Chapter Title: Appendix A SPACE-BASED DIRECTED-ENERGY WEAPONS

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Appendix A

SPACE-BASED DIRECTED-ENERGY WEAPONS

To illustrate the range of issues in sizing and basing a space-based laser, we will focus on one stressing mission, ballistic missile defense, and explore it quantitatively as a function of the missile targets and trajectories and of weapon characteristics, sizing and orbital basing. The allure of space-based lasers against these time-urgent targets is the possibility of extending the engagement down into the atmosphere and of initiating the engagement sooner, without having to first characterize the target's probable future trajectory in order to select weapons that can reach it in time.

SAMPLE PROBLEMS: BOOST-PHASE MISSILE DEFENSE

To quantify the different degrees of urgency in boost-phase missile defense, we will examine three different, representative target cases: short, medium, and intercontinental range. The specific trajectory parameters for these cases are summarized in Table A.1. The intercontinental range burnout times are typical for solid-propellant missiles. Older, liquid-propellant missiles typically have another couple of minutes of burn time. The time to reach 15 km altitude is highlighted to indicate the earliest time that a hydrogen-fluoride laser could engage. Lasers at wavelengths that penetrate deeper into the atmosphere can recover some portion of the previous 45 to 60 seconds—how much depends on when the surveillance system has the opportunity to see the launch unobscured by clouds. Given a total boost time of about 1.5 to 3 minutes, recovering any significant portion of the lower altitude could mean a big difference in a weapon's kill capacity against a salvo of missiles.

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Table A.1
Target Ballistic Missile Trajectory Parameters

	Range (km)	Flight Time (sec)	Time to 15 km Altitude (sec)	Burnout Time (sec)	Burnout Altitude (km)	Highest Altitude (km)
Short	875	500	50	85	53	225
Medium	3,375	1,050	61	110	64	650
Intercontinental	7,825	1,650	44	180	248	1,125

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Figure A.1 shows the shape of the trajectories, from launch to impact. Figure A.2 highlights the boost-phase portion of the same trajectories. To evaluate the effectiveness of various constellations of space-based lasers, we will need to anchor those trajectories at specific launch and target points. For the sake of illustration and variety, implying nothing for future likelihood and no nostalgia for past concerns, we will consider the short-range trajectory from Iraq to Israel, the medium-range trajectory from Korea to Guam, and the intercontinental trajectory from Russia to Washington, D.C.; the ground traces appear in Figures A.3 through A.5.

BASE-CASE LASER

To begin our exploration of space-based lasers, we will start with a target damage threshold at 10,000 joules/cm^2 (at the high end of the 1 to 30 kilojoule range discussed earlier, about 10,000 times the level needed to burn exposed human skin) and will require the laser to

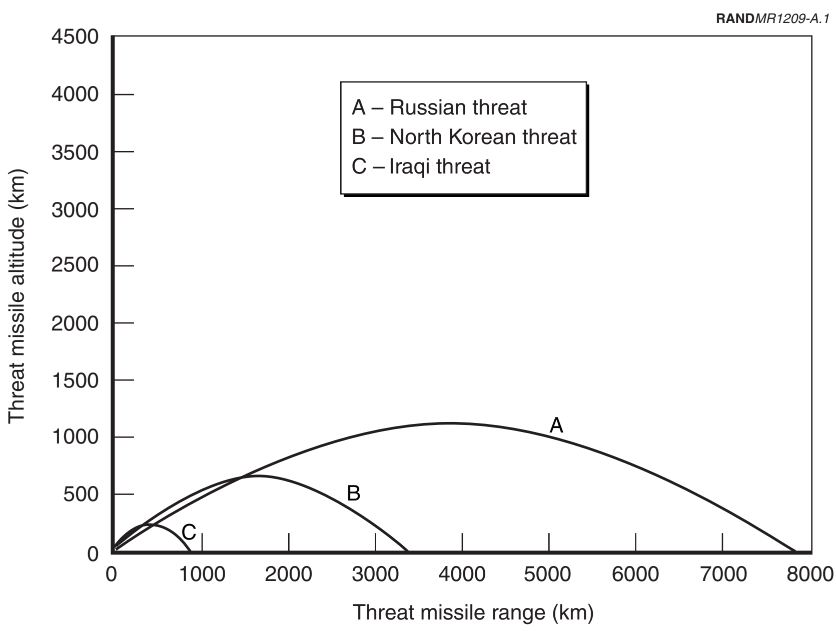

Figure A.1—Ballistic Missile Trajectories, Altitude Versus Range

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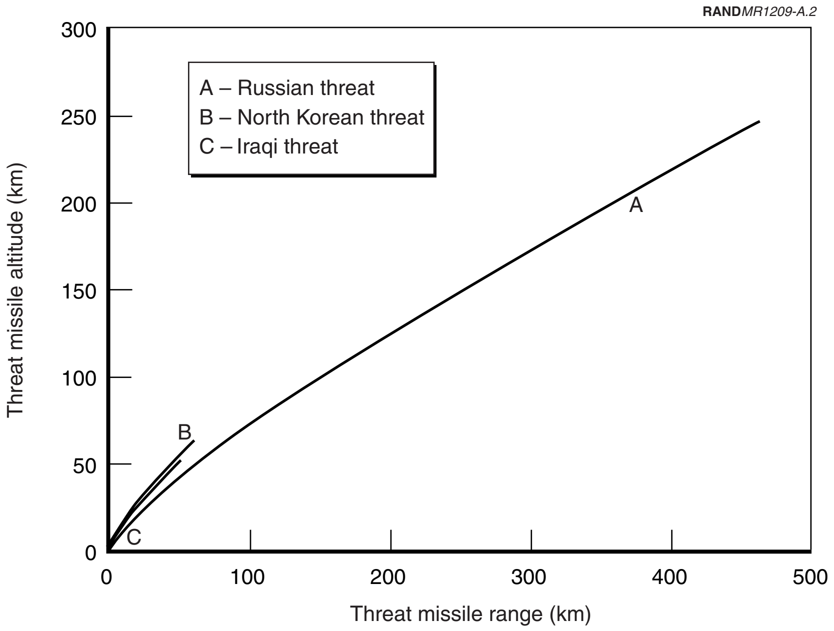

