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The Airborne Laser:
Shooting Down What's Going Up

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Abstract

Future regional conflicts will almost certainly involve politically less stable nations or other regional actors using theater ballistic missiles armed with either nuclear, biological, or chemical warheads. The United States Air Force is attempting to deal with this threat by developing the Airborne Laser (ABL) with the goal of shooting down missiles while they are still under power and before they can release submunitions possibly containing highly toxic biological agents. This paper presents the results of an analysis of this system. It is based solely on information found in the open literature and using the basic physics and engineering involved in transmitting intense laser beams through the atmosphere. The ABL's potential capabilities and possible theaters of operation are discussed at a non-technical level.

The Airborne Laser: Shooting Down What's Going Up

Geoffrey E. Forden

On November 12, 1996, the U.S. Air Force started the process of procuring a system intended to "revolutionize aerial warfare in the 21st Century."[1] The Air Force awarded a contract to Team ABL, consisting of Boeing Defense and Space Group (Seattle, WA), Lockheed Martin Missiles and Space Co. (Sunnyvale, CA), and TRW Inc. (Redondo Beach, CA), on that date to develop a demonstration model of this new weapon. Boeing, the team leader, will handle system integration; Lockheed Martin will provide optics and beam-control, and TRW will supply the high-energy laser. If the model meets expectations the United States will build a fleet of seven modified 747s, each capable of defending vast areas from attack by ballistic missiles. A large mirror in the nose of each billion-dollar plane would focus the beam from a high-energy chemical laser hundreds of kilometers into enemy territory. This beam is designed to destroy missiles above their launch sites while they are still under power. Surprisingly, this new system has attracted little attention and even less understanding from the public at large.

Unlike the well-known Patriot missile defense system, the Airborne Laser (ABL) engages enemy missiles during the period while they are under power. These so-called boost-phase defense systems enjoy many advantages over terminal defenses that attack the small, structurally strong warheads while they reenter the atmosphere. A missile under power has a very bright plume of hot exhaust gases, ideal for detecting the missile's launch. These plumes are so bright in the infrared spectrum that, during the Gulf War, Iraqi SCUDs were routinely detected from outer space by Defense Support Program satellites. Plumes from a liquid-fueled missile typically radiate 40,000 W/m^2 in the atmospheric transmission "window" between 4.1 and 4.5 microns. By comparison, sunlight reflected off snowfields would only contribute 210 W/m^2 to the background in this infrared band. This greatly simplifies location and initial tracking of the missile by the optical systems on board the ABL.

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[1] Air Force Chief of Staff General Ronald Fogleman, Pentagon news conference, November 12, 1996.

Another advantage of boost-phase defense systems is the fragility of a theater ballistic missile during the usual one to two minutes it is under power. It is not uncommon for missiles to experience compressive loads five times their launch weight during the last seconds they are under power. The missile designer has usually had to trade a wide safety margin for range and therefore weight. The result is that even minimal damage to the missile's structural integrity during this phase can result in its destruction.

The missiles' high accelerations also imply that the last seconds of the powered trajectory determine the missile's ultimate velocity and range. Terminating the thrust of an Iraqi SCUD variant even five seconds before the nominal end of its powered flight causes the missile to crash more than 150 kilometers short of its target. This is an optimistic estimate of the range the SCUD will achieve after a successful engagement since it assumes that the missile continues in stable flight. If the ABL succeeds in causing the destruction of the missile the ranges of the debris could be considerably shorter. Thus, the ABL can effectively use almost the entire time the missile is under power.

A final advantage of boost-phase defense systems is their potential capabilities against fractionated warheads. Missiles armed with chemical or biological warheads can release submunitions soon after the end of powered flight. Not only are such bomblets the most efficient method of dispersing aerosols but the tens or even hundreds of mini-warheads soon saturate even the most capable terminal defenses. A boost-phase defense could destroy the missile soon after launch, greatly reducing the maximum range of the debris. Ideally, a rogue state might be deterred from using weapons of mass destruction if it thought the debris could rain down on its own troops or cities. *(Figure 1)*

