

## Section 9: Space-Basing

The ability of satellites to orbit over any part of the Earth has led military planners to consider expanding beyond the current military uses of space. Satellites could be equipped to attack targets on the Earth, to intercept ballistic missiles, to defend U.S. satellites, and to inspect and/or attack enemy satellites.

However, technical factors will determine whether satellites make sense for a particular mission. Examples include how time sensitive a mission is, and the corresponding responsiveness required of the satellite system; how expensive it is to accomplish the mission from space; and what alternate means exist for carrying out the mission.

This section considers the implications of the technical issues discussed in the previous sections for space-based ground attack weapons, space-based boost-phase missile defense, and the military space plane, which has been envisioned for a range of missions. Section 12 considers space-based ASATs and compares them with ground-based anti-satellite weapons (ASATs).

The space-based laser (SBL) is another system that has been discussed for defending against ballistic missiles, attacking satellites, and attacking air and ground targets.<sup>1</sup> Its key attraction is that laser beams travel at the speed of light, so the time to deliver an attack would be set by the time required to position the beam and for the beam to dwell on the target. In addition, the speed of the beam could allow the lasers to be placed in high-altitude orbits (assuming they had sufficiently high power and accurate control over the beam direction), thus reducing the number needed for global coverage of the Earth and all satellites in low orbits. However, the technology for a usable SBL does not currently exist and will not for the foreseeable future.<sup>2</sup> For this reason, this report does not consider it.

### SPACE-BASED KINETIC GROUND-ATTACK WEAPONS

Placing ground-attack weapons in orbit would in principle allow a country to attack any point on Earth. The satellites in the constellation could carry a variety of conventional weapons,<sup>3</sup> including high explosives and kinetic-energy

1. An analysis of space-based lasers is given in Bob Preston, Dana Johnson, Sean Edwards, Michael Miller, and Calvin Shipbaugh, *Space Weapons, Earth Wars* (Santa Monica, CA: RAND, 2002), 24-35. See also, Bruce DeBlois, Richard Garwin, R. Scott Kemp, and Jeremy Marwell, "Space Weapons: Crossing the U.S. Rubicon," *International Security* 29 (2004): 1-34.

2. In response to Congress slashing funds for the space-based laser program, the Missile Defense Agency disbanded the program, although some technology development continues as part of other programs. See Laura Colarusso "Space-Based Laser Program Office Dismantled, Tech Demo on Hold," *Inside Missile Defense* 8 (November 13, 2002): 7.

3. The Outer Space Treaty of 1967, which has been ratified by the great majority of countries, forbids the stationing of weapons of mass destruction in space (<http://www.oosa.unvienna.org/SpaceLaw/outersptxt.htm>, accessed February 2, 2005).

weapons that would use the energy from their high speed to attempt to destroy targets by smashing into them.

Proponents of these systems are interested in a fairly rapid response time, requiring the satellites to be based in low earth orbits. Exactly how many orbiting weapons would be required depends on the desired response time. The system considered below has the capability to deliver weapons to any point on Earth within 30 to 45 minutes of a decision to do so, since that is comparable to the flight time of a long-range ballistic missile, which could also deliver such an attack.

This section compares the costs of delivering ground-attack conventional weapons from space to delivering them by ballistic missile. There are important technical issues related to the transit of weapons through the atmosphere at high speed, including guiding them accurately and dealing with the intense heating, but these issues will be similar for both basing modes. While long-range ballistic missiles have in the past been restricted to nonconventional roles such as nuclear and possibly biological warheads, there is currently some interest in using them for conventional roles, which would allow them to carry out the same kinds of missions discussed for space-based weapons.<sup>4</sup>

The simple model presented below illustrates the factors that determine the number of satellites required for the desired response time, and allows this system to be compared with delivery of weapons by ballistic missiles. A more detailed calculation is needed to look at tradeoffs between numbers of satellites, deployment altitude, and mass.

### *Constellation Size*

The response time for a space-based ground attack weapon, which is the time from a decision to launch the attack until the weapon hits the target, consists of two parts: the time required for the satellite to get into position so it can de-orbit the weapon toward the target, and the time required for the weapon to de-orbit and reach the ground once the satellite is in position.

The number of satellites required depends on the desired response time, the portion of the Earth to be covered, and the lateral reach of the satellites (the distance each satellite can travel perpendicular to its ground track to strike a target). For example, consider a single satellite in a polar orbit at 500-kilometer altitude that has the propellant needed to allow it to de-orbit and attack a ground target. This satellite orbits the Earth in just over 90 minutes. After one orbit, its ground track crosses the equator 2,600 kilometers west of where it crossed on the previous orbit, due to the rotation of the Earth.

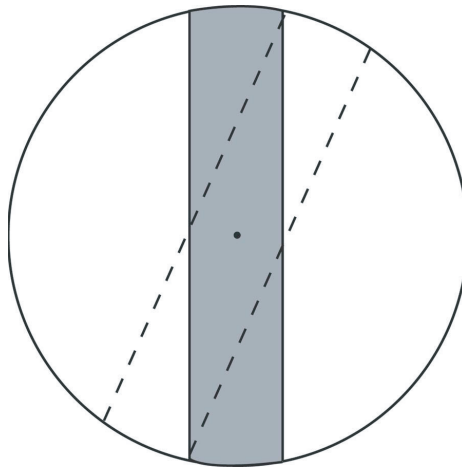
For simplicity, initially assume the satellite is able to reach out laterally as it descends toward the Earth and attack ground targets up to 1,300 kilometers to either side of its ground track.<sup>5</sup> It would then be able to attack any point

4. Important political considerations must be taken into account in when considering such a mission, but this report does not discuss them.

5. Lateral reach can be achieved by giving the object some component of  $\Delta V$  perpendicular to the plane of the orbit and by designing the object to use the strong aerodynamic forces as it re-enters to move it in a lateral direction.

within a 2,600-kilometer-wide band centered on its ground track. As a result, adjacent bands of ground coverage would just abut one another at the equator (see Figure 9.1), and the collection of bands would cover the Earth's surface in 12 hours (during each orbit, the satellite crosses the equator twice, once while going up towards the north pole, and once coming down). The bands will overlap and give greater coverage near the poles. This one satellite in a 500-km-altitude polar orbit would be able to attack any point on Earth twice a day.

**Figure 9.1.** This figure shows a view looking down at the north pole of the 2,600-km-wide bands surrounding two successive ground tracks (one white, one shaded) of a satellite in a 500 km altitude polar orbit. Note that the two bands abut at the equator, which is the edge of the circle.



