Section 12: Topics in Interfering with Satellites

This section discusses in more detail three topics related to interfering with satellites: space-based anti-satellite weapons (ASATs), including space mines; simple ground-based pellet ASATs, which could potentially be deployed by nonspacefaring countries; and attacks on and back-up alternatives to the global positioning system and reconnaissance satellites.

SPACE-BASED ASATs AND SPACE MINES

Space-based ASATs would be launched into orbit in advance of use and would be continuously or occasionally in range of a target satellite.[1] Space mines are space-based ASATs, but the term has no precise definition. Some authors use the term loosely, others define it specifically, but these definitions differ from author to author. This report avoids the term.

Space-based ASATs could be launched at the beginning of a crisis or placed in orbit in anticipation of a potential future conflict. If a country is concerned about its ability to launch promptly due to weather or other factors, or if it is concerned about the potential suppression of its launch capabilities during a conflict, it could address these reliability concerns by positioning its ASATs in space ahead of time. On the other hand, if these objects are identified as ASATs and are seen as threatening, they would be vulnerable to attack. Moreover, satellite reliability degrades over time, so the owner will have decreasing confidence in space-based ASATs after they have been placed in orbit.

Such a weapon is likely to be stationed in one of four ways. It could be co-orbital with the target satellite, mimicking its stationkeeping maneuvers and keeping within a fixed distance; this is referred to as a *trailing ASAT*. It could attach itself to its target, eliminating the need to track the target satellite and carry fuel for stationkeeping; such satellites have been dubbed *parasitic*.[2] (Coming into physical contact with another satellite, however, is likely to be considered unlawful or provocative.) The satellite could be placed in a distant part of the same orbit, which would require it to maneuver to approach and attack the target. Finally, it could be placed in a crossing orbit in the same orbital plane as its target or in a different plane.

In principle, a space-based ASAT could cause temporary or permanent damage to its target using many of the methods discussed in Section 11. We discuss below which means of attack would be possible and practical for

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[1] We do not include in this category those satellites that serve some other primary function (e.g., ballistic missile defense or inspecting other satellites) and have an inherent ASAT capability.

[2] See Gregory Kulacki and David Wright, "A Military Intelligence Failure? The Case of the Parasite Satellite," http://www.ucsusa.org/global_security/china/page.cfm?pageID=1479, accessed February 9, 2005.

space-based ASATs and compare their potential performance with that of ground-based ASATs. Some deployment options may be better suited than others to a particular method of attack. For example, for a kinetic energy attack, an ASAT in a crossing orbit could take advantage of its high speed relative to the target satellite. But a kinetic attack from a trailing ASAT would require it to explode near the satellite or shoot pellets at it, either of which would impart less energy. On the other hand, a trailing ASAT could attack almost instantaneously, whereas a crossing ASAT would need to wait until it was in the proper position. An ASAT in a crossing orbit might, however, be capable of attacking multiple satellites, whereas a trailing or attached ASAT could be used against only one.

Covert Space-Based ASATs

The choice of orbit affects the ability of the owner of the space-based ASAT to keep its existence or its purpose covert. ASATs in crossing orbits would be less suspicious than trailing or co-orbital ASATs and might also be less readily detected.

If an ASAT was not deployed covertly, the owner of the targeted satellite might take action, seeking to make an international issue out of the deployment, particularly if it could determine the owner of the ASAT. The satellite owner or the wider international community could demand that the ASAT be removed or could assign responsibility if it was used, thereby legitimizing retaliation. Equally important, noncovert deployment would remove the element of strategic surprise from an attack and give the targeted country time to develop a contingency plan to compensate for missing satellites. The satellite owner might also decide to preemptively attack the space-based ASAT. However, preemptive attack on parasitic and trailing ASATs is especially difficult because of the proximity of these ASATs to the targeted satellite.

Thus the ASAT's owner is likely to want to keep its existence or purpose covert. However, the owner could not assume that the ASAT would remain covert and would need to factor that into the deployment decision. There may, of course, be situations in which the ASAT's owner would want other countries to be aware of the ASAT's existence in order to send a political signal.

A country seeking to deploy a covert space-based ASAT might attempt to prevent detection of its launch. For example, a small ASAT could be launched along with a legitimate satellite. In addition, the ASAT's owner would try to prevent its detection once in orbit or might conceal its purpose by disguising it.

Currently, most satellites are launched into orbit from a small number of fixed launch pads,[3] and launches are announced in advance. Such space launches are readily observable from the ground and any country that wanted to monitor these launch sites could do so. However, small payloads can be launched from aircraft and smaller ground- and sea-based facilities. While the

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[3] The Sea Launch system is a floating platform used to launch rockets from near the equator. However, it prepares the launcher and loads the satellite in Long Beach, California, and is unlikely to go unnoticed.

United States and possibly Russia could detect such launches with their existing early warning satellites, no other countries currently have that capability. However, the Russian system has never provided global coverage, since it is designed to detect launches from the United States.[4] Thus the United States might be able to covertly launch space-based ASATs from aircraft or small sea-based launch facilities. This possibility only applies to the United States, since all space launches by other countries would be detected by the U.S. early warning system.

Rather than trying to hide the launch itself, a country could attempt to hide the deployment of a small ASAT by placing it on the same launcher as a legitimate satellite and announcing only the deployment of the satellite. If the ASAT was small enough and the bus did not maneuver to place it in orbit, its deployment might go undetected.

Again, such deployment is unlikely to go undetected by the United States, which maintains an extensive Space Surveillance Network (SSN). The SSN consists of optical sensors and radars that track the roughly 8,500 objects 10 centimeters or larger that are orbiting Earth (including some 600 operational satellites, 1,300 rocket bodies, and 6,600 inactive satellites or other space debris). The SSN charts the position of these objects and plots their anticipated orbital paths. When the U.S. early warning satellites detect a rocket launch, the SSN detects its "associated objects," such as debris and deployed satellites. Thus, the United States is likely to detect deployment of even a small space-based ASAT, unless the ASAT uses techniques to reduce its optical and radar signatures.[5] Other countries currently have more modest space detection and tracking capabilities, so that it is possible the United States could deploy a small space-based ASAT without detection.

Even if the launch or deployment of a space-based ASAT were not observed, it might still be detected in orbit—sooner or later. However, if the ASAT did not maneuver to place itself in a new orbit, it could appear to be a piece of debris. The SSN does not have the capability for real-time data analysis and observes the operational satellites more frequently than it does debris. Nevertheless, once the ASAT maneuvered, the SSN would likely identify it as a satellite. All the other space-faring nations (Russia, China, Japan, India, Israel, Ukraine and many of those of the European Union) have sufficient surveillance capability to monitor their own satellites and to detect trailing satellites in low earth orbits and possibly in geosynchronous orbits. It is less likely that these countries would survey objects in an orbit other than the ones their satellites occupy, so it is possible that a U.S. space-based ASAT in a crossing orbit could remain covert, at least for some time.

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4. Pavel Podvig, "History and the Current Status of the Russian Early Warning System," *Science and Global Security* 10 (2002): 21-60, http://www.russianforces.org/podvig/eng/publications/sprn/20020628ew/index.shtml, accessed January 5, 2005.

5. "Misty," a CIA satellite launched in 1990, is thought to have used an inflatable reflective shield to evade detection by Soviet surveillance for many years. Robert Windrem, "A Spy Satellite's Rise...And Faked Fall," July 12, 2001, http://msnbc.msn.com/id/3077830/, accessed February 9, 2005.

However, as noted above, a space-based ASAT could be designed to limit its optical and radar signatures. Moreover, as satellite miniaturization techniques continue to improve, space-based ASATs with dimensions of a few tens of centimeters or smaller will be feasible. In the face of such developments, detection of space-based ASATs may become difficult even for the United States.