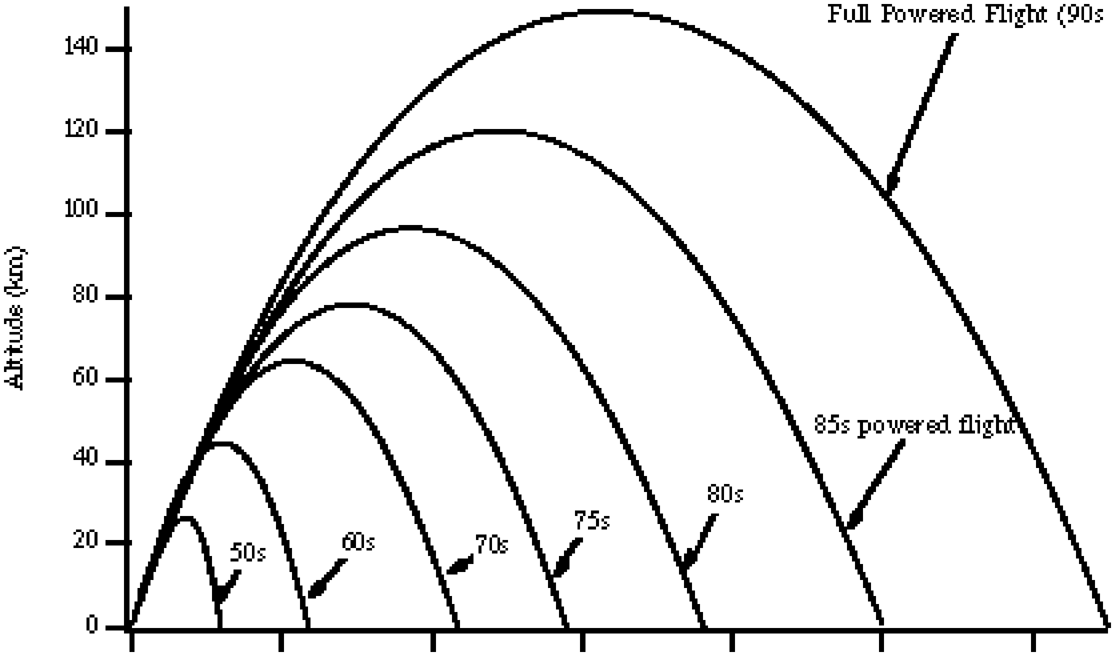

Figure 1. Boost-phase defense systems attack a missile in the brief period immediately after launch, while it is still under power. If the ABL causes the early termination of a missile's thrust the debris will continue along a nearly parabolic trajectory. The maximum ranges for the Al Husayn, an Iraqi variant of the SCUD missile, are shown here as a function of the time thrust is terminated.

Today, missiles commonly deployed by Third World countries use liquid fuel and have metal skins. Both are important details when considering how the missile can be defeated. The ABL attacks these missiles by focusing the primary laser beam on the missile's surface. Some of that beam's energy, perhaps as little as 10% depending on the missile skin's reflectivity, heats the metal. If the beam is allowed to dwell long enough on the same spot the skin's temperature will be raised to a characteristic value where the metal's strength drops dramatically. A fuel tank heated to this point would rupture due to its internal pressure. As will be discussed below in more detail, such a rupture degrades the missile's thrust and therefore its range. It is also possible that the laser beam could cause the missile to fail catastrophically. However, the beam must heat a sufficiently large arc along the missile's circumference to the critical temperature. In this case, the aerodynamic and inertial forces acting along the missile's axis bend the structure in half. This is the best outcome possible for the ABL. Again, just like the kill mechanism where the fuel tank ruptured, it is only effective during the brief time the missile is under power.

The utility of the ABL in future regional conflicts, and the consequent policy options the United States can exercise, will be highly dependent on its range. This in turn is determined by the beam's pointing accuracy, delivered power density, and the structural design of the missile being attacked. The estimates of the ABL's capabilities quoted in this article are from an independent analysis the author has performed. This analysis used only information found in the open literature and the basic physics and engineering involved in propagating intense laser beams through the atmosphere.

Onboard the ABL

A Boeing study started in 1992 picked the 747-400 F freighter as the best existing aircraft to serve as the ABL platform. Criteria included lifting capacity, cruising altitude, and flight duration—all vital for the ABL to complete its mission. For instance, the aircraft must lift the primary laser and a prodigious range of sensors and control systems. Additionally, the large quantities of jet fuel and a sufficient quantity of chemicals used in the laser's power generation also contribute to the weight. Altitude is vital to both facilitate cloud-free lines of sight and reduce the atmospheric degradation of the beam.