If the time requirement was to have one satellite in position to attack any point on Earth within 12 hours of a decision to attack, this mission could be accomplished with one satellite in orbit.<sup>6</sup> One way to shorten the time required for an attack would be to add satellites in other orbital planes. For example, adding a satellite in a polar orbit rotated by 90° to the first would cut in half the maximum time to deliver an attack—to 6 hours.

Adding more satellites in other orbital planes would further reduce the time. Since 8 bands of the type described above cover the Earth at the equator, placing satellites with a lateral reach of 1,300 km in eight equally spaced orbital planes would ensure that a satellite was in a position to attack any target within one orbital period, about 90 minutes.

Assuming a lateral reach of 1,300 km for the satellite simplified the above analysis, but would require very large lateral speeds for the de-orbit times

6. On average, this system would be able to attack within about six hours, but could not guarantee an attack in less than twelve.

considered here.<sup>7</sup> A more realistic value for the lateral reach may be only a few hundred kilometers. The discussion below assumes a lateral reach of 650 km, which would double the number of orbital planes needed to get a satellite in position to attack in 90 minutes, resulting in 16 planes.

Once the satellite is in the proper position, it would accelerate the weapon out of its orbit toward the ground. As discussed in Section 6, a de-orbiting time of 10 to 15 minutes from an altitude of 500 km can be achieved with a  $\Delta V$  of 0.7 to 1.0 km/s. So this configuration—16 orbital planes with one satellite per plane—would allow global attacks anywhere on Earth within 100 to 110 minutes.

The attack time could be further reduced by placing several satellites in each orbital plane. For example, placing six equally spaced satellites in each of the 16 orbital planes would reduce the maximum time for a satellite to move into position to 15 minutes instead of 90. Adding the de-orbit time of 10 to 15 minutes gives a total attack time of 25 to 30 minutes.

Such a constellation—which could attack any point on the Earth within about 30 minutes—would comprise 96 satellites (16 planes  $\times$  6 satellites per plane), and would therefore have an absentee ratio of 96. If the requirement was having *two* satellites in position to attack one or two targets in the same region at any time, the constellation would need to be doubled to 192 satellites.

If the constellation instead consisted of three satellites in each plane, for a total of 48 satellites, its response time would be about 45 minutes.

Thus the responsiveness required of the system quickly drives up the size of the constellation, as does the number of satellites required to be in position at any time. As noted above, increasing the lateral reach of the satellites would reduce the number of satellites needed. Conversely, a smaller lateral reach than assumed here would increase the number of required satellites.

The constellations considered so far assumed the satellites were in polar orbits. These orbits give complete coverage at the equator, but provide overlap of coverage at mid and high latitudes; in other words, a constellation that covered the equator a minimum of twice a day would cover areas near the poles many more times a day.

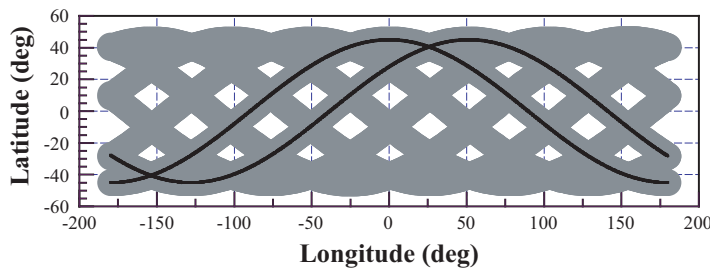
If the attacker were willing to give up coverage of the polar regions, it could reduce the number of orbital planes required by using orbits with inclinations less than 90°. Recall that the ground track of a satellite in an orbit with inclination  $\theta$  does not reach beyond a latitude of  $\theta$  (see Figure 5.1). The inclination of the orbits would therefore need to be approximately as large as

7. Once the satellite de-orbited to a low enough altitude it could use atmospheric forces to turn and move in a lateral direction. However, in the case considered here, the de-orbit time from 80 km altitude to the ground would be roughly 200 seconds. Reaching laterally 1300 km during that time would require an average lateral speed of  $1,300 \text{ km}/200 \text{ s} = 6.5 \text{ km/s}$ , which is higher than the average speed of the re-entering satellite at altitudes below 80 km. Moreover, attempting to turn quickly may lead to unacceptably high forces that could damage the satellite. The satellite could also use propellant to give it a lateral speed at high altitude, in addition to the vertical  $\Delta V$  used to de-orbit. A lateral  $\Delta V$  of 1 km/s would result in a lateral reach of 600 to 900 km during a de-orbit time of 600 to 900 seconds, but the propellant required would add 40% to the mass of the satellite.

the latitude of important potential targets. In addition, if the attacker was willing to have some gaps between the bands near the equator, giving a somewhat longer response time there, coverage could be optimized for targets at midlatitudes.

For a satellite with a lateral reach of 650 kilometers, seven orbital planes with inclination of  $45^\circ$  will cover that part of the Earth with latitude between about  $50^\circ$  north and  $50^\circ$  south,<sup>8</sup> with the coverage optimized for roughly  $30^\circ$  to  $50^\circ$  latitude (both above and below the equator; see Figure 9.2). These latitudes include the Middle East; North Korea; most of Europe, the United States, and China; and part of Africa and South America. They exclude essentially all of Russia.

**Figure 9.2.** The figure shows the ground coverage (gray areas) of satellites in seven equally spaced orbital planes with inclination of  $45^\circ$ , assuming the satellites can reach laterally 650 km as they de-orbit. The two dark lines are the ground tracks of two of the satellites in neighboring planes. This constellation can provide complete ground coverage for areas between about  $30^\circ$  and  $50^\circ$  latitude (both north and south), less coverage below  $30^\circ$ , and no coverage above about  $55^\circ$ . Due to the rotation of the Earth, satellites would pass over the holes in the coverage shown above, but it would on average take longer to attack targets in these areas.



A constellation of 42 satellites, with 6 in each of the 7 orbital planes, will provide single-satellite coverage of the region between about  $30^\circ$  and  $50^\circ$  with an attack time of 25 to 30 minutes. This constellation would have no coverage above about  $55^\circ$  and would require somewhat longer times on average to attack targets below  $30^\circ$ . To be able to attack more than one (say,  $n$ ) targets in the same region at the same time with this responsiveness, the constellation would need  $42 \times n$  satellites.

If the response time were relaxed to 45 minutes, a similar 7 orbital plane constellation could use just three satellites per orbit, for a total of 21 satellites, to provide single-satellite coverage of the same regions.