Figure A.2—Ballistic Missile Trajectories, Boost Phase

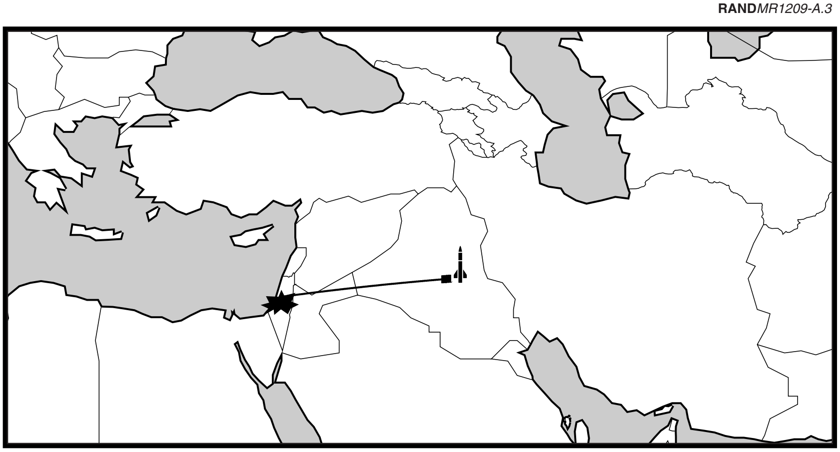

Figure A.3—Ballistic Missile Trajectory Ground Trace, Short Range

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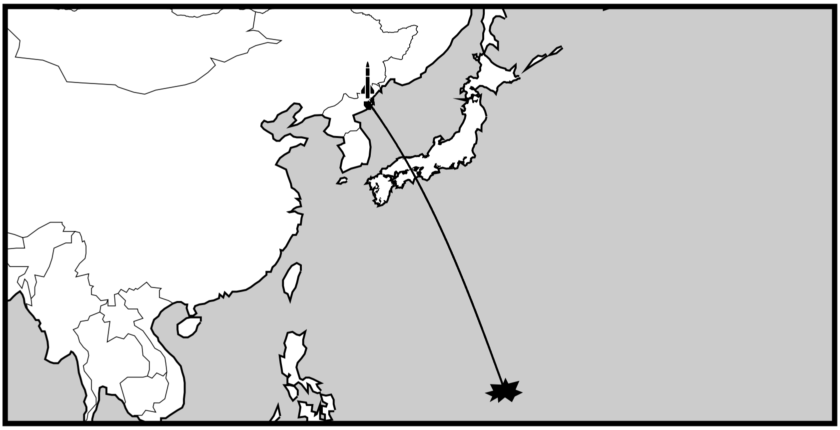

Figure A.4—Ballistic Missile Trajectory Ground Trace, Medium Range

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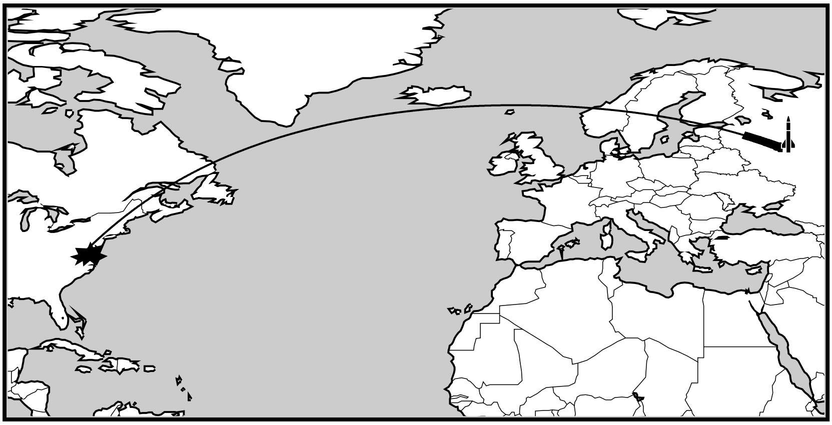

Figure A.5—Ballistic Missile Trajectory Ground Trace, Intercontinental Range

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provide that level of energy in a damage spot with a radius no smaller than 10 cm. The base case for our parametric calculations will be a hydrogen-fluoride laser, which operates at a wavelength of 2.7 μm (and is the space-based laser technology that has received the most funding and development). At that wavelength, the laser will receive credit for engagements beginning at altitudes above 15 km. The base-case laser will operate at a nominal power level of 5 megawatts. The base-case primary mirror will have a diameter of 10 m, with the secondary mirror and supporting structure obscuring 20 percent of that. We will assume the ability to retarget the laser to a new target within half a second[1] and the ability to hold its beam steady to a jitter level of 0.08 microradians, selected arbitrarily as consistent with ideal, diffraction-limited optical performance.

Given these parameters and the 49 seconds available from the time medium-range missile targets reach 15 km altitude until burnout, a single laser could expect to kill about three medium-range ballistic missiles out of a salvo from a range of about 1,700 km and a base altitude of about 550 km with an aspect angle of its line of sight to the target around 30 degrees off of broadside. In the process, it might consume on the order of 500 to 750 kg of laser fuel. The qualifications on that sample statement of capability are a reminder that the actual performance of space-based lasers results from a dynamic combination of factors that fluctuate over time and with the contributions of the entire constellation of lasers. The next section will explore the dynamics of that combination as a function of the constellation and individual laser parameters.