The current plan, according to engineers from Lockheed Martin Missiles and Space Corp., is to have the ABL fly at 12.9 km altitude while on station. Battle management officers on board would most likely choose an elongated figure-eight flight path whose long axis is perpendicular to the direction of the missile's expected launch site. This flight path mitigates the atmospheric degradation of the beam as much as possible, as discussed in more detail below.

Together with the range of the ABL, the flight duration capability of the aircraft also determines the number of systems required to maintain continuous coverage. Consider a case where it takes three ABLs to cover all of a rogue nation's launch sites. Standard operating procedures for aircraft with 18-hour flight durations require seven aircraft to maintain continuous coverage. A hypothetical aircraft with a twelve-hour duration would require nine such ABL platforms. This is a significant consideration when major regional conflicts can last several months, as did the air war in the Persian Gulf.

There are three major laser systems on board the ABL: the primary or "killing" beam, which is a continuous laser, and two pulsed lasers used for tracking and beam transmission quality control respectively. The primary laser is a Chemical Oxygen Iodine Laser (COIL). Positioned in the rear of the 747, the COIL is the heart of the weapon system. This laser produces a continuous infrared beam with a wavelength of 1.315 microns. The ABL will require a megawatt class COIL, considerably higher than the beams in the hundreds-of-kilowatts range achieved on the ground. Calculations performed by the author have assumed a three-megawatt COIL.

The chemicals required to generate the primary beam are inexpensive and can be readily exhausted out the rear of the aircraft. Venting also rids the system of a considerable amount of waste energy, as heat, generated in the initial stages of the chemical chain. Removing this waste heat before it enters the laser cavity reduces the temperature fluctuations present inside the beam and improves the beam quality.

This can be contrasted with the Mid-Infrared Advanced Chemical Laser (MIRACL). MIRACL burns ethylene and nitrogen trifluoride in a reaction very similar to what takes place inside a missile's combustion chamber. The heated products of this reaction are mixed with molecular deuterium (heavy hydrogen) inside the resonance cavity of the laser. Heated shock waves present during this mixing form regions of differing temperatures, which slightly bend the light beams inside the laser in random directions. MIRACL does have the advantage over the COIL system of having undergone a longer period of weaponization. It has been reported that MIRACL has achieved a continuous output power of two megawatts and a maximum lasing duration of 70 seconds. MIRACL's long wavelength, greater than 3.6 microns, limits how small a beam spot can be formed over long distances. This is a major reason why COIL was chosen over MIRACL for the airborne laser system.

After leaving the COIL, the ABL's primary or "killing" beam is directed toward the front of the aircraft. Inside a protective pipe the primary beam passes the operator stations for monitoring target acquisition, missile tracking, beam pointing, and beam quality control. It also passes any facilities needed to handle crew rotation on the ABL's 18-hour flights. These could include sleeping quarters, a galley, and off-duty crew seating.

Just aft of the nose turret the "killing" beam enters a complex optical bench. The bench isolates its optical components as much as possible from the vibrations associated with normal flight. These components do the fine-grained beam control needed to point the primary beam at a transonic missile hundreds of kilometers away. Lightweight mirrors, called fast steering mirrors, are rotated or tilted to follow the apparent motion of the target. The control loop driving these mirror motions uses as input the image of the missile formed by the tracking system discussed below. The shaping and directing of the primary beam is done by mirrors, as opposed to lenses, to reduce power absorbed inside the optical train.

However, a laser beam powerful enough to "melt" the metal skin of a missile would also damage ordinary silvered mirrors inside the optical train. Instead, each of these control mirrors is most likely fabricated from single infrared transparent crystals tens of centimeters across. A series of thin layers, or films, of dielectric materials with alternating high and low indices of refraction (a measure of how much a material affects the speed of light) produce the reflecting surface. Acting together, these layers, less than a micron thick, reflect all but a small fraction of a percent of the laser light. This is possible because of the interference between the light waves reflected and transmitted at each of the tens or possibly hundreds of layers. Most of the light not reflected passes through the crystal backing and is absorbed by a separate, cooled metal block. This beam dump is probably blackened to increase its efficiency. Such mirrors are wavelength specific and can be made to reflect the primary laser light and transmit light from a laser with a slightly different characteristic wavelength.