For all the constellations discussed above, the  $\Delta V$  available for de-orbiting was 0.7 to 1.0 km/s. If the satellite is designed to provide a much higher  $\Delta V$  to

8. As noted in Section 4, the ground track of the satellite will only reach to  $45^\circ$ , but the lateral reach of the satellite allows it to reach somewhat higher latitudes.

the weapon, thereby increasing its de-orbiting speed, a smaller constellation could provide the same response time by placing the satellites in orbits at higher altitudes than considered above.<sup>9</sup> A larger  $\Delta V$  would also increase the speed at which the kinetic weapon hit the Earth, resulting in greater destructive power. However, as Section 6 discusses, the atmospheric drag and heating increase rapidly with the speed of a re-entering object, placing practical limits on the speeds that could be used. Moreover, as discussed in Section 7, increasing the  $\Delta V$  available to the satellite, including for extending the weapon's lateral reach, would rapidly increase the satellite's mass.

### *Comparison to Delivery by Ballistic Missile*

The launch requirements of these space-based ground attack systems can now be compared with those of a ballistic missile system that provides similar capability.

A three-stage missile capable of putting a given mass into low earth orbit is capable of delivering the same mass to a range of 20,000 kilometers—half way around the Earth.<sup>10</sup> The flight time would be roughly 45 minutes. This one ballistic missile could therefore provide global coverage with the same response time as the constellation described above of 48 satellites with three satellites in each of 16 orbital planes.

However, for the space-based system, part of the mass placed into orbit will need to be devoted to propellant to de-orbit the weapon. As noted above, our calculations show that accelerating a satellite out of a 500-kilometer altitude orbit so that it will reach the ground in 10 to 15 minutes would require a  $\Delta V$  of 0.7 to 1 km/s. For a satellite to achieve this  $\Delta V$ , it must carry an additional 25 to 40% of its mass in propellant.<sup>11</sup> Thus, the weapon itself would constitute only 60 to 75% of the mass in orbit. Designing a system with higher  $\Delta V$  to give the weapon a much higher speed as it de-orbited (to reduce the de-orbit time or increase the lateral reach) would increase the propellant mass. For example, for a satellite carrying propellant for a  $\Delta V$  of 5 km/s, the weapon would constitute less than 20% of the mass in orbit, with 80% being the propellant for de-orbiting.

This information can be used to directly compare the launch requirements of a space-based and ground-based system with a 45-minute response time. One ground-based ballistic missile capable of placing a mass  $m$  in orbit could deliver a weapon of mass  $m$  to a target anywhere on Earth within 45 minutes. For the 48-satellite constellation, the capability to deliver mass  $m$  to any point on Earth within 45 minutes would require a total mass of  $60m$  to  $67m$  in orbit (48 satellites, each with a weapon of mass  $m$  and propellant mass  $0.25m$  to  $0.4m$  for de-orbiting). Placing this mass in orbit would require 60 to 67

9. Wang Ting, Beihang University (Beijing University of Aeronautics and Astronautics), personal communication, April 2004.

10. Such missiles could also attack targets at shorter ranges by deliberately wasting fuel.

11. This calculation assumes conventional technology thrusters, with an exhaust velocity of 3 km/s.

launches by missiles of the type used by the ground-based system. The 21-satellite constellation considered above that does not cover areas above  $50^\circ$  latitude would require a total mass of  $26m$  to  $29m$  in orbit to be able to deliver a mass  $m$  to a target in this region within 45 minutes.

This is actually an underestimate of the mass required in orbit since satellites in low earth orbits would require additional propellant for stationkeeping. (Placing the satellites in higher orbits, where there is less atmospheric drag, would reduce the need for stationkeeping fuel, but would require more propellant for de-orbiting to meet the same time goal.) The satellites would also carry components that the missile-launched weapon would not—such as tanks to hold the propellant, solar panels, and ground communications systems—and these will also add mass.

This analysis, based only on launch requirements, shows that acquiring the capability to attack a ground target within 45 minutes would be many tens of times more costly if done from space than from the ground.<sup>12</sup>

Next consider a response time of roughly 30 minutes. Global coverage of one target could be obtained by deploying at widely spaced locations two missiles with a range of 10,000 km and a corresponding flight time of 30 minutes. (However, three or four missiles might be needed, depending on geographic constraints.) To compare the launch capacity required for a space-based system having a 30-minute response time, we again need to consider the mass of de-orbiting propellant that must be launched as part of the space-based weapons. But we must also take into account the fact that a missile can deliver only about two-thirds as much mass to low earth orbit as it could deliver to a range of 10,000 km.<sup>13</sup> This means that it requires about 1.5 times as much space lift to place a mass  $m$  into orbit as it does to deliver it to 10,000 km.

Taking these considerations into account, the 96-satellite system discussed above (global coverage in 30 minutes using 16 planes with 6 satellites in each) would require a total mass of roughly  $125m$  (96 satellites plus their de-orbiting propellant) in orbit to be able to deliver a mass  $m$  to a target anywhere on Earth within about 30 minutes. Using a missile that could deliver a mass  $m$  to a range of 10,000 km, roughly 190 launches ( $125 \times 1.5$ ) would be required to place this mass in orbit. The smaller 42-satellite constellation that would cover the Earth between latitudes of  $50^\circ$  north and  $50^\circ$  south would require a total mass of roughly  $55m$  in orbit, and about 85 missile launches ( $55 \times 1.5$ ) to place this mass in orbit. Since two ballistic missiles would be needed to give equal coverage in either case, the smaller 42-satellite constellation would require

12. In addition, the space-based system would entail significant additional costs, such as building the satellites that deliver the weapons back to Earth.

13. A 10,000-km range missile will typically burn out at an altitude of several hundred kilometers with a speed of roughly 7 km/s. This speed is about 10% too low to place a satellite in a circular orbit at those altitudes. Reaching the necessary speed would require reducing the payload by roughly a third. (Steve Fetter, University of Maryland, personal communication, July 2004. For several different missiles, he calculated the mass that a missile could launch into low earth orbit [200 and 500 km altitude] and compared it with the mass he calculated the same missile could send to 10,000 km range.)

roughly  $85/2 = 42$  times as much launch capacity as the ground-based system and the 96-satellite system would require roughly  $190/2 = 95$  times as much launch capability.<sup>14</sup> As noted above, these are underestimates of the relative launch requirements of a space-based system and a ground-based system of two ballistic missiles; moreover, developing a space-based system would entail additional costs beyond those for launch.