CONSTELLATIONS

Designing a constellation of satellites to provide service to the earth is a matter of selecting the number of satellites, their altitude, and their configuration in some number of orbit planes. Here, measures of performance and cost are the ordinary figures of merit. When the cost includes substantial ground equipment (such as communica-

[1]Although the angular distance the laser boresight must move through will decrease with distance and altitude and the effort needed to move it through that angle will increase with the size and mass of the laser and its optics, we will treat retargeting time as a constant here to illustrate the trends with a broad brush. More detailed engineering studies should include the additional effects.

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tions terminals), the characteristics and costs of the ground equipment may dominate the design and shift expense into the satellites for a lower overall total cost. However, for these weapons, the ground equipment is limited to what is necessary to control the satellites and is not generally a large share of the total expense. Minimizing the overall cost will generally mean minimizing the cost of the portion of the system in space.

Minimizing the cost of the space segment of a weapon system is often misinterpreted as minimizing the number of satellites. Fewer satellites for a given earth coverage mean either that the orbits must be higher to allow a satellite to see more of the earth at once or that the satellites must be spaced farther apart in the planes of their orbits. Both approaches increase the range a laser weapon must reach, and the size and cost of the weapon increase with the square of the range. The second approach also requires a directed-energy weapon to propagate its energy through more atmosphere at shallower angles, which further increases the size and cost. Bearing that generalization in mind, let us examine a specific example.

Figure A.6 is a snapshot of the positions of a constellation of 24 space-based lasers. Each laser is at an orbital altitude of 1,248 km,

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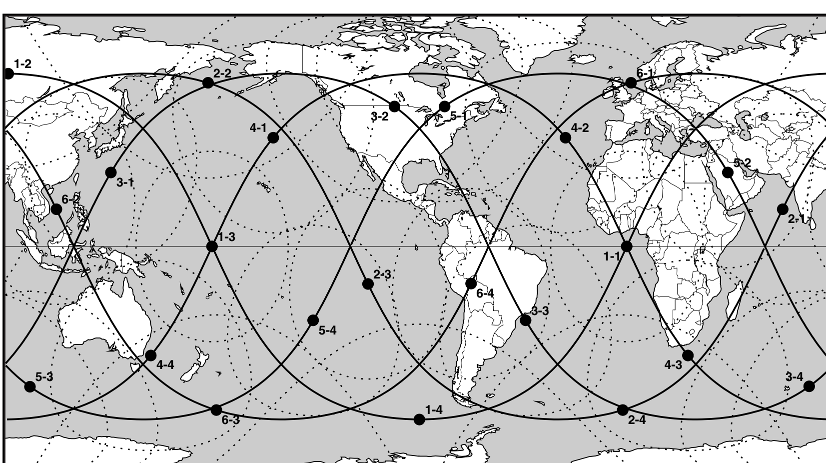

Figure A.6—Space-Based Laser Constellation Snapshot

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and one orbit takes a little more than 110 minutes. The 24 satellites are divided into six groups of four. Each group occupies a plane or ring, with the six planes inclined 60 degrees to the equator and evenly spaced around the equator. The four satellites in each plane are evenly spaced around their orbital plane. The satellites in a plane are offset a sixth of an orbit from those in adjacent planes.

The solid lines that undulate over the map are the ground traces of the subsatellite points of an orbital plane at single moment. The labels indicate which satellite is on which path: Satellite *m*-*n* is in orbit position *n* in ring (plane) *m*. Following the ground trace from left to right shows which ones are ascending or descending on that path. The dotted lines depict the coverage of each satellite at the time shown. The coverage is limited to the 15-km altitude established for a hydrogen-fluoride laser. Taking one satellite as an example, number 1-3, there is a four-pointed star shaped area directly under it where it alone has coverage of targets. That star is bounded by convex lens-shaped areas where the satellite shares coverage with another, adjacent satellite. At the ends of two of those lens-shaped areas are areas where three satellites may engage targets. These shapes shift continuously with time. To visualize the dynamics of this, superimpose the motion of the satellites around their rings every 110 minutes on the motion of the surface of the earth under them every 24 hours. To translate this into constellation lethality, factor in the inverse-square effect of range and the projection[2] of each engaging weapon's line of sight onto the target.

The dynamic translation from geometry to lethality is difficult to visualize but straightforward to compute. Figure A.7 resulted from computing this for the base-case constellation of lasers against a salvo launch of medium-range ballistic missiles from Korea against Guam. The figure shows the number of missiles that the constellation could kill as a function of the time of launch, minute by minute, throughout the day. The graph resembles an amplitude modulation of a higher frequency wave by a lower frequency wave. The high-

[2]As a target's vulnerable surface is angled away from the line of sight of the laser, the laser's beam is projected over a larger area, diffusing its intensity. As the laser beam has to propagate to longer ranges, the area it projects grows with the square of the range, again diffusing its intensity correspondingly.

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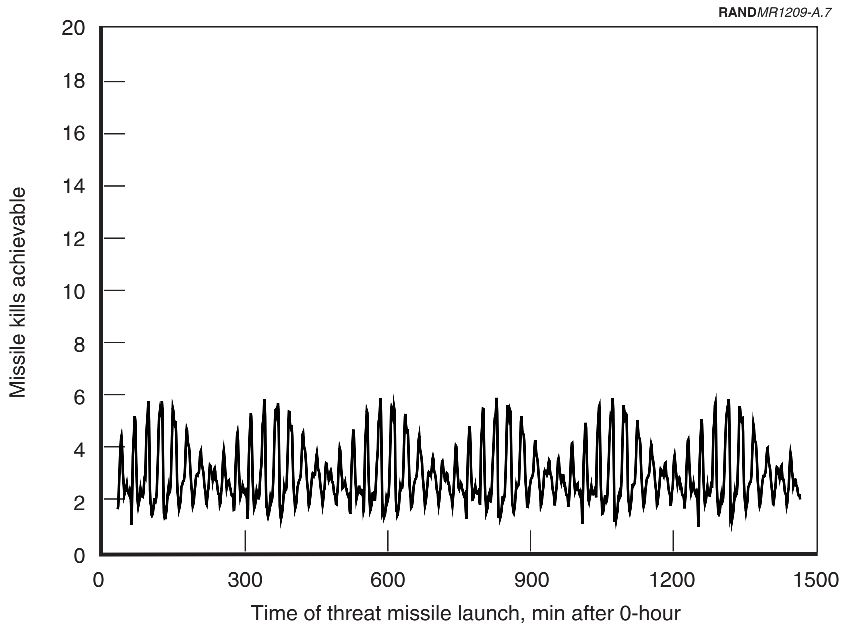