It is important to have the pointing accuracy of the main beam be better than the diffraction limit of the main mirror of one micro-radian. This can be achieved using pattern recognition techniques on the target's image. Failure to control the beam's direction to more than this accuracy will unnecessarily smear the laser's energy over a wider area. Such jitter will increase the dwell time required to produce a kill with the consequent decrease in effective range. The author's calculations show, for instance, that pointing at the merely diffraction-limited accuracy decreases the maximum ABL range against Al Husayn missiles from 470 km to 420 km. This represents a 20% decrease in area coverage.

The optical bench supporting these control elements also contains a special deformable mirror used to preshape the light beam's wavefront (the surface, roughly perpendicular to the beam's axis, on which all the light rays have the same phase). These types of deformable mirrors are usually made from a faceplate thin enough to distort several microns across a surface distance of a few millimeters. Tiny pistons, or actuators, attached to the back of this mirror either push a section of the surface forward or pull it back. This changes the effective path length of light rays from the laser that are reflected from different points on the mirror. Light rays that start in phase get out of phase when they travel these different path lengths. Advancing or retarding the rays at different points across the beam enhances the entire beam's propagation through the atmosphere. Similar adaptive optics technology is used in ground-based observatories to correct for the atmospheric distortion of astronomical images. For instance, the Lick Observatory's Shane three-meter telescope uses 127 such actuators on small correction mirrors. MIT Lincoln Laboratory, for one, has performed experiments using several hundred actuators.

At this point, an additional laser beam , most likely a Nd:YAG laser with a wavelength of 1.06 microns (as opposed to the COIL wavelength of 1.315 microns), is injected into the optical train. This beacon beam is used in determining the needed compensation to counteract atmospheric distortions. Observing the properties of the reflection from the target missile of a special beacon laser determines, in real time, the best shape for the deformable mirror. The next section will discuss the atmospheric distortion and methods for its compensation in detail. The beacon beam is introduced to the killing beam's optical train through the back of a mirror, called a dichroic mirror. This dichroic mirror is narrowly tuned by adjusting the dielectric layers to reflect the primary beam along a given direction while transmitting the beacon laser.

Both the primary beam and the beacon beam must be slewed through the air to follow the target in its trajectory. Consequently, both beams traverse different parts of the atmosphere and experience constantly changing atmospheric imperfections. This forces the deformable mirror's profile to be changed on time scales of less than a thousandth of a second. The purpose of the beacon beam is to sample ahead of time the atmospheric distortions that the killing beam will experience. The direction of the transmitted beacon beam is purposely made different from the primary, or "killing," beam. This enables the beacon to lead the killing beam, thereby compensating for the fact that both the ABL and the target are moving at hundreds of kilometers an hour.

Light from both the beacon and primary lasers then enters the main mirror turret at the front of the 747. This ball-shaped appendage contains a mirror 1.5 meters in diameter. An infrared transparent canopy in front of the mirror facilitates a smooth air flow around the turret. The turret follows the gross motion of the target's trajectory. Such motion can span several degrees of arc during the engagement. Fast steering mirrors mentioned above do the fine corrections to the gross tracking. Angular coverage of the laser system extends across the front of the 747 and backwards on either side until the plane's fuselage gets in the way. In principle this coverage might span 270 degrees in the horizontal plane. Atmospheric effects such as thermal blooming greatly reduce the delivered beam power density in the forward direction. The next section discusses these atmospheric effects in detail. This turret is capable of being pointed up or down to allow the main mirror to follow the target's trajectory.