This discussion is most relevant to a country making the choice between building long-range ballistic missiles or placing ground-attack weapons in space. However, the five declared nuclear weapon states already have long-range ballistic missiles based on submarines and on the ground. For those countries, deploying ballistic missiles with kinetic ground attack weapons would not require large additional investments.

#### SPACE-BASED BOOST-PHASE MISSILE DEFENSE

*Boost phase missile defense* systems would be designed to destroy a missile during its boost phase—when the rocket is still burning. For long-range missiles, the boost phase lasts for only 3 to 4 minutes, requiring a defense with a very short response time.<sup>15</sup>

The United States is considering or developing several types of Earth-based boost phase systems, including ground- or ship-based interceptors with kill vehicles that would use their sensors to home on the bright flame of the boosting missile and attempt to destroy the missile by direct impact. These interceptors would need to be based close to the missile launch site to reach the missile during its boost phase. Another option under development is air-based lasers, which must be within a few hundred kilometers of their target to destroy it.

A space-based boost phase defense would consist of a constellation of space-based interceptors (SBI) in low earth orbit. These satellites would remain in orbit until a missile launch was detected; an SBI near the missile launch site would then use its onboard propulsion to accelerate out of orbit and maneuver toward the missile. The intercept must occur above 80 to 100 km altitude, since the interceptors are not designed to operate lower in the atmosphere where they would be subject to high heating. As a result, the defense would be unable to defend against shorter range missiles, since these would burn out too low in the atmosphere to be engaged by the space-based interceptors.

Proponents of deploying a space-based system argue that it could defend against missiles launched from anywhere in the world. Indeed, the geographic and political restrictions on where surface- or air-based defenses could be located means that space-based interceptors may be uniquely able to reach missiles launched from some locations during their boost phase. Thus, unlike the case for ground-attack weapons, it is not possible to make a direct comparison between space-based and Earth-based systems that can carry out the

14. Of course, a land-based missile that was out of range of the target would not be launched in an attack, whereas all of the satellites would have to be launched into orbit to put in place the space-based constellation with the desired response time.

15. Shorter range missiles would have shorter burn times.

same mission. Instead, we assess the ability of the space-based system to perform its mission and the launch capacity required to place the system in space. We end by discussing the ASAT capability of SBIs.

### *Vulnerabilities of SBI*

A key technical difficulty of a space-based missile defense is the vulnerability of the system to attack. The SBI could be tracked from the ground and their locations would be well known. Because the SBI would be in low-altitude orbits (300 to 500 km), they could be attacked by ASATs on short-range missiles with ranges of 600 to 1,000 km. Such missiles would burn out too low for the SBI to intercept them in their boost phase. If the SBIs were programmed to ignore short-range missiles, the SBI would be vulnerable to attack while in their orbits. But because an SBI must be launched quickly after detection of a missile launch, the SBI might have to launch before it could determine the range of the missile. Causing an SBI to be launched would remove it from orbit and deplete the constellation as effectively as destroying it with an ASAT.

Since short-range missiles are much less expensive than long-range missiles, a country could launch enough ASATs on short-range missiles to create a hole in the constellation. The attacking country could launch a long-range missile through this hole when it reappeared after an orbital period of roughly 90 minutes or could even plan to launch from a location the hole passed over shortly afterward.

Many systems containing satellites can be structured so that the vulnerability of individual satellites does not cause the overall system to fail to complete its mission. However, space-based missile defense is an exception. Because only the SBI closest to the region where a missile is launched are able to engage the missile in the time available, destroying interceptors and creating a hole in the system prevents the defense from engaging missiles launched through that hole.

While no countries currently deploy ASATs, countries that have developed the technical sophistication and the aerospace expertise to launch long-range missiles would also be expected to have the technical capability to build ASATs that could attack SBIs. Developing or acquiring the capability to carry out such attacks would become a high priority for any country that had developed long-range missiles.

Even if the SBIs were not attacked, the defense could be easily overwhelmed, although this may not be the most cost effective way of foiling a space-based system. As discussed below, SBIs have a large absentee ratio, i.e., a large number of satellites are needed in a constellation to ensure that even one SBI is in position to engage a missile launched from a particular location. The total number of SBI needed in the constellation in order to engage  $n$  simultaneous launches from the same location is  $n$  times the absentee ratio. To avoid large numbers of SBIs in orbit, most proposals for space-based missile defense consider systems that would be able to engage only a small number of missiles ( $n$  is typically one or two) launched nearly simultaneously from the same location. If the attacker launched more than that number of missiles, the defense would not be able to engage them all.

While a ground-based defense system can also be overwhelmed by simultaneous launches, the large absentee ratio of the space-based system means that it is much more expensive to increase the number of simultaneous launches it can handle compared with a ground-based system.

### *Constellation Size and Launch Requirements*

A space-based missile defense would require large numbers of interceptors and deploying even a thin defense would be expensive. Recall that a ground-attack system with a 30-minute response time and global coverage would require nearly 100 satellites. A missile defense with a response time of only a few minutes would require many hundreds of satellites, as discussed below.

Similar to the ground attack system analyzed above, the structure of the missile defense constellation would depend on what parts of the Earth the system was intended to cover. Truly global coverage would require some satellites in polar orbits. A system using satellites in orbits with inclinations less than about 45° would not be able to defend against launches from locations with latitudes above about 45°. Such a system would cover the Middle East and almost all of the United States and China, but would not cover Russia or northern Europe.

The Brilliant Pebbles system proposed as part of the Global Protection Against Limited Strikes (GPALS) system in the early 1990s by the first Bush administration was intended to include 1,000 SBIs for global coverage of one or two missiles launched simultaneously from a single site.

A technical analysis of boost-phase missile defense published by the American Physical Society (APS) in July 2003 found that a similar number of interceptors were required.<sup>16</sup> The APS panel considered a constellation of SBIs in orbits at an altitude of 300 km that would place a minimum of one and occasionally two interceptors within range of any launch site between 30° and 45° latitude (which includes North Korea and the Middle East), but would provide no coverage above 45° and somewhat limited coverage near the equator. They determined that this system would require roughly 1,600 SBIs to engage solid fueled missiles (with a boost phase of 170 seconds), and roughly 700 SBIs to engage liquid-fueled missiles (with a boost phase of 240 seconds).

Increasing the regions of the Earth covered by the system would significantly increase the number of SBIs needed; global coverage would roughly double the number required.<sup>17</sup> Moreover, a system that could engage a mini-

16. American Physical Society (APS), *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense*, July 2003, [http://www.aps.org/public\\_affairs/popa/reports/nmd03.html](http://www.aps.org/public_affairs/popa/reports/nmd03.html), accessed January 5, 2005.