In addition to detecting the physical presence of a space-based ASAT, it may be possible to discover an ASAT by detecting its communications with the ground, although these may be short and infrequent.

Even if a space-based ASAT was detected and tracked and determined to be a satellite, its purpose could remain covert. A space-based ASAT could be disguised as a legitimate satellite. However, the ASAT's orbit would give a clue to its purpose, especially if it closely trailed another satellite. A satellite in a crossing orbit would be less likely to raise suspicions.

In sum, no country can assume it would be able to detect the ASATs deployed by other countries. At the same time, no country can assume that its deployment of space-based ASATs would remain covert, not even the United States. However, this situation may change in the future, given current trends in satellite miniaturization and techniques to reduce satellite signatures.

Space-Based ASATs vs. Ground-Based ASATs

Depending on the means of attack, space-based ASATs and ground-based ASATs have relative advantages and disadvantages.

Section 11 considers the suitability of ground- and space-basing for the various methods of interference considered there; Table 12.1 summarizes those results. As discussed in Section 11, jamming and dazzling are not well suited to space basing, since they would require essentially constant maneuvering to be in position to attack a target satellite. For the foreseeable future, using space-based lasers to damage the structure of a satellite, as opposed to its sensor, is not technically feasible. On the other hand, high power microwave attacks are not well suited to delivery from Earth, but can be delivered from space-based HPM generators.

Table 12.1. The Xs indicate that the method of interference is well suited to basing on the ground or in space.

	Ground-based	Space-based
Uplink jamming	X	
Downlink jamming	X	
Dazzling	X	
Partial blinding	X	X
High power microwaves		X
Laser damage	X	
Kinetic energy	X	X
Nuclear weapon	X	

The analysis in Section II shows that it is feasible to partially blind a satellite's optical sensor using either a ground-based laser or a modest sized space-based laser in a crossing orbit, although in either case the number of pixels affected would likely be small. Kinetic kill attacks could also be conducted using either ground- or space-based ASATs.

This subsection examines in more detail the relative advantages and disadvantages of using ground- and space-based ASATs designed to partially blind a satellite or destroy it by kinetic means. For these two types of attacks, we assess the relative ability of space- and ground-based ASATs to

- undergo covert development, testing, and deployment and thus deny strategic warning to an adversary
- work effectively and reliably
- deliver an attack on multiple satellites in a short period of time and thus limit tactical warning.

We also consider the ability of the adversary to counter an attack. Relative cost is not discussed, although in practice this will be an important consideration.

Covert Development and Testing. Although the development and testing of ASATs—whether space- or ground-based—would not be as provocative as ASAT deployment, it could nonetheless raise objections within the international community and warn potential adversaries of forthcoming deployment. Hence a country developing such weapons would likely prefer to do so covertly.

A space-based ASAT designed to partially blind a satellite could not be fully tested unless it was placed in orbit, which would pose a risk of detection. However, the purpose of the ASAT could be kept covert, and it is unlikely that others could detect the actual testing. A country could test ground-based lasers against its own satellites—either those at the end of their lifetime or satellites designed for this purpose—with little risk of detection.

Homing kinetic energy ASATs would impact their target at closing speeds of roughly 7 to 14 km/sec. The ability to directly impact a moving target at such high closing speeds can be assessed only by intercept testing. A country would find it difficult to conduct a covert intercept test of either ground- or space-based kinetic energy ASATs, since the resulting collision would generate significant debris and eliminate the original satellite. The United States would certainly be able to detect such a collision relatively quickly. Other space-faring countries would also be able to detect it, sooner or later.

On the other hand, a country could conduct the required tests in the context of developing an exo-atmospheric hit-to-kill missile defense system, since the closing speeds are comparable. In the intercept tests of the U.S. Ground-Based Midcourse Defense (GMD) to date, the time and details of the attack were known in advance, the trajectory of the target warhead was known by the defense, and there were no decoys. While these conditions are not appropriate to test a realistic attack by a ballistic missile warhead, they are appropriate to test intercepting a satellite in low earth orbit.

Covert Deployment. As discussed above, a country may be able to covertly deploy space-based ASATs. This would be more feasible for ASATs in crossing orbits than for co-orbital ASATs. On the other hand, because ground-based lasers for partial blinding need not be enormous, they could be deployed covertly. And, while not covert, the deployment of interceptors as part of a ground-based midcourse missile defense provides a significant inherent ASAT capability against satellites at altitudes of up to several thousand kilometers, although this capability may not be widely recognized.[6]

Effectiveness. There is no reason to expect ground-based kinetic energy ASATs to be more or less effective than their space-based counterparts, whether homing interceptors in crossing orbits or co-orbital space-based ASATs that would explode near the target satellite or fire pellets at it. Additional analysis is required to assess whether the effectiveness of ground- and space-based laser ASATs designed to partially blind a target satellite differs significantly.

Reliability. A ground-based system might be more reliable than space-based ASATs, because it could be regularly maintained and upgraded. It may also be more feasible for a country to have back-up ground-based ASATs to use if the first ASAT, ground or space-based, fails.

Time to Deliver Attack. The ability to respond on the scale of minutes once an attack is ordered may not be essential for ASATs, in contrast to ground attack weapons that might seek to destroy mobile targets. However, a short response time might be useful in some situations.

Because of its proximity to the target satellite, a trailing kinetic energy ASAT could in principle attack rapidly once a decision was made to do so. This assumes, however, that the owner could communicate quickly with the ASAT, which may not be possible if the ASAT is not in view of a ground station or relay satellite to receive instructions. For the United States, which has ground stations worldwide, communication could be quick. A country with limited global presence could take considerably longer to send the signal to attack, although the signal may be simple enough that it could be sent from the country's diplomatic missions.

In contrast, an ASAT in a crossing orbit may require hours before it is in position to attack. Similarly, it could be hours before a ground-based ASAT was in the proper position to attack a satellite in low earth orbit. This time could be reduced if ground-based interceptors were positioned at various places around the globe, such as kinetic energy ASATs on aircraft. A ground-based kinetic energy ASAT would reach a satellite in low earth orbit in a matter of minutes, but it would take several hours to reach a satellite in geosynchronous orbit.

Perhaps more useful would be a capability to attack multiple satellites simultaneously or in a short period of time rather than over several hours or

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[6] See David Wright and Laura Grego, "Anti-Satellite Capabilities of Planned US Missile Defense Systems," December 9, 2002, http://www.ucsusa.org/global_security/space_weapons/page.cfm?pageID=1152, accessed January 17, 2005.

days. Such a rapid multiple attack could limit tactical warning for the targeted country and thus its ability to take action. A short attack time (the duration of the attack, once initiated) would not require a short response time (the time between a decision to attack and initiation of the attack).

If the attacker used trailing kinetic energy ASATs, these could attack numerous satellites essentially simultaneously, providing no tactical warning. A simultaneous attack would be more difficult using ASATs in crossing orbits, whose trajectories would need to be synchronized.

The ability to launch a multisatellite attack of short duration using ground-based ASATs would depend in part on how widely separated the satellites were at the time of attack and on whether the country could deploy ASATs at different locations.

Feasibility of Defense. Once an attack was under way, countering either a ground- or space-based kinetic energy ASAT would be difficult. Perhaps the most feasible approach would be to try to destroy the ASAT using a space-based kinetic energy weapon. Doing so would require the ability to observe launches, which only the United States is capable of doing globally. However, for attacks against satellites in low earth orbit, the warning time would likely be too short to allow a counter attack. It may, in principle, be possible to intercept a kinetic energy ASAT attacking a geosynchronous satellite.