Figure A.7—Example Space-Based Laser Kill Capacity

frequency variation is tied to the time it takes satellites to orbit the earth. The time between the rapidly varying peaks (or, equivalently, valleys) corresponds precisely to one-fourth of the 110-minute orbital period, reflecting the spacing between the four satellites in a ring. Each peak in the short variation corresponds to the passage of a laser satellite over the launch point (or as nearly over it as the orbital plane allows at that time of day).[3]

The slower variation is tied to the earth's rotation under the constellation. The time between peaks of the slow variation corresponds to one-sixth of the 24-hour period of the earth's rotation. Drawing a horizontal latitude line across the map in Figure A.6 at the launch point to trace its path under the orbit planes through the day illus-

[3]The rapidly varying peaks would be even higher, because the beam spot size shrinks with decreasing range and increases intensity, except that we have limited the spot size to a minimum of 10 cm and have deliberately defocused the beam to keep the spot at the minimum when proximity would otherwise have made it smaller.

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trates where the slow peaks and valleys occur. The valleys occur when the launch point is under areas farthest from the ground traces of the orbital planes. The peaks occur when the launch point passes closest to the intersections of the six ground traces of the orbital planes.

The shape of this pattern points out an important aspect of laser performance claims. The shape and timing of this pattern are predictable and readily available to any opponent sophisticated enough to have ballistic missiles. He will know when to launch a salvo to achieve the best penetration of the laser defense. He may not be confident of the relative hardness of his missiles against the power of the lasers (and so of the minimum salvo size needed to have some penetrate), but he will know with certainty when his best opportunities are. And they will be regular and frequent. This is not something the owner of the space-based lasers can prevent.

Because of their size, the lasers would be extremely difficult to hide or to maneuver enough to be unpredictable. The opponent could easily field a space surveillance capability to keep track of them but, thanks to the Internet, would probably not need to have his own tracking capability. Amateur astronomers are likely to publish the orbits electronically.[4] The opponent will certainly time his missile launches to coincide with the lowest points.

Claims of laser constellation lethality should be checked carefully for their assumptions about the timing of launch. A claim at the maximum kill rate assumes a willfully self-destructive opponent. A claim based on the average assumes a blissfully oblivious opponent. Only a claim based on the minimum is reasonable for this class of time-urgent targets. Any apparent excess of maximum over minimum kill rate capacity is surplus or wasted (at least for this target).

However, for slower targets or alternative missions in which the laser's owner can choose the time and geometry of engagement, this surplus target capacity could be put to use without compromising the constellation's capability against ballistic missile targets, which would presumably avoid launching at times of peak lethality. For example, a laser whose wavelength has been chosen to penetrate low enough into the atmosphere could be used against airplanes or

[4]The SeeSat-L Internet mailing list is an example; see Clifford and DePontieu (1994).

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cruise missiles in flight or even against terrestrial targets, such as above-ground fuel tanks, missiles still on their launchers or transporters, fuel trucks, and other relatively thin-skinned or flammable targets. To the degree that such targets are vulnerable to the kind of surface-heating damage that a laser can inflict, engaging them should require amounts of laser fuel similar to those for a missile target.[5] Of course, any use of the excess kill rate capacity would still have to fit within the logistic limits of energy storage (electrical or chemical) and replenishment.

Certain approaches to weapon and constellation design could reduce the two sources of variation in kill rate capacity we observed in the base case. The approaches can be used separately or in combination. Reducing the large, rapid variation associated with the passage of a satellite over the target area requires reducing the relative range-to-target difference between the minimum and maximum engagement ranges. This can be done by adding lasers to reduce the spacing between them and increase the overlap of their coverage, which will reduce the range of angle away from the local vertical, where a single laser would have to carry the burden alone. Adding more lasers in additional orbital planes to reduce the spacing between rings would reduce or fill in the gaps that provide the slow variation.

Alternatively, having fewer lasers requires increasing their altitude to smooth out the variation in kill capacity. Of course, maintaining lethality at the longer ranges would require a corresponding increase in laser power (and/or aperture). Number, size, and orbit altitude determine the logistic cost of deploying and sustaining the constellation. Size and power, which determine fuel consumption in operation of the lasers, influence the logistic costs of operation. Figure A.8 shows the effect for the same target of raising the lasers from the base-case altitude of 1,248 km to 3,367 km (see Table A.2 for a summary of the parameters varied across the various laser case figures). To compensate for the increased range, we have increased the laser's

[5]The engagement could require less for nonlethal and indirect effects, such as illumination or stimulating fluorescence in aircraft canopy materials to degrade the pilot's view out of the cockpit. The laser could also presumably pick the times of engagement to take advantage of the shortest ranges to target.