The main mirror not only focuses the killing and beacon beams on the target but images the target for tracking purposes as well. The imaging system must resolve the missile's body on a short time scale to avoid distortion by the target's motion. For instance, a North Korean Nodong-1 missile launched 200 km away from the ABL has a vertical speed of 290 m/s as it crosses the engagement plane. This is combined with the horizontal speed of the ABL of 200 m/s, assuming it is flying perpendicular to the direction of the Nodong, to yield a total apparent speed of 350 m/s. Taking this relative motion into account, a "shutter speed" of 6×10^{-5} seconds produces an acceptable smearing of the image of two cm, a tenth of the diffraction limit of the main beam. This integration time is too small to be able to rely on ambient light, even in full daylight. Instead, multiple ancillary infrared lasers are directed at the target's body. They are most likely Nd:YAG lasers (which are solid state lasers) with characteristic wavelengths around 1.06 microns. Light from these lasers illuminates a region around the missile's nose cone, probably five to ten meters in diameter. *(Figure 2)*

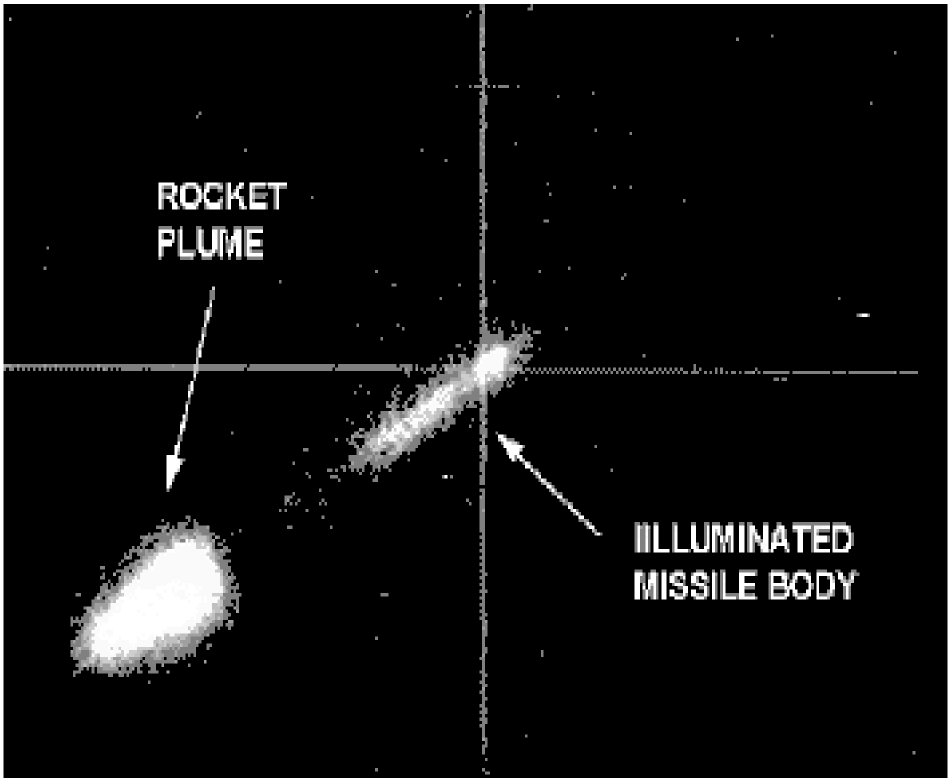

Figure 2. The ground-based SEA LITE/Beam Director imaged and tracked this Black Brant 9 missile during the summer of 1996. Final active tracking of a missile involves illuminating the nose cone region of the ballistic missile with a pulsed infrared laser. Key features of the missile are then reconstructed using pattern recognition techniques and used as input for the tracking control loops. Photo source: Phillips Laboratory.

An image of the illuminated target, formed from the 1.06 micron reflected illuminator laser light, is directed back along the main beam axis. On the same optical bench used for beam steering the dichroic mirror transmits the image to the beacon beam side of the optical bench. Features of the missile, such as the point of the nose cone, are found using pattern recognition techniques. A tracking control loop uses these features to point the primary and beacon beams. Fitting to the recognized features is the only way to accomplish the required precision.

The precision needed for the final beam control is achieved using a suite of detection and tracking systems of increasing magnification and decreasing field of views. Some of these are onboard the ABL but the initial warning and direction to look must come from external systems with wide fields of view. Satellites in geosynchronous orbits are capable of viewing a large fraction of the earth's surface at once and give the initial warning of launch. This information is transmitted to the theater of operations and can be used to direct more precise tracking systems in the general direction. Radar carried by other aircraft, such as AWACS or the newer JSTARS surveillance air planes, is a possible source for narrowing the possible directions to the launch site.