Once a ground-based blinding laser was attacking a satellite, its location could be determined and it could presumably be destroyed. A space-based laser in a crossing orbit would be vulnerable to attack by a kinetic energy ASAT. However, since partial blinding occurs quickly, this destruction would only prevent future attacks, not defend against the current one.

SIMPLE GROUND-BASED PELLET (NON-HOMING) ASAT

Discussions of ASATs frequently refer to a low-tech method for attacking satellites in low earth orbit, which consists of a missile that does not home on the target satellite but lofts a large mass of sand or pellets into its path. Because the satellite in orbit is moving faster than 7 km/s, a collision with even a small particle can do severe damage to the satellite. Moreover, since the pellets are lofted into the path of the satellite and are not placed into orbit, they can be launched on relatively short-range missiles to attack satellites in low earth orbits.[7]

This subsection analyzes the probability that such a pellet ASAT successfully destroys a satellite. The results indicate that, in its simplest form, a pellet ASAT may have limited effectiveness. A country with sufficient technical capability could take various steps, discussed below, to increase the probability of intercept. Thus the technical capability assumed of the country using the ASAT must be clearly delineated. A simple pellet ASAT might be used by a

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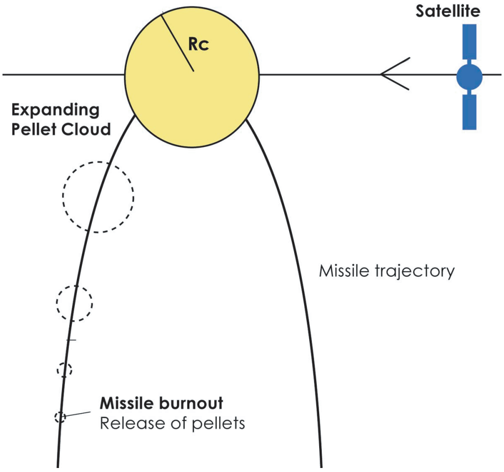
[7] Since the pellets are not placed in orbit, they would fall back to Earth and not constitute orbital debris. If they struck a satellite, some of the particles produced could become long-lived debris, depending on their speed and direction of motion.

country lacking the technical capability to develop an ASAT that would provide higher confidence of success, such as a homing interceptor. (A homing interceptor might dispense a cloud of pellets to increase the probability of killing the satellite, but this would be a small cloud released shortly before the intercept, rather than a large cloud released much earlier.)

The ASAT considered here uses a missile fired roughly vertically to loft a cloud of pellets into the path of a satellite. Shortly after the missile burns out and stops accelerating, an explosive charge or other mechanism disperses the pellets carried by the missile so that they form an expanding cloud (see Figure 12.1). The size of the cloud when it reaches the intended intercept point depends on the expansion speed of the pellets and the amount of time between the release of the pellets and when they reach the intercept point.[8] The path the cloud follows is controlled by aiming the missile, that is, controlling the missile's speed and direction at burnout. The center of mass of the cloud follows the same trajectory as would a simple warhead released from the missile.

Figure 12.1. At burnout, a missile releases a cloud of pellets, which expands as it travels toward the intercept point, shown here at the apex of the trajectory, with a radius R_c. Timing errors can be minimized by arranging to have the cloud reach its maximum height at the altitude of the satellite's orbit.



The effectiveness of a pellet ASAT depends on the probability that one or more pellets strike the satellite and that those strikes disable the satellite. The probability that pellets strike the satellite depends on several factors:

- the accuracy with which the attacker can determine the satellite's trajectory, which determines how accurately the future position

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[8] For the situation considered here, the pellet cloud expands for about 340 s from the time it is released after missile burnout until it reaches apogee at 600 km altitude. As a result, the pellets need a speed of only about 3 m/s to produce a cloud radius of 1 km at apogee.

of the satellite can be predicted and an intercept location and time can be calculated

- the accuracy with which the attacker can deliver a missile payload to a specific point in space, i.e., the calculated intercept point
- the size of the cloud of pellets and the number of pellets in the cloud
- the size of the satellite, in particular, the cross-sectional area it presents to the pellet cloud.

Each of these is discussed further below.

A country using such an ASAT can attempt to compensate for uncertainties in the location of the satellite and in the accuracy of placing the cloud in its path by making the pellet cloud large, which increases the probability that the satellite passes through the cloud. However, for a given number of pellets, a larger cloud size means a lower density of particles and therefore a lower probability of impact. Increasing the number of particles requires either increasing the total mass the missile must lift into space, which is limited by the capability of the missile, or reducing the mass of each pellet, which reduces a pellet's ability to damage the satellite if it hits.

Even if one or more pellets hit a satellite, the satellite may not be disabled. While a satellite may present a relatively large area to the cloud of pellets, the portion of the satellite that must be hit to disable it may be much smaller than its total area. For example, a large part of a satellite's total area may be solar panels. Pellet hits might degrade the performance of the solar panels, but the panels may be able to sustain a number of hits before the damage disables the satellite.

Moreover, if the pellets are too small, they may not cause sufficient damage to disable the satellite. The ability of a pellet to damage a satellite depends on both its diameter and mass.[9] For this reason, grains of sand may be too small to be effective, especially if the satellite uses simple shielding.[10] Shielding materials now available could protect sensitive parts of a satellite from strikes by particles with mass greater than 1g and diameter greater than 1 cm.[11] While shielding has the disadvantage of adding to the satellite mass,

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[9] For high-speed collisions, the ability of a pellet to penetrate a target, such as the outer wall of a satellite, increases with its size. Once the pellet hits the target, it continues to penetrate until the shock wave created by the impact at the front of the pellets travels to the rear of the pellet. See, for example, Stephen Remillard, "Debris Production in Hypervelocity Impact ASAT Engagements," Air Force Institute of Technology (DTIC # AD-A230-467), December 1990, 26.

[10] For example, a piece of debris estimated to be 0.2 mm in size and traveling at 3 to 6 km/s chipped but did not penetrate a window of the space shuttle. Grains of sand typically have diameters of 0.05 to 2 mm and masses in the range of 0.1 to 10 milligrams (see Marina Theodoris, "Mass of a Grain of Sand," 2003, http://hypertextbook.com/facts/2003/MarinaTheodoris.shtml, accessed January 5, 2005).

[11] See, for example, "3M Nextel Ceramic Fabric Offers Space Age Protection," 3M (98-0400-5217-1) 1997, http://www.3m.com/market/industrial/ceramics/pdfs/CeramicFabric.pdf, accessed December 5, 2005, and International Space Information Service, *Technical Report on Space Debris*, UN (A/AC.105/720) 1999, Section III.B.1, http://www.oosa.unvienna.org/isis/pub/sdtechrep1/sect03b1.html, accessed December 5, 2005.

high-value satellites are likely to include some shielding against orbital debris. Such shielding would set a lower limit on the size of pellets required for a successful attack.

The Appendix to Section 12 describes a simple model to calculate the probability that, under various conditions, a satellite is hit by one or more pellets. For each set of conditions, the calculation gives the intercept probability as a function of cloud size. It considers the case of an attacker with a missile that can carry 500 kg of pellets to an altitude of 600 km. According to the "1/2 Rule" (Section 8), such a missile would be roughly comparable to a North Korean Nodong missile.[12]

Uncertainty in Satellite Position

The accuracy with which a country can determine the orbit of a satellite depends on the type and number of sensors it has to observe the satellite and on the software it has to calculate, based on its observations, the satellite's orbit and location at a future time. If the orbit remains essentially constant over time, the estimate of the orbit can be made more accurate over time by including data from additional observations. If the orbit changes on a relatively short time scale due to atmospheric drag, stationkeeping, or other maneuvers, additional observations will provide no help in refining the estimate of the orbit.