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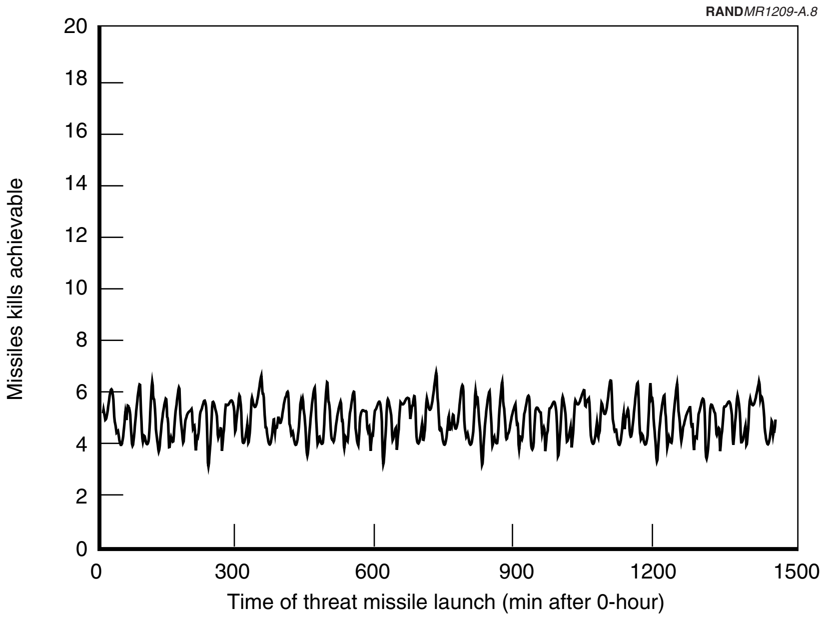

Figure A.8—Space-Based Laser Kill Capacity, Higher-Altitude Constellation

power to 35 megawatts, but we have cut the number of lasers on orbit in half to twelve. The rapid variations in kill capacity that we saw in Figure A.7 are broadened by the increase in orbital period to 159 minutes and smoothed out by the relatively flatter difference between minimum and maximum target ranges.

In the other direction, Figure A.9 shows the effect of reducing the altitude roughly by half, to 550 km; increasing the number of satellites by a factor of five; and decreasing the individual laser power by a factor of five from the base case. To the degree that the logistic cost for the entire constellation depends on the total weapon power on orbit, the cost for this much-larger constellation of smaller lasers should be similar to that of the base case. However, this constellation's performance against the ballistic missile threat is much better. Its profile is not as smooth as those of the base and the highest-altitude orbit (its orbital period, 96 minutes, is slightly less than that of the base case), but the magnitude of the swing between high and

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Table A.2

Key to Laser Cases

Figure	Laser Type	Laser Wavelength (μm)	Minimum Altitude (km)	Laser Power (Mw)	Laser Aperture (m)	Laser Orbit Altitude (km)	Number of Lasers	Target Missile Range	Case Description
3.2	HF	2.7	15	5	10	1248	24	Medium	Base case
A.7	HF	2.7	15	35	10	3367	12	Medium	Higher altitude
A.8	HF	2.7	15	1	10	550	120	Medium	Lower altitude
A. 9	HF	2.7	15	1	10	550	120	Short	Short-range targets
A.10	HF	2.7	15	1	10	550	120	Long	Long-range targets
A.11	COIL	1.3	5	1	10	550	120	Medium	Short wavelength
A.12	DF	3.8	5	1	10	550	120	Medium	Long wavelength
A.13	FEL	0.351	0	35	10	3367	2[a]	Medium	Relay mirrors

[a]Two ground lasers and 24 relay mirrors.

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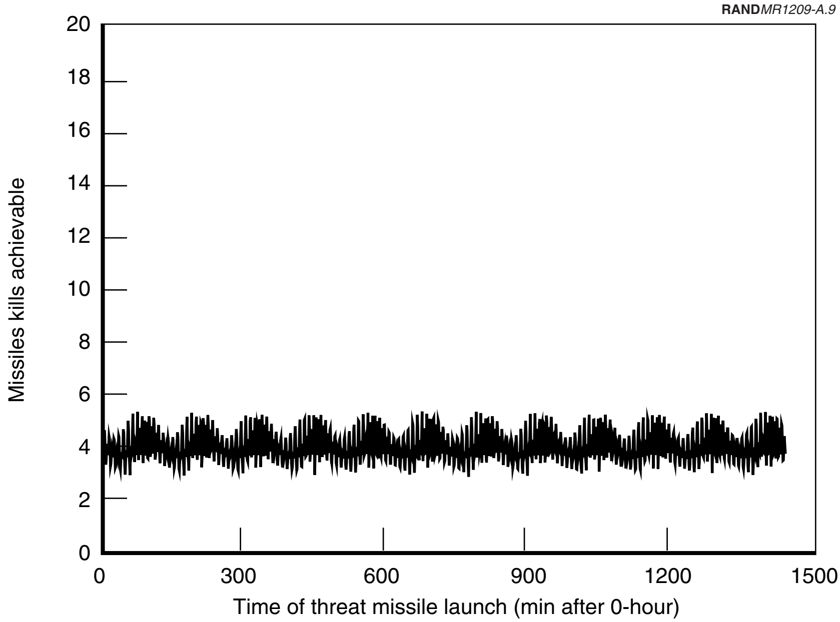

Figure A.9—Space-Based Laser Kill Capacity, Lower-Altitude Constellation

low is smaller than in the base case, and the minimum capacity is higher than in the base case. As an added benefit, this constellation is much more robust to failure or loss of an individual laser.

