces and facilities in forward deployed positions. Nevertheless, the military utility of the imagery to the so-called rogue nations or terrorist organizations needs careful examination. During the first Gulf War, the United States obtained the cooperation of France and Russia and denied all commercial satellite imagery to Iraq. Such imagery could have shown troop movements involved in the "left hook" operation. The ability to exert shutter control over commercial satellites in times of conflict will remain an important priority for the U.S. military. Processing and interpreting images requires expertise, which may or may not be readily available. An assessment of which actors could benefit from commercially available satellite imagery and to what extent they could benefit might help bound the problem.

c. Orbital Debris

The issue of orbital debris in low earth orbit (LEO) is relevant to debate on space-based weapons from two perspectives: the first is the generation of additional debris from the destruction of ballistic missiles; the second is the threat to the orbiting weapons themselves from the background debris, which consists of parts of rockets and satellites, and the natural meteoroid background. While debris from missile intercepts is transient, background debris is semi-permanent. Moreover, the background flux is several orders of magnitude larger than the transient flux. It is shown in Appendix E that over a period of a year or more the threat from the background debris poses a considerable hazard to space assets in LEO. However, it is not seriously enhanced by effects from a ballistic missile interception and destruction. These risks are not thought to be great enough to pose a serious operational risk to the overall space based interceptor systems effectiveness. A combination of shielding, orientation, system redundancy and replacement should be capable of overcoming all but the most catastrophic transient random events. There is, however, the issue of maintenance for assets deployed in space where they will be constantly degraded by collisions with smaller (< 1 cm) debris and meteoroid particles. From this perspective, space based weapons do not have the advantage of ground and sea based weapons which are safely sequestered. Based on current information regarding the anticipated levels and types, orbital debris does not appear to be a critical factor in the debate over the viability of deploying space weapons. Debate over the efficacy of such weapons should be based first and foremost on their technical feasibility and reliability, cost, and a host of other factors which are beyond the scope of this chapter. The APS study of the boost-phase missile defense (2003) has raised the issue that there are uncertainties in the assessment of debris generation from interception of ballistic missiles in space. The interception of BMs or BMWs in space may cause a (self-sustaining) "chain-reaction" that over an extended period of time will destroy many satellites (Primack 2001). Others contend that debris generation from BM interception is negligible (Canavan 2003, Johnson 2003).

To address this issue, the FAS Panel supported a study to determine the OD effects from space based interception of BMWs, in a post-boost or mid-course phase in space, and for BMs during the launch phase. Since the interaction thought to generate the most debris is that from a high speed (~ 10 km/s relative impact velocity) mechanical impact by a kinetic-kill vehicle (KKV), fragment generation from this type of impact was studied and analyzed in some detail. The number and velocity of the fragments generated from such an interaction depends on many parameters such as the trajectory of the ballistic missile, relative sizes of the interceptor KKV and missile, densities and structural (including inhomogeneities) properties, relative impact velocity, and other factors. However, empirically derived computational guidelines exist, which estimate relationships between the number and size of the fragments generated from a high speed collision, and are used in Appendix E.

Our study's conclusion was that because a boost-phase interception by either a KKV or a high power laser will be so destructive from exploding fuel, it would most likely prevent the ballistic missile from reaching a sufficiently high altitude in LEO to be capable of generating a significant amount of orbital debris. Based on statistical kinetic modeling, the few fragments that might explode with an extremely high (escape) velocity in the upper atmosphere would not significantly increase the debris background. The energy to generate these fragments is initially derived from the available interaction energy within the center of mass impact interaction and subsequently from the exploding fuel. However, the atmospheric drag effects on these irregularly surfaced fragments will rapidly reduce their velocity and they will just fall to earth. For this reason, it is unlikely that either a KKV or a laser kill in the boost-phase will create an OD problem.

Unlike an interception in the boost-phase, where a laser can trigger secondary explosions and subsequent fragmentation, a laser-kill in a post-boost or mid-course interception is very difficult to achieve. The missile warhead is significantly less vulnerable to infrared laser energy, from such weapons as the proposed Airborne Laser than the boost vehicle and its components, which are the targets in the boost-phase interception. Therefore, the worst case scenario for OD generation is expected to be that from a KKV impacting a missile warhead at a hypervelocity, i.e. ~ 7-10 km/s) in the mid-course or post boost phase of its trajectory.

In this analysis, there is an implicit assumption that the nuclear warhead would not be set off by the interaction and it would render the nuclear weapon incapable of detonating as designed; however, radioactive fallout is likely to occur. This is a good assumption because the triggering of a nuclear weapon requires a precise sequence of interactions. If the high explosive charge designed to initiate the nuclear reaction detonates without actually initiating a nuclear reaction, additional fragmentation along with radioactive fallout would result, an unavoidable problem associated with the uncontrolled destruction of NWs. The additional velocity changes and ranges of the high explosive-induced fragmentation can be computed, but are not taken into consideration in this report because the possibility of and effects from such explosions will strongly depend on the detailed designs of both the missile warhead and the weapon. Of course, if a nuclear warhead detonates in space and there is radioactive fallout, the results could be severe to all the satellites and other assets within the radiation region. The fallout would also result in a radioactive debris cloud that would impact a large area of the earth.