At the simplest level, telescopes can be used to measure a satellite's angular position in the sky. But telescopes cannot determine the distance to an object and therefore cannot directly measure the altitude of the satellite at any point. Instead, measuring the period of the orbit, and the satellite's position and angular speed at various points on the orbit provides the information necessary to estimate the shape and orientation of the orbit. Since the orbit will in general not be circular, the altitude of the satellite varies with its position on the orbit. A country may have difficulty collecting sufficient data to determine the orbit accurately for several reasons. For example, it may not have the ability to collect information from locations distributed around the world.[13] Since optical measurements require seeing sunlight reflected off the satellite, the satellite will be in the proper position to be seen from a given location for only relatively short periods of time during the day, which limits the data that an observer can collect as the satellite passes over. The observer may also not have the equipment and the ability to make highly accurate measurements. And, as noted above, the satellite may be maneuvering.

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[12] The Nodong missile is believed to have a maximum range of about 1,300 km with a 700 kg payload. Since the payload would need to include the structure of the stage containing the pellets and the mechanism to distribute them, the actual mass of pellets that such a missile could lift to this altitude would probably be less than 500 kg.

[13] Allen Thomson has suggested that countries might take optical measurements from its embassies around the world as a way of collecting global data. See Allen Thomson, "Satellite Vulnerability: A Post-Cold War Issue?" *Space Policy* 11 (1995) 19–30, http://www.fas.org/spp/eprint/at_sp.htm, accessed December 5, 2005.

It is relatively difficult to determine the satellite's altitude at a given point on its orbit to high accuracy using measurements of this type. As shown below, even uncertainties in altitude of a few kilometers out of a total orbital radius of 7,000 km—corresponding to uncertainties of a few hundredths of a percent—are enough to significantly reduce the effectiveness of an ASAT.

Other types of measurements, if available, could reduce the uncertainty. If a country had a radar system that could detect the satellite to be attacked, it could determine the distance to the satellite accurately using the travel time of a radar pulse to the satellite and back to the radar. However, a country such as North Korea may have difficulty acquiring a radar with this capability. Laser radar, which determines the range in the same way using light pulses, may be more feasible.

Inaccuracy in Positioning the Pellet Cloud

The inaccuracy in aiming the center of the cloud at a particular location is caused by errors in controlling the burnout speed of the missile (so-called *guidance and control errors*). These can be estimated from the accuracy with which the missile can deliver a warhead to a ground target. This accuracy is quantified by a *circular error probability* (CEP), which is the radius of a circle that includes half of the impact points of a large number of warheads fired at the same target. A country with relatively low technical sophistication will not be able to control the burnout speed accurately, which will lead to a relatively large CEP.

The CEP of the Nodong missile at its maximum range is estimated to be several kilometers. Assuming the guidance and control errors are a significant component of the total CEP,[14] this implies that the burnout velocity can be controlled to a few meters per second (compared to the burnout velocity of the Nodong of about 3 km/s). The analysis in this report assumes this level of technology.

If the pellet cloud is fired vertically to an altitude of 600 km, an error in the horizontal component of velocity of ±3 m/s leads to an error in the horizontal position of the center of the cloud of roughly ±1 km. Similarly, an error of ±3 m/s in the vertical velocity leads to an uncertainty in the maximum altitude, or apogee, of the missile trajectory of roughly the same amount. Moreover, these errors introduce an uncertainty into the time to reach apogee of several tenths of a second.

The CEP describes the spread of missile impact points. In general, that pattern of impact points will not be centered at the aim point of the missile due to systematic errors in guiding the missile, which affect all launches the same way, rather than shot-to-shot errors, which affect each launch differently. The distance between the aim point and the center of the impact pattern is called the *bias.* A large bias can increase the distance by which the pellet cloud misses its aim point. Since the CEP and the bias are determined statistically, a country that has done relatively few flight tests of the missile may have little information about the CEP or bias of the missile.

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[14] Unpredictable atmospheric forces during reentry will contribute to the CEP when attacking targets on the ground, but not targets in space.

A country with sufficient technical ability could more accurately position the pellet cloud in space by taking measures to increase the accuracy of its missiles. One possibility is to add a small maneuvering bus to the missile that uses a GPS receiver and small thrusters to reduce the guidance and control errors.

Timing Errors

In order for an intercept to occur, the satellite and pellets must be at the same place at the same time. Errors in timing can arise from uncertainties either in predicting when the satellite will arrive at a certain point on its orbit or in delivering the pellet cloud to a given location at the right time.

A significant timing error can be tolerated if the satellite passes directly over the ASAT launch site, so that the ASAT is fired vertically and the cloud has no horizontal velocity. The ASAT is then fired so that the intercept point is at the apogee of the pellet cloud's trajectory. Since at apogee the cloud stops moving vertically and begins to fall, it remains in the satellite's path for tens of seconds.[15]

However, if the satellite's orbit does not pass directly over the ASAT launch site, the ASAT will need to travel some distance horizontally as it travels vertically to the proper altitude. As a result, the pellet cloud will have a horizontal component of speed V_h when it reaches the proper altitude, and a timing error of Δt will result in a position error for the cloud of $\Delta t \times V_h$.

Since the time from launch until the pellet cloud reaches an altitude of 600 km is about 440 s for a missile like the Nodong, the horizontal speed of the pellet cloud would be about 225 m/s for each 100 km of horizontal distance that the ASAT needs to travel from its launch site to the intercept point. Assuming the total timing uncertainty from all sources is 0.5 s, the cloud's horizontal speed would lead to a position uncertainty of about 110 m for each 100 km of horizontal distance. As a result, it would be advantageous for the country using this ASAT to launch its attack at the time the satellite passes roughly overhead or to launch the ASAT from a mobile launcher that could move directly under the satellite's path. Since the ASAT is launched on relatively short-range missiles, such mobility is possible. The Nodong missile, for example, is designed for use on a mobile launcher.

Results of the Calculation

The simple model described in the Appendix to Section 12 estimates the effectiveness of an ASAT of this type and describes the important parameters. The analysis considers a missile that can carry 500 kg of pellets to an altitude of 600 km. It uses the following parameter values for the base case and then considers variations around them:

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[15] This possibility was suggested by Richard Garwin. At 600 km altitude, the cloud stays within 1 km of its apogee for 31 seconds, within 0.5 km of its apogee for 22 seconds, and within 0.25 km of apogee for 15 seconds.

- *The uncertainty in the location of the pellet cloud.* The base case assumes an uncertainty of 1 km, which corresponds roughly to the accuracy of a Nodong missile, as discussed above.[16]
- *The uncertainty in the location of the satellite.* The base case assumes that the attacker can determine the horizontal position of the satellite to about 0.1 km, but can predict the satellite's altitude at the planned intercept point only to within 1 km.[17]
- *The frontal area of the satellite in which the collision with a pellet could disable the satellite.* The base case assumes an area of 10 m^2.
- *The number of pellets in the cloud.* The base case assumes the cloud contains 500,000 pellets, each weighing 1 g, distributed uniformly within a spherical region. A 1-g spherical pellet made of aluminum has a diameter of 0.9 cm.

The calculation varies the size of the pellet cloud to find the size that gives the maximum value of the intercept probability for each set of parameter values. The pellet cloud is assumed to be spherical, as discussed in the Appendix to Section 12.