The difference between minimum and maximum kill capacity for the different orbital altitudes is primarily due to the way that the range to target varies with altitude as the laser engages targets at angles directly below it as opposed to those at the "horizon." Where the horizon falls depends on how closely the lasers are spaced and the altitude at which they can begin engaging targets. Table A.3 gives the range, angle, and relative (to the shortest range) power needed at the horizon for the 15-km minimum target altitude for the hydrogen-fluoride laser.[6]

[6]For a given orbital altitude, we could reduce the angle and range to the horizon by adding lasers to reduce the spacing between them as we did in the lower-altitude vari-

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Table A.3

Hydrogen-Fluoride SBL Horizon Parameters

Orbit Altitude (km)	Angle to Horizon from Nadir (deg)	Range to Horizon (km)	Relative Power Needed at Horizon vs. Nadir
554	67	2680	24.7
1248	57	4158	11.8
3367	41	7355	4.8

MISSILE TARGET VARIATIONS

For these constellation trends, the driving factors are short missile flight times and the limited range of accessible target altitudes. Figures A.10 and A.11 help illustrate the urgency of the missile problem by comparing the variations in laser power and constellation against the data for shorter- and longer-range missiles from Table A.1. Figure A.9 shows the performance of a large, low-altitude, small-laser constellation against a short-range missile launched from Iraq to Israel. Against this more stressing, shorter-range missile, the constellation's minimum kill capacity is about 2. Figure A.10 shows the performance of the same constellation against the longer-burning, longer-range, intercontinental missile launched from Russia to Washington, D.C. Now, the constellation's minimum kill capacity is about 12.

WAVELENGTH

Laser wavelength is another variable. If the laser's power and the physical size of its optics are kept constant, changing the wavelength of the laser will change how well the optics can focus the energy on the target.[7] Shorter wavelengths will do better. The wavelength in

ation above. We could also increase the spacing between lasers and engage targets above the horizon at greater ranges, but the lasers' effectiveness fal ls off with the square of the increased range, and we would give up the time it takes the target to reach the higher engagement altitude.

[7]This presumes that the shape of the optical surfaces remains accurate to the corresponding tolerance of the new wavelength.

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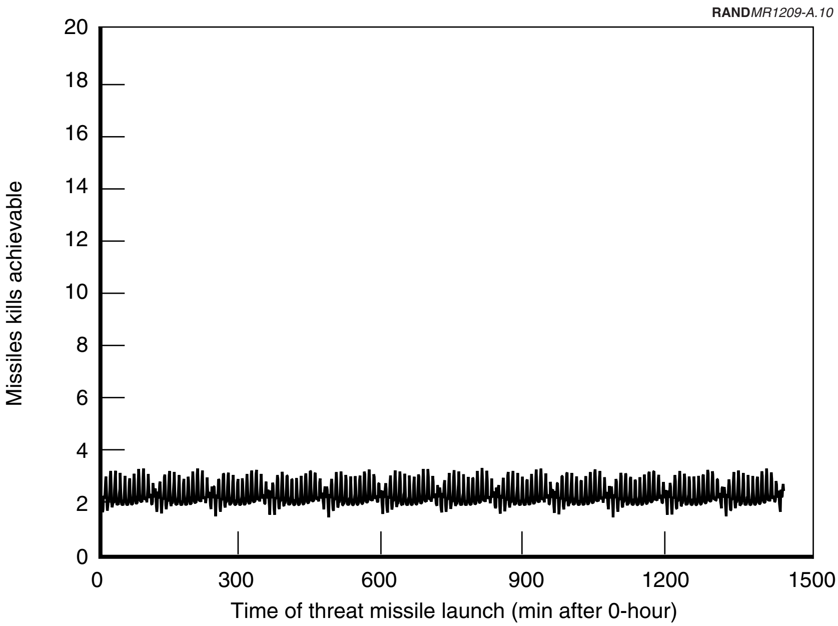

Figure A.10—Space-Based Laser Kill Capacity, Lower-Altitude Constellation, Short-Range Missile Target

Figure A.9 was 2.7 µm; in Figure A.12, the wavelength has been decreased to 1.3 µm, corresponding to replacing the hydrogen-fluoride laser with an oxygen-iodine laser. The change in wavelength should improve the kill rate by roughly a factor of four because of the tighter focus at most ranges. This does not account for defocusing to keep the energy at the minimum spot size at the shortest ranges with the shorter wavelength.[8]

Another significant source of improvement with this change in wavelength is that this wavelength propagates better through a window in the atmosphere's absorption profile, yielding the opportunity

[8]The shorter-wavelength laser could focus to about 80 percent of the minimum spot size assumed for the 15-km target altitude directly below the laser.

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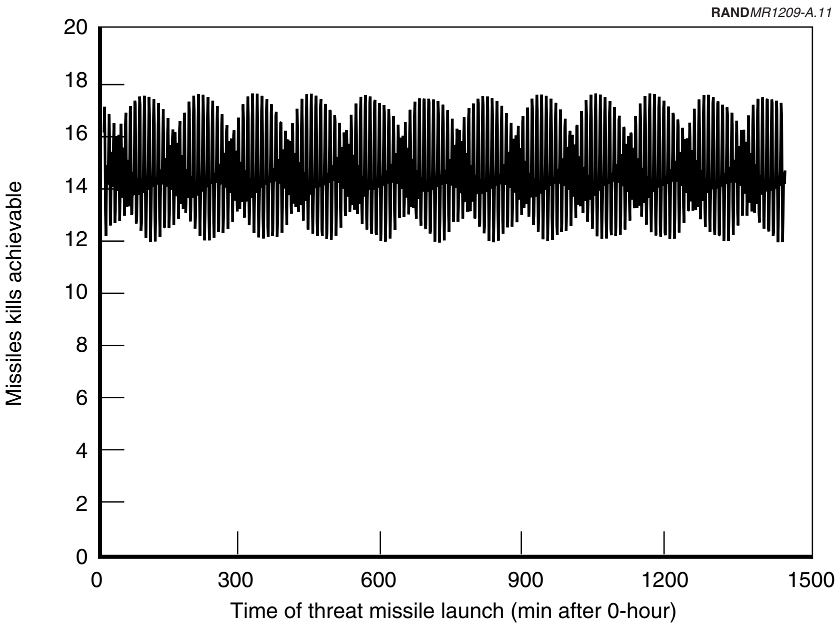

Figure A.11—Space-Based Laser Kill Capacity, Lower-Altitude Constellation, Long-Range Missile Target

to engage targets at lower altitudes. Figure A.12 gives the constellation of lasers credit for being able to engage missile targets at altitudes as low as 5 km.