These coarse tracking systems pass their information to the suite of detectors onboard the ABL. Several small infrared telescopes, with diameters similar to those commonly used by amateur astronomers, are mounted along the body of the 747. The tracking system uses these for the initial onboard infrared detection of the target missile's plume. They have a much wider field of view than the primary mirror when it is used for tracking, probably 2^o x 2^o. The width of this field of view is about four times the diameter of the full moon.

As mentioned above, the optical train for the primary laser runs the entire length of the 747. There will be low-power secondary lasers used to align the optics over this length. Alignment lasers will probably also be used to establish a reference direction between the separate acquisition telescopes and the primary mirror. Other low-power lasers will presumably supply the reference beams for internal adaptive optics. These are particularly needed for compensating for thermal distortions inside the COIL itself.

There is a very sophisticated sensor for diagnosing the shape of the returned beacon light. The same dichroic mirror used to inject the beacon beam into the primary laser's axis splits off the returned beacon light for this analysis. A fast computer must then calculate the proper shape for the deformable mirror.

Complex, state-of-the-art equipment is required, all of which must function nearly perfectly in a combat environment. Even when all the systems do function perfectly, the ABL must overcome substantial difficulties presented by the environment. Several of the most important of these atmospheric phenomena, and the methods that can be used to overcome them, are presented in the next section.

Up in Thin Air

Cloud cover is a very serious drawback to laser missile defenses. While not a serious detriment to radar, clouds completely screen a missile from a laser. They do this in two ways. First, the ABL cannot optically track the missile through dense clouds. It must instead wait until the missile has gained enough altitude to show above any clouds that might intervene. Only then can the tracking algorithms start to lock onto the target. Expectations from high-altitude balloon experiments sponsored by Phillips Laboratory in New Mexico suggest that this might take several precious seconds. Second, clouds thin enough to allow the missile's plume to be visible might interfere with the high-energy laser. It is possible to "burn" through clouds of water droplets given enough time. However, the ABL is constantly slewing the beam through new clouds as it tracks the missile. Even if the laser could burn through the cloud cover it would deposit so much energy in the atmosphere as to induce serious changes in the air's optical properties. This is an example of thermal blooming, one of the difficulties intense laser beams face in propagating through even clear air. Thermal blooming, together with atmospheric turbulence (the other important propagation phenomena), lowers the effective beam intensity. This has the effect of decreasing the range of the ABL.Both phenomena are discussed in greater detail below.

Flying the ABL above most of the clouds mitigates both problems, allowing the laser to start firing horizontally at the missile. There is a well-established height below which most clouds occur. This corresponds to the tropopause, the boundary for convective circulation in the lower atmosphere. Clouds stop at the tropopause because the humidity associated with them cannot be transported higher. The nominal ABL cruising altitude of 12.9 kilometers is above the tropopause in most latitudes. There are still cases, however, when clouds have been observed above this boundary. Also, the tropics have a much higher tropopause of nearly 18 kilometers. Some potential ABL theaters of operation, such as Iraq or Libya, border the tropics and might have a greater incidence of high-altitude clouds. It is conceivable that the country starting a conflict with the launch of ballistic missiles could choose the time to maximize cloud height and avoid ABL engagements.

Even clear air attenuates, or reduces, the power of the laser beams. The mechanisms for doing this vary with the wavelength of the light. Absorption and scattering by aerosols, chiefly water droplets, dominate the wavelengths associated with the ABL lasers. When a water droplet scatters light it removes energy from the beam. This is a relatively benign process since it merely diminishes the delivered power density, measured in megawatts per square meter. Absorption of the light starts a much more pernicious nonlinear effect. The energy lost to the beam by absorption heats up the column of air the beam is passing through. Since the column is being heated nearly uniformly along its length the air must expand radially outward. Radial migration of molecules along the beam produces a drop in the density of the air on the central axis. Over the hundreds of kilometers that the beam must travel a significant lensing effect can build up, known as thermal blooming. This causes the beam to diverge and dilutes the delivered power density at the target.