The values given here are the probabilities that the vulnerable area of the satellite is struck by at least one pellet. The analysis does not address the issue of whether the pellets that strike the satellite will disable it. For the base case, the calculation shows the probability of the satellite being hit by at least one pellet is less than 30%, and the probability it would be struck by at least two pellets is 10%. The optimum radius of the pellet cloud in this case is about 1.4 km.

If the attacker can reduce his uncertainty in the altitude of the satellite from 1 km to a few tenths of a kilometer, the probability of pellet impact increases to about 35%. In this case, the optimum cloud radius is still well over 1 km since the inaccuracy in the placement of the cloud is still large. On the other hand, if the altitude uncertainty increases to 2 km, the probability of at least one pellet impact decreases to less than 20%. If it is as large as 5 km, the intercept probability is well under 10%.

If the missile accuracy is improved so that it can deliver the pellet cloud with an accuracy of 0.5 km rather than 1 km, the intercept probability of the base case increase to about 45%. If the accuracy is instead 1.5 km, the probability drops to under 20%.

Increasing the number of pellets by a factor of two, from 500,000 to 1 million increases the intercept probability of the base case to slightly over 40%. Since the total mass of pellets a given missile can carry is determined by the altitude the pellets must reach, increasing the number of pellets requires reducing the mass of each pellet to 0.5 g. However, as noted above, it may be possible to shield sensitive parts of the satellite against pellets of this size.

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[16] In particular, the probability distribution of the location of the pellet cloud at apogee is given by a Gaussian distribution with a standard deviation of 1 km. As a result, the center of the cloud falls within a circle of radius 1 km about 40% of the time.

[17] In particular, the location of the satellite is given by a two-dimensional Gaussian distribution with standard deviations of 0.1 and 1 km in the horizontal and vertical directions.

Indeed, to ensure that a pellet penetrates the satellite skin and causes damage if it hits, an attacker may want to use larger pellets. Increasing the pellet mass to 1.5 g (which roughly corresponds to a 1-cm diameter sphere of aluminum) reduces the number of pellets this missile can loft to 600 km to 333,000 and the intercept probability for at least one hit to 20%. If the vulnerable area of the satellite is 15 m^2 rather than 10 m^2, the intercept probability of the base case increases to about 35%.

If there is a systematic error, or bias, in controlling the missile that releases the pellet cloud, this reduces the probability of intercept. Moreover, as noted above, if the launcher is not directly below the path of the satellite, the pellet cloud has a horizontal speed that carries it across the satellite's path, and any a timing errors will cause that motion to result in a spatial inaccuracy that would enter the calculation in the form of a horizontal bias. Unless the value of the bias or the inaccuracy resulting from the timing uncertainty are comparable to the inaccuracy of delivering the cloud, these effects have no significant effect on the intercept probability.

If both the uncertainty in cloud location and satellite location can be reduced to a few tenths of a kilometer, the probability that at least one pellet will hit the satellite is close to one. Notice, however, that both of these uncertainties must be reduced in order to achieve a high intercept probability.

Conclusions

These results show that a simple pellet ASAT of the type considered here, used by an attacker with relatively low technical sophistication, may be relatively ineffective. The effectiveness depends on the values of several key parameters, so that the ASAT would not be very effective unless the attacker can determine the satellite orbit accurately, control the missile accurately, and lift large masses of pellets to orbital altitudes.

Moreover, the outcome of using such a weapon could be very uncertain. The attacker may not even be able to quantify the uncertainty in missile accuracy or predicted satellite location; for example, a country may not have done enough missile tests to determine the missile's accuracy. The attacking country could therefore have little confidence in its ability to carry out a successful attack, even if it fired several missiles at the satellite. As a result, such an ASAT is unlikely to have a high military value.

U.S. planners need to take into account the possibility that such a weapon would work, but their assessment of the threat must consider the attacker's capabilities, as described above. Moreover, the United States could take various steps to make such an attack more difficult. Adding shielding to vulnerable parts of key satellites could defeat such an attack or force the attacker to use pellets with larger mass, which decreases the number of pellets in the cloud for a given payload and reduces the probability of intercept.

Moreover, if the United States detected a missile that appeared to be attacking a satellite, even a relatively small maneuver could essentially eliminate the probability of intercept. The satellite could have more than 300 s to maneuver after the missile was detected, so that a ΔV of only 10 m/s would move the satellite off its predicted orbit by several kilometers, significantly reducing the probability of intercept.[18]

An attacker with a sufficient level of technology could significantly increase the effectiveness of this type of ASAT. If the attacker could both deliver the pellet cloud accurately and accurately determine the satellite's altitude, it could have a high probability of intercept against a target that did not attempt countermeasures, such as maneuvering. A country with these capabilities, however, is likely to have the technical capability to build an interceptor that is more effective and reliable, such as one with a homing interceptor. Given the uncertainties associated with its use, a simple pellet ASAT seems unlikely to be the ASAT of choice.

THE GLOBAL POSITIONING SYSTEM AND RECONNAISSANCE SATELLITES

Section 11 discussed a variety of threats that satellites can face. This subsection puts these threats in perspective by looking in more detail at two important U.S. satellite systems: the Global Positioning System (GPS), which provides global navigation, and the U.S. system used to provide military reconnaissance. As described below, the GPS system has been designed to be robust, resistant to interference, and able to perform its missions even if a few satellites are lost. Moreover, even if the entire satellite system was lost, its capabilities can be provided by other means—at least on a provisional basis. The reconnaissance system is inherently more vulnerable—in part because the satellites are in low earth orbits—but backup capabilities also exist for this mission.

The Global Positioning System

The U.S. military developed GPS as a navigation aid. It remains under military management and performs critical military missions, such as mission planning, guidance of precision munitions, and navigation for troops and vehicles on the ground and in the air. The GPS system has also become integrated deeply into the civil infrastructure. GPS signals are used for civil navigation, for air traffic management, and as a global time standard that synchronizes everything from cell phones to scientific experiments. Degradation or loss of the signal without prior planning could seriously compromise military and economic life.

The GPS constellation consists of 24 operational satellites, with four in each of six different orbital planes at an altitude of 20,000 km.[19] In addition, several spare satellites are usually in orbit, since replacements are launched in advance of the need to replace older ones.[20] Between five and eight satellites are visible from

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[18] This point is also mentioned in the *Ensuring America's Space Security* (Washington, DC: Federation of American Scientists, 2004), 22, http://www.fas.org/main/content.jsp?formAction=297&contentId=311, accessed December 5, 2005.

[19] "USNO GPS Timing Operations," http://tycho.usno.navy.mil/gps.html, accessed January 15, 2005.

[20] United States Naval Observatory (USNO), "Block II Satellite Information," ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt, accessed January 16, 2005. As of January 16, 2005, there were 30 satellites in orbit, with three orbits having 1, 2, and 3 extra satellites, respectively.

any point on the Earth at all times. However, only four satellites are required to be in view to provide position and time information to a user.[21] If the user can receive signals from more than four satellites, the accuracy improves.

An important feature of the GPS constellation is that its ability to provide navigation information would degrade gradually, rather than catastrophically, under an attack. For example, the minimum requirement of four satellites would be available for almost the entire day to a user in Beijing even if six satellites were lost, even if those six were chosen to give the greatest loss of service for that location.[22]

The GPS system also has some innate protections from attack. The satellites operate at a high altitude, which puts them out of reach of ground-based kinetic energy attacks using modified short-range or intercontinental ballistic missiles. At this altitude, the space environment is difficult to operate in: the flux of charged particles from the Van Allen belts is high (see Section 5), and any long-lived ASAT that was intended to trail a GPS satellite would need to be designed to handle this danger. Blinding and dazzling would not affect the ability of the satellites to provide navigation information since doing so requires no optical sensors.[23] The satellites themselves are designed to withstand heat imbalances from distant laser attacks.[24] Moreover, the satellites are in six separate orbital planes and their spacing within those orbits is such that a single ASAT would have difficulty targeting more than one satellite.