Figure A.13 examines the performance of the example constellation against a medium-range missile salvo but with a longer-wavelength laser to penetrate farther into the atmosphere than the hydrogen fluoride baseline. Instead of hydrogen fluoride, this laser is deuterium fluoride, with a wavelength of 3.8 μm. The figure gives credit for reach into the atmosphere to missile targets at a minimum altitude of 5 km. Increasing the wavelength should reduce the kill capacity by a factor of two because the focusing ability decreases for the same size mirror. However, the increased reach into the atmosphere has kept this constellation's performance on a par with the hydrogen-fluoride laser. This is not to say that deuterium is a good choice. Aside from

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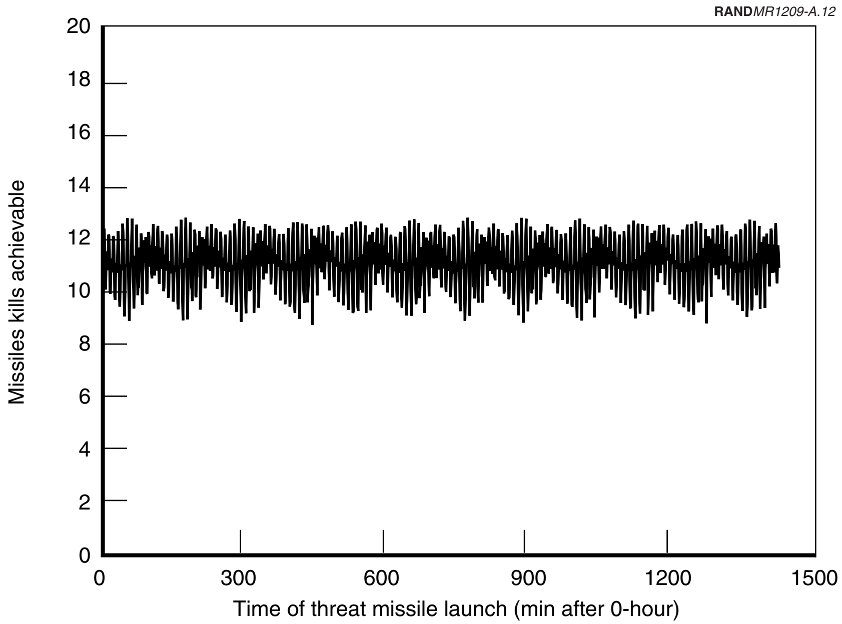

Figure A.12—Space-Based Laser Kill Capacity, Shorter Wavelength

its longer wavelength, it is a very rare isotope of hydrogen and likely to be expensive. Other things being equal, we would probably prefer the oxygen-iodine laser to either the hydrogen- or deuterium-fluoride lasers.[9]

RELAY MIRRORS

Once the choice of a suitable wavelength has moved the laser's effect on targets further into the atmosphere, the next conceptual step is to move the entire laser down to the earth's surface, keeping only the

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[9]Among the other things that are not equal, oxygen-iodine lasers have not been in development as long as hydrogen-fluoride lasers. Also, a political, arms control, or other external imperative *not* to be able to engage targets deeper into the atmosphere from space could rule out the benefits of the shorter-wavelength laser.

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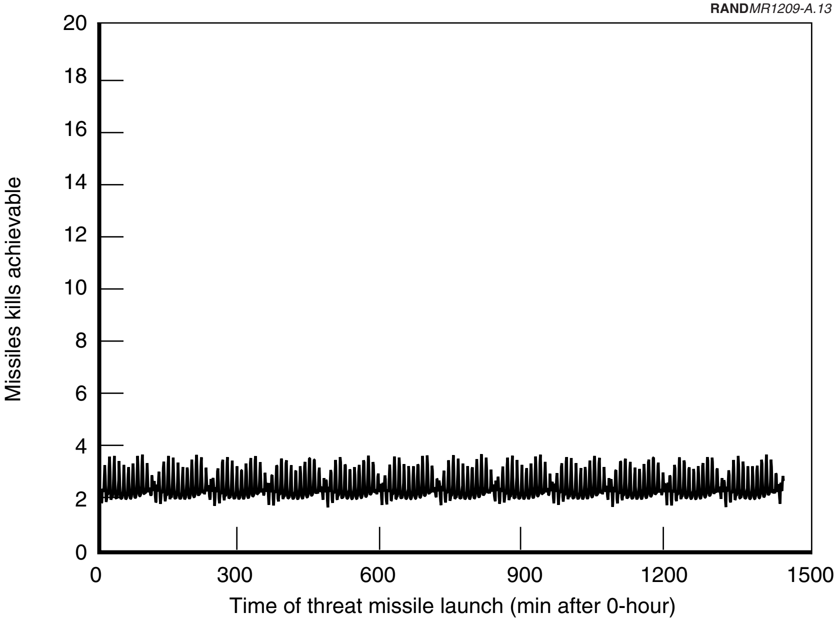

Figure A.13—Space-Based Laser Kill Capacity, Longer Wavelength

mirrors in space to redirect the energy to targets around the globe. This has the significant benefit of moving the logistic problem of replenishment to the ground, where transportation is less expensive. It has the additional benefit of largely eliminating the laser absentee problem and limiting absenteeism to the relay mirrors.

Some degree of redundancy in the ground-based lasers is, however, still necessary. Bad weather over the ground-based laser could cause it to be just as absent from the fight as a satellite-based laser whose orbit has carried it away from the target. There must be enough lasers located far enough away from each other to be confident that at least one site will have clear weather when a weapon is needed. This might be as few as two locations, say Hawaii and somewhere in the desert Southwest of the United States, depending on the climatology of the locations and the degree of assurance needed. But the absentee ratio here would still be a lot lower than those for the space-based components.