17. Conversely, by restricting the coverage of the system to considerably smaller geographical areas, the system can be designed to have many fewer SBIs. One recent study looks at concentrating the coverage in a band of latitude that is less than 400 km wide, which is only designed to engage missiles from a restricted set of launch sites (G. Canavan, "Estimates of Performance and Cost for Boost Phase Intercept," September 24, 2004, [www.marshall.org/pdf/materials/262.pdf](http://www.marshall.org/pdf/materials/262.pdf), accessed December 20, 2004; I. Oelrich and S. Fetter, "Not So Fast," February 1,

num of two missiles launched simultaneously from the same area or that could launch two interceptors at one attacking missile would require doubling the number of satellites.

The APS study also showed that a substantial  $\Delta V$  would be required to give the SBI sufficient maneuvering capability to be effective in the face of intrinsic uncertainties in the engagement. The required  $\Delta V$  has two main contributions: that needed to accelerate the interceptor out of its orbit and toward the boosting missile and that needed for maneuvering to achieve an intercept. The study determined that the SBI would require a thruster that could provide a  $\Delta V$  of 4 km/s with high acceleration to kick it out of orbit with sufficient speed to reach the boosting missile in time. Reducing this speed would require the SBIs to be spaced more closely in orbit, increasing the size of the constellation. The study also determined that an additional  $\Delta V$  of 2.5 km/s would be required to allow the kill vehicle to maneuver and home on the boosting missile, which is an accelerating target that could be deceptively maneuvering.<sup>18</sup>

As discussed in Section 7, large values of  $\Delta V$  require large propellant masses. Assuming technology available in the next decade, the APS panel determined that the engines and propellant would increase the mass from about 60 kg for the unfueled kill vehicle to more than 800 kilograms per SBI.<sup>19</sup>

Since the SBI is intended to remain in orbit for many years at a low altitude, it must also carry propellant for stationkeeping. In addition, typical designs assume that while in orbit the SBI would be housed in a *garage* or *life jacket* to protect it from radiation and debris and that would have communications equipment and solar panels for power—all of which would be left behind when the interceptor was accelerated toward a missile. According to the APS study, adding the garage mass would bring the total mass in orbit for each SBI to more than a ton.

Using these assumptions, a constellation of 1,600 SBI needed to defend against solid-fuel missiles would require a total mass in orbit of nearly 2,000 tons.<sup>20</sup> Assuming a launch cost of \$20,000 per kilogram (see Section 8), the launch cost would be roughly \$40 billion. A constellation of 700 SBI needed to defend against liquid-fuel missiles would require a total mass in orbit of 850 tons, leading to an estimated launch cost of \$17 billion. Recall that these systems could engage only one or two missiles launched simultaneously from a single site. Placing 1,000 tons in orbit would require the equivalent of more than 100 Delta or Atlas II/III launches or more than 50 Atlas V launches. In

2005, [www.fas.org/resource/01312005123203.pdf](http://www.fas.org/resource/01312005123203.pdf), accessed February 15, 2005). While North Korea is discussed as a geographically small country for which such a system might be appropriate, the size and location of North Korea makes sea-based boost phase systems appear feasible, so that the space-based system should be compared with surface-based alternatives for this case.

18. APS, 110.

19. APS, 111. The mass of the (unfueled) kill vehicle for the model used in the APS study is 60 kg, and it carries nearly 80 kg of propellant for maneuvering as it attempts to strike the missile. The additional mass is due to the thruster and propellant used to accelerate it out of orbit.

20. For the case of defending against solid-fuel missiles, the APS study finds a total mass of 2,000 tons (APS, 114, 126).

recent years, the launch rate has been roughly seven Delta launches and five Atlas launches (a mix of II, III, and V),<sup>21</sup> so launching such a defense would require a significant increase in launch capability.

Moreover, assuming the satellites have a 10-year lifetime, roughly 100 satellites would need to be launched every year to maintain a 1,000-satellite constellation. This would entail a cost of \$2 billion per year, given a launch cost of \$20,000 per kilogram.

These total mass figures could be decreased by reducing either the number of interceptors or the mass of the SBI. The issue of how light the SBI can be made is controversial and depends, in part, on the timeline considered. The APS study based its model of the SBI on the technologies it judged to be realistic in the next decade. It considered further possible reductions in the mass of the SBI that might reduce it by about 60%.<sup>22</sup> Other estimates have raised the possibility of even lighter SBIs—considerably lighter than the lightest APS model—although the timeline and other details of these estimates have not been made public.<sup>23</sup>

Reducing the SBI mass may make it possible to increase its  $\Delta V$  without a prohibitive increase in propellant mass, and this increase in speed may increase the optimal orbital altitude and decrease the number of interceptors required in the constellation. For example, a July 2004 Congressional Budget Office analysis considered a fast, lightweight SBI having a  $\Delta V$  of 6 km/s rather than the 4 km/s assumed by APS, a fueled kill vehicle mass of 30 kg rather than the 136 kg assumed by APS, and a garage mass of 90 kg rather than the 440 kg assumed by APS. CBO found that if such an SBI could be built, it would reduce the total number of interceptors in orbit compared with the APS values by roughly a factor of three (for defending against solid-fuel missiles) to 4.5 (for defending against liquid-fuel missiles). In addition, it would reduce the total mass of interceptors in orbit compared with the APS values by roughly a factor of seven (for defending against solid-fuel missiles) to ten (for defending against liquid-fuel missiles).<sup>24</sup>

21. See, for example, “History of the Delta Launch Vehicle,” <http://kevinforsyth.net/delta/>, accessed January 5, 2005, and “Atlas Launch Information,” [http://home.cfl.rr.com/atlas/info\\_atlas.html](http://home.cfl.rr.com/atlas/info_atlas.html), accessed January 5, 2005.

22. APS, 125-126.

23. For example, in its July 2004 study of boost-phase defenses, the Congressional Budget Office (CBO) considered the effects of using a model for the kill vehicle that was briefed to the CBO by researchers at the Lawrence Livermore National Laboratory in November 2003 (CBO, *Alternatives for Boost-Phase Missile Defense* [July 2004], 24). The model used for the kill vehicle has an unfueled mass of 11 kg (Canavan, 6) and a fueled mass of 30 kg; the SBI can accelerate out of orbit using a  $\Delta V$  of 6 km/s and has a mass of 442 kg, without the garage (CBO, *xviii*). The CBO report states that producing this model “would require a technological leap in miniaturization” (CBO, 43).