Uplink jamming of the command signals from ground stations is difficult. However, even if an attacker succeeded in jamming the uplink, the satellites are able to operate for 14 days without contact from the command station and up to 180 days in an autonomous navigation mode (AUTONAV). Moreover, the most recent version (Block IIR) can do so while maintaining full accuracy.[25] In autonomous mode, the satellites communicate only with each other using cross links, which are protected against jamming by using frequency hopping and directional antennas that can receive signals from other satellites but not the ground.

Three types of interference attacks that might succeed are downlink jamming, and to a lesser degree, spoofing and meaconing.

Downlink jamming is not technically demanding and can lead to significant interference locally. Sites on the internet provide blueprints for a GPS jammer that could be built by someone with an undergraduate technical

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[21] To obtain the highest accuracy reading with four satellites, they should be positioned so that three satellites are spread evenly around the horizon and one is overhead.

[22] Geoffrey Forden, "Appendix D: Sensitivity of GPS Coverage to Loss of One or More Satellites," *Ensuring America's Space Security* (Washington, D.C.: Federation of American Scientists, 2004), http://www.fas.org/main/content.jsp?formAction=297&contentId=311, accessed January 15, 2005. Forden finds that four satellites would be observable from Beijing for 22 hours of the day.

[23] Each GPS satellite carries optical sensors as part of the Nuclear Detonation Detection system, but these are not used for navigation.

[24] Ashton B. Carter, "Satellites and Anti-Satellites: The Limits of the Possible," *International Security*, 10 (1986) 90.

[25] USNO, "Block II Satellite Information."

degree,[26] as well as advertisements for GPS jammers for sale. A small, lightweight, short-lived jammer that could deliver up to 100 W of emitted power can be purchased or constructed for less than $1,000. Jammers that can deliver kilowatts of power can be made for about $100,000, and those that produce tens to hundreds of kilowatts would cost a million dollars or more.[27] However, such high power jammers are likely to be vulnerable, as they can be located rapidly and accurately and then targeted.

Multiple smaller jammers would likely be the preferred scheme. They could be readily distributed in large numbers over terrain in which an enemy wished to deny GPS tracking. If a jammer can send its signal over a wide area without obstruction—for example, by broadcasting from an airplane—it could affect a large number of users. An airborne jammer emitting only 1 W of power could deny GPS tracking to active users (those who have already locked onto the GPS signal) within 10 km and could deny users up to 85 km away the ability to locate GPS satellites and receive an accurate signal.[28] In addition, before a GPS receiver can recognize that it is being jammed and cease providing position data, it may provide inaccurate data for tens of seconds, thereby endangering pilots who do not employ backup navigation measures.

The United States has taken some steps to mitigate the GPS system's vulnerability to jamming. The GPS modernization program will increase the strength of the signal broadcast from the satellites and the number of frequencies the signal is broadcast on. This will raise the bar for jammers, requiring additional signal strength and the ability to jam multiple frequencies. New GPS receivers are being built with additional antijamming features. For example, by using multiple antennas, an analog receiver can use nulling techniques to eliminate the interfering signal, and new digital receivers can be made even more jam resistant.[29]

Spoofing, as Section 11 indicates, mimics the characteristics of a true signal so that the user receives the fake signal instead of the real one. Meaconing is similar to spoofing but entails receiving the real signal and then rebroadcasting it with a time delay. Because two GPS signals are broadcast at different frequencies, a civilian signal and a military signal that is encrypted, it is possible to interfere with one but not the other.

The potential advantage of spoofing and meaconing over jamming is that they could be done covertly, since the user will generally not be able to determine that the receiver is being spoofed or meaconed. In both cases, the

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[26] Marks ("Wanna Jam It?") describes an Air Force team that built a jammer to work against an ultrahigh frequency satellite, with just an internet connection and $7,500 worth of materials. It would be fairly simple to adapt the same technique to the GPS frequency.

[27] John A. Volpe National Transportation Systems Center, "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," Appendix A, August 29, 2001, and references therein.

[28] P. Ward, "GPS Receiver RF Interference Monitoring, Mitigation, and Analysis Techniques," *Navigation—Journal of the Institute of Navigation*, 414 (1994): 367.

[29] Robert K. Ackerman, "Jam-Proof Signals to Guide Navigation," *Signal Magazine*, November 2001, http://www.afcea.org/signal/articles/anmviewer.asp?a=481&z=6, accessed February 9, 2005.

antenna would be more difficult to locate than a jammer's antenna, since the signal strength of the spoofed or meaconed signal must be the same as that of the true GPS signal. If the location of the spoofing or meaconing antennas were determined, receivers could be told to ignore the false signals.

Spoofing a GPS satellite signal is technically much more difficult than jamming it, as the spoofed signal must have the same characteristics as the real one, including frequency structure and signal encoding. Because it is encrypted, the GPS military signal would be extremely difficult to spoof, but the civil signal has a well-known structure. Moreover, GPS satellite simulators, which are used by manufacturers to test GPS receivers and related products, are available commercially and can be purchased (for $10,000 to $50,000) or rented. These simulators produce fake satellite signals at a higher power than the real GPS civil signals. Someone with an advanced understanding of electronics could also build a GPS simulator from scratch using information available on the internet.[30] There are some technical countermeasure strategies that the GPS receiver could implement relatively easily, but none are in wide use.[31] Meaconing also requires considerably more technical sophistication than jamming, but may be easier to use against the encrypted military systems.

Jamming could be made even more difficult in a theater conflict by using pseudosatellites or *pseudolites*, which are high power GPS transmitters that can be deployed on ground systems or unmanned aerial vehicles (UAVs).[32] These transmitters would broadcast a signal locally that would be a great deal more powerful than the satellite signals.

If the GPS civil signal is interfered with in one of these ways, users may have other options for navigation aid and precision guidance. The European Union is developing an independent satellite navigation system, Galileo, which is similar to GPS. The Galileo system was originally planned to have an operating frequency band that would overlap the U.S. encrypted military signal. This would have prevented the United States from jamming the Galileo signal without also jamming its own military signal. This was an intensely negotiated aspect of the Galileo system, and it appears that a compromise has been reached in which the Galileo system will not interfere with U.S. military operations.[33]

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30. Roger G. Johnston and Jon S. Warner, "Think GPS Cargo Tracking = High Security? Think Again," September 24, 2003, http://www.eyefortransport.com/index.asp?news=38732&nli=freight&ch, accessed January 16, 2005.

31. Jon S. Warner, Roger G. Johnston, "GPS Spoofing Countermeasures," December 2003, at http://www.homelandsecurity.org/bulletin/Dual%20Benefit/warner_gps_spoofing.html, accessed January 8, 2005.

32. Maryann Lawlor, "Researchers Locate Satellite Options," *Signal Magazine*, November 2001, http://www.afcea.org/signal/articles/anmviewer.asp?a=480, accessed February 9, 2005.

33. Robert Wall and Michael A. Taverna, "Navigating Hurdles: U.S. and Europe ink agreement on coexistence of GPS and Galileo," *Aviation Week & Space Technology*, June 28, 2004, 31.

The Effects of a Diminished GPS Capability.[34] As GPS is so widely used in military and civilian activities, an exhaustive discussion of what effects temporary outages and diminished accuracy of GPS would have is beyond the purpose of this report. Instead, impacts on a few GPS applications are examined here.