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For the sake of propagation, the preferred locations for lasers will have dry climates (at least at the altitude of the laser) and high altitudes, such as mountaintops. A mountaintop would need infrastructure—roads, power, communications, and so forth. A handful of suitable mountains have already developed this kind of infrastructure to support astronomical observatories.[10] These locations also might be attractive for the ground-based laser component of relay system—assuming that the observatories have not run out of mountaintop real estate and that the laser's normal operation can be made compatible with the astronomical observations. The larger earthbound astronomical telescopes have begun sounding the atmosphere with laser guide stars to correct their own observations through adaptive optics. This might make a colocated laser weapon compatible, since the laser weapon also needs a laser guide star. Astronomers might even welcome the laser if its large optics could also be used to increase observing time when not needed for weapon operations, maintenance, or training. Also note that the common technical interests make such observatories a logical place to look for covert development and emplacement of such laser weapons.

There is, however, a price to be paid in space for moving the resupply logistics and the laser itself to the ground. Once again, the dominant factor is distance. In space, the laser weapon has the advantage of shorter distance to its targets when they are in its line of sight. The relayed path will be longer, unless the targets are relatively near the laser.[11] Over the longer path, the beam would ordinarily diverge and diffuse within the angle in which the originating mirror could concentrate the energy, the intensity of the beam at the target being divided by the square of the distance traveled. This could be done with a single large, flat mirror at each point along the way, angled to deflect the beam to its next destination and with the size of the mirror at each point increasing as the beam travels. It would be more practical, however, to use two large bifocal primary mirrors at each relay point connected to each other by a secondary optical path of smaller

[10]These include the observatories atop Arizona's Kitt Peak (AURA, 1999), New Mexico's Sacramento Peak (NOAO, 1999), California's Mt. Hamilton (UCO, 1999), and Hawaii's Mauna Kea and Haleakala volcanoes (Wainscoat, 1997; Maberry, 1998).

[11]In that unlikely case, something other than a space-based weapon would be more appropriate for local defense.

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mirrors, much as the space-based laser would be connected to its large primary mirror. One of the bifocal mirrors would capture the incoming beam and the other would refocus it on its way. Compared with the space-based laser constellations in the previous section, moving the lasers to the ground effectively doubles the number of large mirrors in space.[12] All the mirrors require the same kind of precise, stable pointing as the space-based laser's mirrors but are at least not physically connected with the laser's mechanical disturbances. Because the beam inevitably spills some beyond the edges of the capturing mirror(s) in the relay, some additional power is lost at each relay. The saving grace of this arrangement is that it should be easier to make up the losses with a higher-power laser because the cost of emplacing and supporting a smaller number of lasers on the ground is lower.

The effects of orbital basing on the mirrors for the relay architectures parallel those for the space-based laser architectures in the previous section. To illustrate this, Figure A.14 plots kill capacity for the medium-range missile threat throughout the day for a constellation of 24 10-m diameter bifocal relay mirrors orbiting at an altitude of 3,367 km. Two 35 megawatt lasers, hypothetically in Albuquerque, New Mexico, and operating at the free-electron laser wavelength of 0.351 μm, complete the system.[13] The mirror altitude is similar to that in Figure A.7. The laser power is about seven times greater, which balances reasonably with the longer path lengths. Also, the number of mirrors and the laser wavelength are different. The higher power and shorter wavelength are responsible for the apparent improvement over Figure A.7.[14]

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[12]There have been proposals to reduce the total number of mirrors in a relay architecture by giving them a mixture of high- and low-altitude orbits. The idea was to use a small number of very large "relay" mirrors at high altitudes and a larger number of smaller "fighting" mirrors at lower altitudes. Generally, depending on the difficulty and cost of the optics, these architectures do not perform as well as or cost less than architectures of self-relaying fighting mirrors at lower altitudes.

[13]Note that this laser would require correspondingly more-stringent pointing than the longer-wavelength lasers used in the space-based examples.

[14]We also gave the ground-based laser credit for lower jitter, which contributes some to the improvement.

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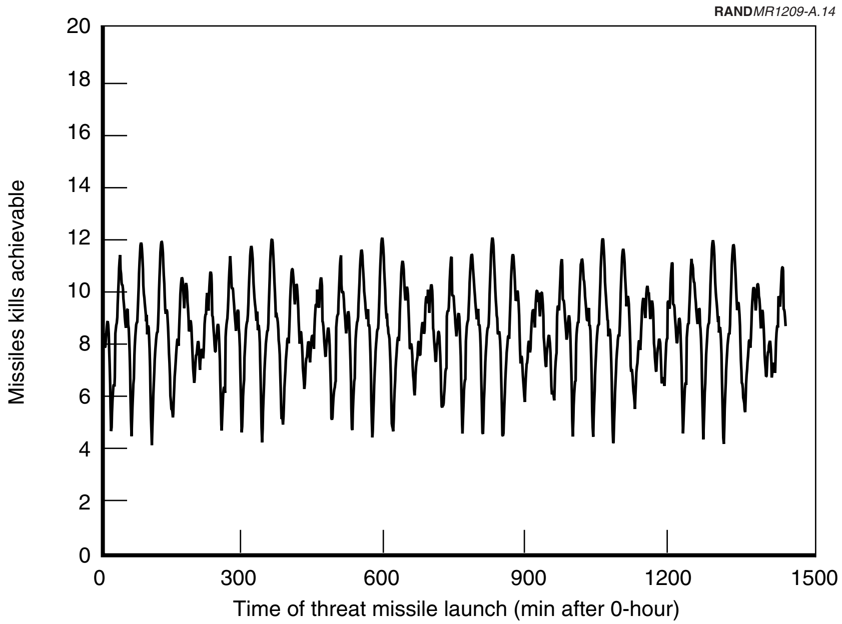

Figure A.14—Space-Based Laser Kill Capacity, Relay Mirror Constellation

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