24. CBO, 30, 35. The SBI model called Option 4 in the CBO report has a higher average acceleration than the APS model, so the number of interceptors required is less than that calculated by APS.

### *ASAT Capability of SBI*

While the large constellation of SBIs needed for missile defense could not be deployed for many years, small numbers of prototypes could be deployed earlier. These systems are important to consider since they could have the capability to attack satellites with little warning, including satellites in geosynchronous or semisynchronous orbits.

Assuming it was designed with sensors that could detect a satellite in orbit, an SBI designed to intercept a boosting missile would have more than enough maneuverability to intercept a satellite in orbit. Moreover, the large  $\Delta V$  the SBI would possess for accelerating out of orbit would also allow it to change its orbit to attack satellites in orbits significantly different from its own, including geosynchronous orbit.

The orbital speed of the SBI would be roughly 8 km/s; adding the 4 km/s it would need to reach a boosting missile, it could reach a total speed of up to 12 km/s.

Our calculations show that such a speed would allow it to travel from low earth orbit to geosynchronous orbit in an hour and a half and still have a speed of nearly 7 km/s at that altitude. Ground observations could determine the location of the satellite to be attacked with sufficient accuracy to launch the interceptor and allow the onboard sensors to detect the satellite when it was close enough.

Whether a kill vehicle designed solely for missile defense could be used to attack satellites in this way depends on details of its design, such as the type of sensors it contains and the length of time it is designed to operate (a matter of minutes to reach a boosting missile versus an hour to reach geosynchronous orbit). It is clear, however, that these are design decisions and that these capabilities could be built into the SBI to give them the capability to also serve as high-altitude ASATs. The sensors that are designed to enable the SBI to detect the missile plume during the boost phase may not be suitable for detecting a satellite, but lightweight sensors exist that could be added for the ASAT mission. Since geosynchronous satellites are in the sunlight during all or nearly all of their orbit, they would reflect sunlight and would have a relatively high surface temperature, both of which could be used for homing.<sup>25</sup>

### THE MILITARY SPACE PLANE

An analysis of maneuverability is especially relevant for the proposed Military Space Plane (MSP), which usually refers to the combination of a maneuvering vehicle that is placed in orbit and the launcher that would place it in orbit. The technical issues raised by these two components differ substantially.

25. For a discussion of the temperature of objects in space, see Appendix A of Andrew Sessler et al., *Countermeasures*, Union of Concerned Scientists and MIT Security Studies Program, April 2000, [http://www.ucsusa.org/global\\_security/missile\\_defense/page.cfm?pageID=581](http://www.ucsusa.org/global_security/missile_defense/page.cfm?pageID=581), accessed January 5, 2005.

The various missions that have been discussed for the MSP are to launch weapons for prompt, global, precision strike;<sup>26</sup> to carry sensors that could provide reconnaissance in a manner that an adversary could not predict; to launch satellites to either augment or reconstitute space assets; to take part in various types of anti-satellite missions; and to inspect or service satellites that are in orbit. It would not be designed to carry humans. For these missions, the design of the launch vehicle is not particularly important, and existing space-launch vehicles could be used.

Another mission commonly given for the MSP is affordable, rapid, on-demand space-launch capability that could place an object in low earth orbit within 5 to 12 hours of a decision to launch. However, new launcher technology would be required to achieve this goal. While the development of reusable and single-stage-to-orbit launch technologies are often discussed as part of the space plane, they are really part of a broader effort to develop new launch technologies.

This section focuses on the orbiting component of the MSP. This object, often called the Space Maneuver Vehicle (SMV), can be thought of as a small, unmanned Space Shuttle (see Figure 9.3). It would have a cargo bay that could carry a range of different payloads and would carry propellant to allow it to maneuver while in orbit. To reduce costs, it is intended to be reusable, so it would carry propellant to allow it to return to Earth from orbit and land like an airplane. The SMV could be launched into orbit on an existing launch vehicle, so it can be considered separately from the new launch technologies mentioned above.

The SMV would be much smaller than the Space Shuttle, with a mass, including propellant, of 5 to 8 tons (compared with 94 tons for the Shuttle) and a payload capability of up to 1 or 2 tons (compared with roughly 20 tons for the Shuttle). As noted, it would not carry humans. It is expected to draw on technology being developed for a test vehicle planned for flight testing in FY2006 (the X-37 Orbital Vehicle),<sup>27</sup> but the development time of a usable SMV is unknown.

The term “space plane” suggests that the SMV could be operated like an airplane and could move through space similar to the way an airplane can maneuver in the air. However, this analogy is not appropriate: the physics of orbital dynamics places much greater restrictions on what an orbiting vehicle can do, as Sections 4–6 describe.

26. For example, one proposal envisions “100-minute or less on-alert delivery time” from bases in the continental United States “to points around the globe” (ONE Team, “The Military Space Plane: Providing Transformational And Responsive Global Precision Striking Power,” January 2002, <http://www.spaceref.com/news/viewstr.html?pid=4523>, accessed December 20, 2004).

27. X-37 Fact Sheet, <http://www1.msfc.nasa.gov/NEWSROOM/background/facts/x37.html>, accessed December 20, 2004; B. Iannotta and B. Berger, “NASA Brings Back Plans to Fly X-37 Demonstrator in Orbit for 270 Days,” *Space News*, November 17, 2003, [http://www.space.com/spaceneews/archive03/x37arch\\_120103.html](http://www.space.com/spaceneews/archive03/x37arch_120103.html), accessed February 4, 2005.

**Figure 9.3.** This photo shows the X-40a, a 6.7 m long model of an SMV built for testing.



(Source: [http://boeingmedia.com/images/one.cfm?image\\_id=866](http://boeingmedia.com/images/one.cfm?image_id=866), accessed February 7, 2005).  
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The vision is that the SMV would exploit its maneuverability to carry out the missions discussed above. To deploy multiple satellites into different orbits, the SMV would place itself in the first orbit, release the first satellite, maneuver into the next orbit, release the next satellite, and so on. Using a maneuverable vehicle, or *bus*, to release several satellites can reduce the number of space launches required to place these satellites in orbit. In fact, a non-reusable bus is used routinely to place multiple satellites in different orbits. Maneuvering a sensor in space is also a mission that requires changing from one orbit to another. Similarly, rendezvousing with different satellites to, for example, inspect, service, or possibly interfere with them, requires placing the SMV in the same orbit as the first satellite, then changing orbits to that of the second satellite, and so on.