Temporary outages of GPS may not have a serious impact on ground- and sea-based navigation, especially if the outages were detected and backup systems put into use smoothly. The temporary loss of GPS may be least problematic for ships at sea, since they move slowly. Exceptions include situations where this loss is combined with another aggravating effect, such as low visibility, bad weather, or complicated terrain.

For air navigation, such outages would be more serious, especially in situations with high traffic or difficult terrain. Frequent and random outages from, for example, small and numerous jammers may make traffic control chaotic and dangerous. This could be particularly dangerous for civilian air traffic, which would not be as accustomed to functioning in crisis situations as is military traffic. However, for this reason, such vulnerable systems do not now and are unlikely in the future to rely solely on GPS systems.

If a threat to GPS seemed imminent, civilian applications such as surface shipping and business coordination can implement backups. Systems currently extant in the United States should suffice for this purpose. For example, LORAN-C[35], a ground-based system that transmits navigation signals, can provide two-dimensional navigation in the continental United States and serve as an accurate time standard. However, it cannot replace systems that require high precision in three dimensions, including some aspects of aviation. Although GPS was scheduled to replace LORAN-C, a December 8, 2004, presidential directive makes it more likely that it will be retained as a backup system. This directive gave the Department of Homeland Security responsibility for developing contingency responses in case GPS is disrupted within the United States.[36]

Reconnaissance Satellites

Satellite reconnaissance is used to perform numerous strategic and tactical military missions, including mapping terrain, gathering information on the military and industrial capabilities of other countries, monitoring one's own troop movements, choosing targets during a conflict, and assessing battle damage.

The United States has a number of dedicated military reconnaissance satellites: three optical imaging reconnaissance satellites, with ground resolution reported to be 12–15 cm; and three synthetic aperture radar satellites, with

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[34] This analysis is based on "Vulnerability Assessment of the Transportation Infrastructure."

[35] See the U.S. Coast Guard Navigation Center's web pages on LORAN-C beginning at http://www.navcen.uscg.gov/loran/default.htm, accessed December 15, 2004.

[36] "New Presidential GPS Policy Elevates Executive Oversight, Security Issues," *GPS World*, January 1, 2005, http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=140849 accessed on January 16, 2005.

ground resolution reported to be roughly a meter.[37] (There are a number of signals intelligence satellites, too—satellites that detect radio signals.) Many other countries operate reconnaissance satellites as well.

Ownership of reconnaissance satellites is not restricted to governments. A few commercial satellites take optical and infrared images useful for intelligence work. For example, the French SPOT system of satellites[38] takes images of the ground with up to 2.5-m resolution. The EROS-A[39] satellite can deliver images from 1- to 1.8-m resolution. The Ikonos satellite[40] provides images with up to 1-m resolution. The U.S.-based Quickbird satellite[41] provides images with resolution below 1 m. In principle, these satellites provide imaging data to anyone who will pay for them. In practice, a country could exercise "shutter control," as the United States did during the beginning of the war in Afghanistan by buying the exclusive rights to the images in some parts of the Ikonos orbit.

Remote sensing satellites are vulnerable to blinding and dazzling attacks from ground-based lasers, as Section 11 discussed. Because they are usually in low earth orbits, they are also vulnerable to kinetic energy attacks launched by ballistic missiles.

If remote sensing satellites are compromised, some of their functions can be provided by other systems, especially for regional or tactical use. For example, unmanned aerial vehicles (UAVs) can be used to augment satellite reconnaissance. In a conflict where the area of interest is confined to a theater of operations, the reduced field of view available at these lower altitudes (see Figure 5.2) may be compensated for by using multiple UAVs.[42] An airplane-based radar system, such as the U.S. Air Force synthetic aperture radar system JSTARS,[43] could also be used for tactical reconnaissance. Using UAVs and airplane-based radars is viable only in a region where the party has air superiority.

It may also be possible to use satellite-based systems to provide backup tactical reconnaissance capabilities. For example, the United States is developing launch vehicles that could launch small payloads with a minimum of

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[37] Robert Windrem, "Spy Satellites Enter New Dimension," *MSNBC News*, October 9, 2001, http://msnbc.msn.com/id/3077885/, accessed January 31, 2005.

[38] SPOT 4 and SPOT 5 are currently in orbit. See Spot Image, http://www.spotimage.fr, accessed January 18, 2005.

[39] EROS-A, launched on December 5, 2000, is owned ImageSat International N.V., a commercial endeavor founded by a team of engineers from the Israeli space program. See ImageSat International, http://www.imagesatintl.com/index.shtml, accessed January 18, 2005.

[40] Space Imaging provides optical images obtained with the Ikonos satellite; see Space Imaging, http://www.spaceimaging.com, accessed January 18, 2005.

[41] Digitalglobe provides images obtained with the Quickbird satellite; see DigitalGlobe, http://www.digitalglobe.com/, accessed January 18, 2005.

[42] See Bruce M. DeBlois et al., "Space Weapons: Crossing the U.S. Rubicon," *International Security* 29 (fall 2004): 61.

[43] For more information, see the U.S. Air Force Fact Sheet on E-8C Joint Stars, http://www.af.mil/factsheets/factsheet.asp?fsID=100, accessed January 31, 2005, and the Air Force Technology.com's web page on JSTARS, http://www.airforce-technology.com/projects/jstars/, accessed January 31, 2005.

preparation time. Such launch vehicles could put into orbit imaging satellites that are smaller and less expensive than current reconnaissance satellites. These satellites could be in lower orbits than the current reconnaissance satellites to compensate for their lower power optics and thus provide adequate ground resolution.

Section 12 Appendix: Calculating the Effectiveness of a Pellet ASAT

This section describes how to calculate the probability that at least one pellet strikes the satellite. The parameters that enter this calculation are

- the uncertainty in the location of the pellet cloud
- the uncertainty in the location of the satellite
- the number of pellets in the cloud
- the size of the pellet cloud
- an area that represents the vulnerable frontal area of the satellite.

The cloud radius is varied for fixed values of the other parameters, giving the intercept probability as a function of cloud radius, R_c. The maximum of this function gives the intercept probability at the optimum cloud radius. The pellet cloud is assumed to be spherical. While the shape of the pellet cloud could be optimized to increase the probability of intercept, doing so would require that the country be able to control the orientation of the cloud; otherwise, doing so could instead decrease the intercept probability. Since the case of interest is that of a low-tech ASAT, the attacker is assumed to use a spherical cloud.

The problem can be analyzed as a two-dimensional problem in a plane lying perpendicular to the satellite's trajectory. The spherical pellet cloud is then replaced by a disk of radius R_c with an area density of pellets equal to the two-dimensional projection of spherical density. For simplicity, in this calculation this two-dimensional projection of the density is replaced with a uniform density across the disk.[44]

The satellite is assumed to pass directly over the ASAT launch site; in this case, arranging the pellet cloud to have its apogee at the altitude of the satellite's trajectory eliminates timing errors. If the satellite does not pass over the ASAT launch site, inaccuracies in cloud position due to timing errors are added to the calculation as an increased uncertainty in cloud position.

It is useful to describe the calculation in two steps. The first step assumes the attacker knows exactly the location of the satellite and illustrates the effect of uncertainty in the location of the pellet cloud. The second step includes the uncertainty in satellite location.