Based on the analysis of a KKV impacting a ballistic missile warhead in either a post-boost or the mid-course phase, and assuming that the mass of the BMW is assumed to be much greater than the mass of the KKV, we obtained the following results:

1. Compared to the background orbital debris and meteoroid flux, the number of fragments generated in each impact (equivalent to 100,000 g, the assumed weight of the KKV,) would be negligible compared to the number of background particles (Johnson 2001). The region of interception, low-Earth orbit (LEO) is vast, ~ 1012 km^3.

2. The vast majority of fragment velocities are low enough to produce debris that would be considered sub-orbital, essentially following a dispersed variation of the original warhead's center of mass trajectory. The fragments would be a transient orbital phenomenon. The only satellites or SBI platforms that would be encountered by the sub-orbital debris are those within the immediate volume swept out by the transient debris cone. There would be no noticeable long-term effect.

3. There can be certain synchronous scenarios in localized regions in LEO where deliberate KKV impacts can generate an anomalous increase in the debris flux. But to generate a sufficiently high level of flux in order to create a kinetic "chain reaction" that could sequentially destroy satellites in LEO, would be extraordinarily difficult. Even a massive (~ 100) missile interception is not likely to set off a mechanical "chain reaction."

Overall, assuming 500 space-based interceptor platforms, the probability that a single satellite within the entire LEO population will be hit by a fragment weighing 1 gram or larger fragment of SOD is about one in five. The number of hits on another SBI platform by debris from other SBI impacts is about two. So in this case of "fratricide" one could expect to lose two SBI platforms from the total number; one of which may already have been launched its KKVs.

One must understand that these results are only estimates and cannot predict what will actually happen in space warfare. The main point is that the interaction numbers are so low that they really do not provide an anti SBI rationale in of themselves.

In Table 2 of Appendix D, estimates are provided for the number of collisions per year for debris with sizes 1, 0.5 and 0.1 cm, respectively, on 500 SBI platforms each with areas 10 and 50 m^{2}. Here, a 1-cm size OD with a density of about 3 g/cm3 will have a mass of about 1 gram. Meteoroid densities are typically ~ 1 g/m3 or slightly less. On average, each year there is only likely to be a single platform that is significantly damaged. However, several platforms are likely to sustain minor damage if the appropriate safeguards are carried out. The meteoroid flux 0.3 cm is likely to gradually degrade several platforms. Whether and in what manner the background flux will impact the SBI mission effectiveness is uncertain. The results of these calculations show that although most SBI platforms survive in LEO for several years there is nonetheless a process of continual degradation from background OD and meteoroids. This background flux is the single greatest threat to the optimal performance of the putative SBI platforms, and can and must be addressed. [However, the primary advantage of placing SBI in LEO > 400 km altitude is that they can maintain an orbit for an extremely long period of time without having to use fuel. Other advantages of being in LEO are (if the SBI platforms are strategically deployed) the capability of intercepting BMWs as they pass by. Not only does a strategic deployment allow a range reduction which in turn reduces booster mass, but it also allows greater decision time to act. The reduction in KKV booster mass will substantially reduce launch costs (~$20,000/kg).

Collisions with either background orbital debris or meteoroid flux even from destruction by spacebased interceptor (SBI) is unlikely to critically damage satellites in LEO or a significant fraction of the SBI. But the continual degradation of the SBI platforms in LEO, primarily from background debris and meteoroids, will create the need to continually monitor the SBI platform systems for signs of damage that can render them non-functional at the high operational level required. If damage is detected either a repair mission or replacement launch will be required. This will create a level of uncertainty in the operational effectiveness and long term costs of a space-based weapons system, which will have to be balanced against the tactical, strategic and cost advantages of deploying in LEO. The conclusions reached in the Panel's orbital debris analysis are based on straightforward models and assumptions. However, the actual design and implementation of a KKV and its potential range of interactions with a ballistic missile are complicated. Nonetheless, the Panel believes its analysis presents a fair starting point regarding this important debate.

Loss of the GPS Constellation

The GPS constellation consists of 24 satellites, which are spread over different orbital planes at an altitude of 20,000 kilometers. In order to substantially degrade the GPS, the satellites have to be attacked individually, which is difficult to do. The satellites are also hardened against nuclear effects and have on-orbit spares.

The robustness of the GPS constellation has been analyzed by Geoffrey Forden and reported in Appendix D. The analysis shows that the GPS constellation is robust to the extent that it can lose up to four satellites and yet only suffer from periodic loss of usable signal at any place. Therefore, the vulnerability of the GPS constellation to ASAT-type attacks is rather small.