The propellant required for the SMV to maneuver would place significant limits on the amount of maneuvering it could carry out. The SMV is likely to have a total  $\Delta V$  of 3 to 4 km/s in normal operation.<sup>28</sup> As Section 6 discusses, maneuvers within an orbital plane require a  $\Delta V$  of a few tenths of a kilometer per second (assuming the SMV remains in low earth orbit), but changing orbital planes at low altitudes can require a much greater  $\Delta V$ .

To illustrate this, consider an SMV designed to have a total  $\Delta V$  of 3 km/s. Some of this total must be used to de-orbit the SMV to bring it back to Earth so it can be reused, leaving roughly 2.5 km/s available for maneuvering. A  $\Delta V$  of 2.5 km/s would allow the SMV only one plane change of less than  $20^\circ$  at an altitude of 500 kilometers. Even if it were carrying enough propellant to give

28. Aaron R. Shirk, "The Feasibility of the Military Space Plane for Rapid Response Surveillance and Reconnaissance Satellite Constellation Deployment," April 17, 1998, <http://www.stormingmedia.us/00/0026/A002653.html>, accessed December 15, 2004, discusses several models of an SMV. See also Orbital Sciences, "Re-Energizing America's Space Program," November 21, 2002, <http://www.spacecoretech.org/coretech2002/Papers/RLVs/pdfs/Orbital%20Presentation.pdf>, accessed December 20, 2004, and Air Force Research Laboratory, "Space Maneuver Vehicle," September 2002, <http://www.vs.afrl.af.mil/Factsheets/smv.html>, accessed December 20, 2004.

a total  $\Delta V$  of 6 km/s, the SMV would only be able to change orbital planes separated by roughly  $40^\circ$ .

As a result, the SMV could deploy several satellites into different orbits within one plane, but would have limited ability to deploy satellites into different planes or to rendezvous with other satellites in different orbital planes. The Appendix to Section 9 contains a detailed discussion of these two missions.

Increasing the maneuverability of the SMV by increasing the  $\Delta V$ , as Sections 7 and 8 showed, would quickly drive up the SMV mass and the associated launch costs.<sup>29</sup> If the SMV was given a significantly larger maneuvering capability, launching the satellites into orbit individually using multiple separate launches would require less launch capacity.

For example, using an SMV to place three 300-kg satellites into orbits in different orbital planes would, as discussed in the Appendix to Section 9, require launching a total mass of several tons, even if the SMV had only a relatively modest maneuvering capability. In contrast, launching each satellite individually into its own orbit would require putting a total mass of less than a ton into orbit. This approach could be much less expensive since the mass of each satellite by itself is small enough that a small launcher or an air-launched vehicle might be used.

Similarly, the limits on maneuvering have implications for other possible missions for the SMV. For example, an SMV could vary its orbit within its orbital plane to change the revisit time of a sensor it was carrying using only relatively small amounts of  $\Delta V$  (see Section 6). But it would have limited ability to change the orbital plane of the sensor.

In the same way, the SMV would be able to rendezvous with several satellites in the same orbital plane, but it would have limited capability to rendezvous with satellites in orbital planes with different inclinations. Because of the large mass of an SMV relative to a small satellite that might be specifically designed to inspect other satellites, the SMV would require a much greater propellant mass to carry out the same maneuvers. It would therefore not be well suited to this mission.

This analysis illustrates the significant constraint that the physics of maneuvering places on space systems. These constraints must be taken into account when considering the utility of the space plane in carrying out a particular mission.

It is also important to note that the maneuverability foreseen for the SMV does not represent a new capability: the upper stage of current space launch vehicles provides comparable maneuverability. For example, the Fregat Upper Stage used on the Russian Soyuz launch vehicle has an engine that can be restarted multiple times, and would have a mass of 7.4 tons and a  $\Delta V$  of more than 4 km/s for a one-ton payload.<sup>30</sup> The main potential advantage of the SMV would appear to be its reusability.

29. Shirk suggests that the  $\Delta V$  available for maneuvering might be increased to 6 km/s by carrying an additional propellant tank. However, the rocket equation shows that the additional propellant required to do so would more than double the mass of the SMV. This additional propellant mass is much greater than the payload of the SMV. Increasing the  $\Delta V$  of the SMV to 6 km/s therefore seems unlikely.

30. Starsem Corp., *Soyuz User's Manual*, April 2001, 26-27, [http://www.starsem.com/services/images/soyuz\\_users\\_manual\\_190401.pdf](http://www.starsem.com/services/images/soyuz_users_manual_190401.pdf), accessed December 20, 2004.

## Section 9 Appendix: Comparison of the Military Space Plane versus Multiple Launches

This appendix considers two potential missions that have been discussed for the military space plane: releasing multiple satellites in orbit and rendezvousing with multiple satellites to inspect, service, or attack them.

### DEPLOYING MULTIPLE SATELLITES

To reduce the number of space launches required to place multiple satellites in orbit, a maneuvering orbital vehicle or bus can be used to place several satellites in different orbits.<sup>31</sup> As noted above, a bus is used routinely to place satellites in different orbits in the same plane, but quickly becomes impractical if the satellites are in different planes. The propellant requirement is an important consideration for deploying a constellation of multiple satellites in multiple orbital planes, which is required for space-based missile defense or ground-attack weapons, or a network of communication satellites in low earth orbit.

As an example, consider a Space Maneuver Vehicle (SMV) on a mission to release three identical satellites of mass  $m_s$  into three different orbits. Assume the SMV itself has a mass  $M_{SMV}$  of 3 tons (without payload or propellant). It must carry a propellant mass  $m_p^{deorbit}$  of nearly a third of a ton to allow it to de-orbit and return to Earth after releasing the satellites (a  $\Delta V$  of 0.3 km/s for de-orbiting would require 315 kg of propellant).<sup>32</sup>

Assume the SMV is launched into the proper orbit for the first satellite and releases it. It then maneuvers into the orbit of the second satellite, which requires a velocity change  $\Delta V_1$  and a corresponding propellant mass  $m_p^{(1)}$ . In doing so, the total mass that must be moved by the thrusters is the mass of the SMV and its de-orbiting propellant, the mass of the remaining two satellites, and the propellant mass  $m_p^{(2)}$  needed for the second maneuver to place the third satellite into orbit. The propellant mass  $m_p^{(1)}$  needed for this first maneuver is found by using Equation 7.4:

$$m_p^{(1)} = (e^{\Delta V_1/V_e} - 1)(M_{SMV} + m_p^{deorbit} + 2m_s + m_p^{(2)}) \quad (9.1)$$

where  $V_e$  is the exhaust velocity of the engine. Similarly,

$$m_p^{(2)} = (e^{\Delta V_2/V_e} - 1)(M_{SMV} + m_p^{deorbit} + m_s) \quad (9.2)$$

31. Similarly, a maneuvering bus is used to launch multiple nuclear warheads against different targets using a single missile. The bus carries propellant and maneuvers to place each of the Multiple Independently Targeted Re-entry Vehicles (MIRVs) on a different trajectory, each of which is part of an orbit that intersects the Earth. The maneuverability of the bus determines over how large an area the warheads from a single missile can be spread. U.S. MIRV buses can provide a total  $\Delta V$  of up to about 1 km/s (the START I Treaty limits the total  $\Delta V$  of a bus to 1 km/s or less).