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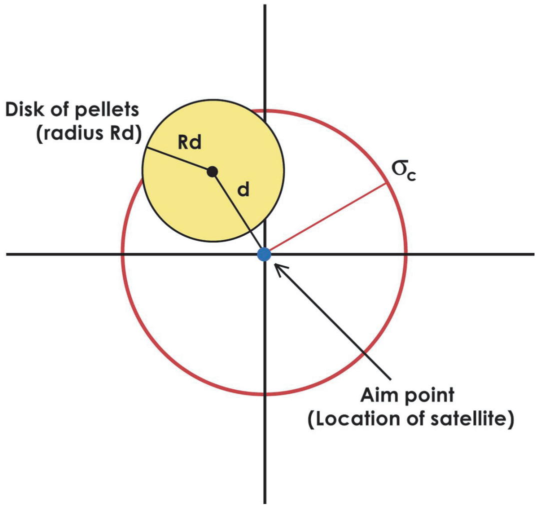
44. Consider the results of dispersing the same number of particles uniformly in a disk and a sphere of the same radius. Let ρ be the area density of particles in the disk. Compare this to the effective area density that would result from projecting the spherical density onto a plane perpendicular to the direction of motion of the satellite; this is the physical quantity that matters as the satellite sweeps through the cloud. The effective area density is 1.5ρ at the center of the sphere and falls to zero at the edge of the sphere; it is 1.3ρ halfway to the edge of the sphere, and 0.99ρ three-quarters of the way to the edge.

If the attacker knows the position of the satellite at the predicted intercept, the ASAT is aimed at that point. Because of errors in guiding the missile perfectly, the center of the pellet cloud instead arrives some distance from the aim point. The uncertainty in the location of the cloud is described by a Gaussian distribution:

$$p(d) = \frac{1}{2\pi\sigma_c^2} e^{-d^2/2\sigma_c^2} \tag{12.1}$$

where d is the distance between the center of the pellet cloud and the aim point in a plane perpendicular to the satellite's trajectory, and σ_c describes the uncertainty in the location of the pellet cloud due to the inaccuracy of the missile launching it, assuming the bias is zero (see Figure 12.2). The center of the cloud lies within a circle of radius σ_c roughly 40% of the time.

Figure 12.2. This figure shows a plane perpendicular to the path of the satellite; the satellite passes through the plane at the point marked "aim point." While the ASAT is aimed at this point, inaccuracies cause the center of the cloud to arrive at a distance d from the aim point. Roughly 40% of the time, the center of the cloud falls within the circle marked σ_c.



The probability that a pellet hits the satellite is the product of the probability that the satellite passes through the cloud, multiplied by the probability that a pellet hits the satellite if the satellite passes through the cloud. The first probability is just the probability that d is less than or equal to the cloud radius R_c, which is given by integrating $p(d)$ in Equation 12.1 for d between 0 and R_c; this integration gives

$$P_{satellite\ in\ cloud} = 1 - e^{-R_c^2/2\sigma_c^2} \tag{12.2}$$

Next we calculate the probability that the satellite is hit by at least one pellet if it passes through the cloud. As discussed above, for simplicity assume that the area density of pellets in the plane perpendicular to the path of the satellite is constant throughout the cloud. Let N be the total number of particles in the cloud and A_S be the area of the satellite perpendicular to its direction of motion.

Each pellet has equal probability of being anywhere in the disk of area πR_c^2. As a result, the probability that n pellets hit the satellite, assuming the satellite passes through the pellet cloud, is given by the binomial distribution

$$P_{n\ hits} = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n}, \quad p = \frac{A_s}{\pi R_c^2} \tag{12.3}$$

For large N, this approaches the Poisson distribution[45]

$$P_\lambda(n) = \frac{\lambda^n e^{-\lambda}}{n!}, \quad \lambda = Np = \frac{NA_s}{\pi R_c^2} \tag{12.4}$$

The probability that the satellite is hit by at least one pellet if it passes through the pellet cloud is

$$P_{\geq 1\ hit} = 1 - P_\lambda(0) = 1 - e^{-\lambda} \tag{12.5}$$

Similarly, the probably that the satellite is hit by at least two pellets if it passes through the pellet cloud is

$$P_{\geq 2\ hit} = 1 - P_\lambda(0) - P_\lambda(1) = 1 - (1+\lambda)e^{-\lambda} \tag{12.6}$$

The total probability that at least one pellet hits the satellite is then given by the product of Equations 12.2 and 12.5.

STEP 2

In reality, the attacker does not know the exact location of the satellite, but can determine it only with some uncertainty. The aim point of the ASAT is therefore the best estimate of the satellite's position. In the plane perpendicular to the path of the satellite, the uncertainty around this best estimate is described by a two-dimensional Gaussian probability:

$$r(d_x, d_z) = \frac{1}{2\pi\sigma_x\sigma_z} \mathrm{e}^{-\frac{1}{2}\left[\left(\frac{d_x}{\sigma_x}\right)^2 + \left(\frac{d_z}{\sigma_z}\right)^2\right]} \tag{12.7}$$

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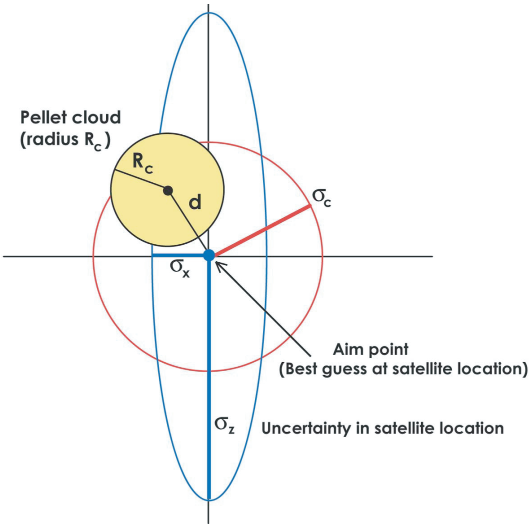
[45] "Poisson Distribution," http://mathworld.wolfram.com/PoissonDistribution.html, accessed February 10, 2005.

Here $r(d_x, d_z)$ is the probability that the satellite is actually located a distance d_x and d_z from the best estimate in the horizontal and vertical directions, respectively, where σ_x and σ_z describe the widths of the Gaussian uncertainty in these two directions. In general, these widths are not the same: the uncertainty in altitude (σ_z) is generally several times larger than the uncertainty in horizontal position (σ_x), for the assumed case of optical tracking.

Calculating the probability of a pellet hitting the satellite including both the uncertainty in the location of the pellet cloud and of the satellite involves the following steps. To determine the probability that the satellite passes through the debris cloud, we first calculate the probability that the actual location of the satellite is such that it would pass through a pellet cloud located at a particular point (x_c, z_c). We then integrate over all possible locations of the pellet cloud. Finally, we multiply by the probability that at least one pellet hits the satellite if the satellite does pass through the cloud (see Figure 12.3).

Figure 12.3. This figure adds to Figure 12.2 an ellipse giving the uncertainty in the location of the satellite's position.



More specifically, we assume that the missile delivers the pellet cloud so that its center is at the point (x_c, z_c), and that the cloud has a radius R_c at the time the satellite crosses the plane containing the center of the cloud. The probability that the satellite passes through a cloud at this location is found by integrating the function $r(x,z)$ describing the location of the satellite (Equation 12.7) over the area of the pellet cloud, i.e., over a disc of radius R_c centered at (x_c, z_c). This integral, which is a function of x_c and z_c, is then multiplied by the function from Equation 12.1, which gives the probability that the center of the cloud is located at (x_c, z_c), then the product is integrated over the entire plane, i.e., over all possible cloud locations. This integration gives the total probability that the satellite passes through the cloud.

Multiplying this result by the probability that the satellite will be struck by at least one pellet if it passes through the cloud (Equation 12.5) gives the total probability that the satellite is struck by at least one pellet, when the cloud radius is R_c. Multiplying by Equation 12.6 gives the probability of at least 2 hits. The calculation is repeated for a range of values of R_c, and these points are plotted to find the optimum cloud size and the corresponding maximum intercept probability.