There are several factors that affect thermal blooming, the most important being altitude and crosswinds. The net effect of increasing altitude of any point along the laser beam's path is to decrease the size of the thermal blooming. This is because the aerosol content of the atmosphere, and therefore the absorption of beam energy, is larger at lower altitudes. Crosswinds blowing perpendicular to the beam's direction also mitigate thermal blooming. They effectively blow the heated, expanding gases out of the beam. High-speed crosswinds can be very effective at reducing the degrading effects of thermal blooming on the beam. Slewing the beam in following the missile's trajectory has the same desirable effect as crosswinds but is less effective near the aircraft. Obviously, the aircraft's motion can play a large role in determining the magnitude of the crosswinds.

Consider a hypothetical engagement between the ABL and a North Korean Nodong-1 missile launched at Japan. The ABL would most likely be flying parallel to the North Korean coast, but approximately 90 km out into the Sea of Japan to avoid surface-to-air missiles. A

Nodong launched toward Japan would fly over the ABL, coming from a direction perpendicular to the ABL's flight path. In this case, the beam is fired to the side of the ABL and the air stream, with a speed of 200 m/s. This crosswind is fairly efficient at reducing the effect of thermal blooming to an acceptable level. The author's calculations show that in this engagement geometry thermal blooming would reduce the peak beam intensity by roughly a factor of ten.

If the Nodong-1 was "fortunate" enough to launch during the brief period when the ABL is making its turn, at the end of the figure eight, thermal blooming would be considerably worse. The air stream is not blowing the heated gases out of the beam but along it. Only the slewing motion of the beam as it follows the target introduces a "crosswind". This motion is ineffective at mitigating thermal blooming, with the author's calculations showing a reduction by a factor of a thousand in the peak intensity.

Turbulence is the remaining significant atmospheric effect on laser beams. This is not the turbulence associated with the plane's motion through the air, but rather the turbulence associated with slight fluctuations in temperature at different positions. These fluctuations generate small volumes of expanding or contracting air. Atmospheric turbulence produces the twinkling of stars and the waving of images of distant objects in the desert.

The size of these turbulence cells increases with altitude as the atmosphere becomes more homogeneous. The author's calculations suggest that typical average cell diameters along the laser beam are 30 cm. As with thermal blooming, these regions have different indices of refraction. These variations cause the light rays passing through them to be minutely bent in random directions. If the turbulence cells are smaller than the laser-beam diameter (1.5 meters as it leaves the main mirror) the beam is dispersed. It is possible to have so much dispersion that the beam breaks into multiple separate smaller beams. If this happens, adaptive optics based on deformable mirrors cannot correct the beam.

As a rule of thumb, turbulence decreases with altitude. The model of the atmosphere the author used has a completely homogeneous atmosphere above 20 km and therefore no turbulence above that height. But there can be large fluctuations on a day-to-day basis and also possible latitude dependencies. Phillips Lab ran a series of experiments, known as ABLE ACE, to measure these fluctuations as well as geographic dependencies. Two aircraft flew at separations up to 180 km and measured the atmospheric distortions on a low-power laser beam. These planes measured the beam distortions over the United States and also deployed to South Korea and Japan to measure the distortions there.

Directing the beam slightly upward reduces the amount of the turbulence dispersion. Thus, a given engagement will have a characteristic average turbulence cell size. This length, called the coherence diameter, is determined by averaging the cell sizes at every point along the light path. A larger coherence diameter means a smaller dispersion of the beam. The effective actuator spacing on the deformable mirror inside the ABL's control optical bench should be smaller than the coherence diameter. Typical ABL engagements require only several hundred actuators to correct the beam, well within the capability of the current state-of-the-art. MIT Lincoln Laboratory, for one, has already used deformable mirrors for turbulence compensation with 241 actuators.

As was stated above, the ABL must direct the adaptive optics beacon in front of the killing beam. The beacon beam originates from a pulsed laser. This implies that the shape of the deformable mirror is determined by turbulence slightly different than that encountered by the killing beam. Increasing the beacon pulse repetition rate reduces the beam dispersion caused by not using the instantaneous corrections. These considerations require that the beacon laser pulses several thousand times a second. This is not a problem since Nd:YAG lasers have run in pulsed mode with repetition frequencies far greater than this. It does require some sophistication to avoid range ambiguities when there are multiple pulses in the air at once.