32. These calculations assume conventional thruster technology with a  $V_e$  of 3 km/s.

Using these equations, we can calculate the total launch mass required for specified values of  $\Delta V_1$ ,  $\Delta V_2$ , and  $m_s$ .

As an example, consider a case in which the satellites have a mass  $m_s$  of 300 kg and for which  $\Delta V_1 = \Delta V_2 \equiv \Delta V$ . The results are given in Table 9.1.

**Table 9.1.** This table shows the total launch mass required to deploy three satellites (each of mass 300 kg) in different orbits, with  $\Delta V$  needed to maneuver between the release of each of the satellites, as described in the text.

$\Delta V$ (km/s)	Total launch mass (metric tons)
0.5	5.7
1.0	7.8
1.5	11
2.0	15
2.5	20

Keep in mind that the total mass of the three satellites in this case is just under one ton. The presence of just the maneuvering vehicle and the propellant for de-orbiting increase the mass that must be launched into orbit to over 4 tons; the additional propellant for maneuvering can further increase the mass by an additional 1.5 to 16 tons. A mass of 8 tons corresponds roughly to the capacity of a Delta III launcher (see Table 8.1); 20 tons is greater than the launch capacity of an Ariane 5 and is the maximum capacity of an Atlas V launcher. Clearly, building in the capability to place multiple satellites into different orbits adds significantly to the launch requirements: if significant maneuverability is required, it will be cheaper to launch the satellites on separate launchers.

To put the numbers in Table 9.1 in perspective, recall from Section 6 and Table 6.1 that in-plane maneuvers require relatively small values of  $\Delta V$ . For example, a  $\Delta V$  of 0.3 km/s could allow the SMV to move from a 400 km to 1,000 km altitude orbit in the same orbital plane, so that it could release the satellites in orbits with different altitudes. Or, by changing altitude and then returning to the original orbit, the SMV could release the satellites at different places on the same orbit (see Section 6). By using a  $\Delta V$  of 0.1 to 0.2 km/s, the SMV could maneuver in about 24 hours to release a second satellite halfway around the same orbit from the previous satellite.

However, maneuvers that change the orbital plane require considerably more propellant: a  $\Delta V$  of 1.0 km/s corresponds to changing the inclination of an orbit at an altitude of 500 km by only  $7.5^\circ$ , and a  $\Delta V$  of 2 km/s to  $15^\circ$ , which are relatively small out-of-plane changes.

A similar analysis would apply if the SMV were intended to carry propellant to refuel several satellites, assuming that a significant amount of propellant was to be delivered to each satellite. The numbers listed in Table 9.1 would also apply to the case in which the MSV was to deliver 300 kg of propellant to each of three satellites.

Inspector satellites are satellites that approach other satellites and inspect them, by taking images or other data. They may be useful for maintenance of the satellite or for space law verification. Having an inspector satellite rendezvous with one satellite and then maneuver to rendezvous with a second satellite means that it must move between these two orbits. In general, this will require maneuvering the inspector satellite to change its orbital plane, to change the size and shape of its orbit, and to change its position with respect to the other satellite in the orbit.

Not surprisingly, designing an inspector satellite with enough maneuverability to inspect satellites in different orbital planes can lead to requirements for large increases in the mass of the inspector satellite.

Whether this increase in propellant mass is a problem depends on the mass of the empty inspector satellite (i.e., without propellant). If the satellite is small enough, the total mass of satellite and propellant may not be prohibitively large. For example, simple maneuvering microsattellites carrying sensors are being developed with masses of tens of kilograms. Even if the propellant mass resulted in a total mass several times larger, a small launcher could still launch the satellite and its propellant.

If the inspector satellite limited its activities to inspecting satellites in or near a single plane, the propellant requirements could be moderate. An example would be an inspector intended for geostationary satellites, since these all lie in or near the equatorial plane. A second example would be an inspector intended for a single plane of a constellation that consisted of multiple planes with multiple satellites in each plane (as would be the case for space-based missile defense interceptors and ground-attack weapons, and communication satellites in low earth orbit). Keep in mind that satellites with the same inclination may lie in different orbital planes that are rotated around the Earth's axis with respect to one another; this is important to take into account when determining the amount of propellant mass needed to move between one satellite and another.

To see the implications of out-of-plane maneuvers on the propellant mass required for an inspector satellite, consider an inspector satellite (with propellant for moderate in-plane maneuvering) with a mass  $m_s$ . Adding enough propellant to allow it to inspect two satellites in low earth orbits that lie in orbital planes separated by only  $30^\circ$  in inclination would require a propellant mass of  $3m_s$  (assuming conventional thrusters). Launching this satellite would require placing twice as much mass in space as launching two inspector satellites on two launchers into the two orbital planes.

As illustrated above, the propellant requirements increase rapidly for larger plane changes. Rendezvousing with two satellites in orbital planes separated by  $90^\circ$  would require a propellant mass of  $39m_s$  (e.g., the total launch mass would be 400 kg for an inspector satellite of mass 10 kg)—and would require placing 20 times as much mass in space as launching two satellites separately.

As noted above, if the mass of the inspector satellite is small enough, the overall launch mass of the satellite and propellant may not be prohibitively

large. However, if an on-demand launch capability exists, such as an air-launch capability, it may be more efficient to place an inspector satellite in the proper orbit once a particular need arose, rather than attempting to station a highly maneuverable inspector satellite in orbit.

The propellant mass could be reduced by using an ion thruster rather than a conventional chemical thruster, but as shown in Section 7, the maneuvers would take much longer. For missions that are not time critical this may be acceptable.