Once the beam has been propagated through the atmosphere to the missile we must consider how it interacts with the missile's skin. It is also important to determine what happens to the missile system as a whole. There are areas on the missile that are surprisingly resistant to laser defenses. Fortunately for understanding the ABL's effectiveness, there are examples of missiles or space launch vehicles failing in circumstances similar to ABL engagements. The next section discusses these matters in detail.

Doing Damage

The goal of the ABL is to do maximum damage to the ballistic missile with the laser's beam. All the damage must be done in the short time the missile is visible under power. This requirement will become apparent from an examination of accidents where missiles failed in circumstances similar to ABL engagements. It should be made clear at the start what the beam does not do. It does not vaporize or even melt the missile's skin. Instead it heats the skin until whatever internal forces present cause the skin to fail. This failure can be either a rupture caused by internal pressure or a collapse due to axial compressive loads.

As an example, according to the author's calculations, the maximum beam intensity focused on the surface of an Al Husayn missile (an Iraqi variant of the Soviet SCUD-B), when it is launched from 350 km from the ABL, is approximately 2 MW/m^2. A highly reflective skin might absorb only 0.2 MW/m^2. At this power density it would take 40 seconds to melt a small patch on the missile's 1 mm thick steel skin. However, the Al Husayn is only under power for 27 seconds above the engagement plane at this distance. Instead, the beam can heat the missile's skin to approximately 460^o C, at which point the structural strength of the steel drops dramatically. It takes the beam roughly 17 seconds to heat the skin up to this "rupture" temperature. Increasing the thickness of the skin increases all these dwell times. Obviously the actual kill mechanism will be very dependent on the details of missile's structure.

The Al Husayn is a direct descendant of the German V2 from the last World War. The missile programs of the former Soviet Union, China, North Korea, and Iraq could all trace their origins to the same designs. This has resulted in theater ballistic missiles with very similar characteristics. Potentially hostile third world countries currently deploy liquid fueled missiles with metal skins doubling as the walls of the fuel tanks. It is known that the SCUD variants, including the Al Husayn, do not have internal structural members, at least over most of their body length. The missile skin must support all the axial loads encountered during its powered flight. It must also withstand the lateral forces of being transported across rough terrain via a specialized truck (known as a Transporter, Erector, Launcher, or TEL).

Designers of the SCUD solved the problems posed by these forces by constructing the missile out of steel. The thickness of the steel varies between one and two millimeters. Structural compositions of more advanced designs, such as the North Korean Nodong-1 missile, are not known with any certainty. Several analysts have suggested that the

Nodong-1 is made from steel perhaps three to four millimeters thick. They based these estimates on assumptions about the evolutionary process of missile development and published reports for the Nodong range. Uncertainty in the details of a missile's design lead to uncertainties in estimating the effective range of the ABL. These uncertainties exist in both this analysis and the decisions made by battle management officers on board the ABL.

The details of the missile skin, including the surface roughness and even the paint color, determine the ABL's kill mechanism. Videos of ground tests against SCUD-like fuel tanks show the laser beam quickly separates paint from the missile's surface. In flight, the air stream would remove any remaining paint chips. These could otherwise act as a protective barrier shielding the missile surface. The bare steel surface is then heated up to roughly 460^{o} C. At this temperature the structural strength of steel drops dramatically. Either of two possible kill mechanisms, discussed below, can then occur. But both depend on the laser being directed at a relatively weak portion of the missile. The nose cone, containing the warhead, is usually both strengthened and thermally insulated to survive its atmospheric reentry during the descent. These make it a hard target for the laser. The region around a liquid-fueled rocket engine usually has considerable internal structural supports. The SCUD-B, for instance, has what appear to be massive U struts inside the skin. These support the engine and transmit its thrust to the rest of the missile. They make the engine also a very hard target to attack with a laser beam. The fuel tanks, which make up the majority of the missile, are the weakest structural members and will most likely be the primary target of the laser.

One possible kill mechanism utilizes the internal pressure of the fuel tank to blow a hole in the missile's side. Most liquid-fueled missiles maintain a pressure inside the fuel tank of between 130 and 200 kPa. This helps assure a constant fuel rate into the turbopumps feeding the combustion chamber. It is sufficient to heat the missile skin up to the critical temperature, 460^{o} C for steel and 182^{o} C for aluminum, to cause the fuel tank to rupture. *(Figure 3)*

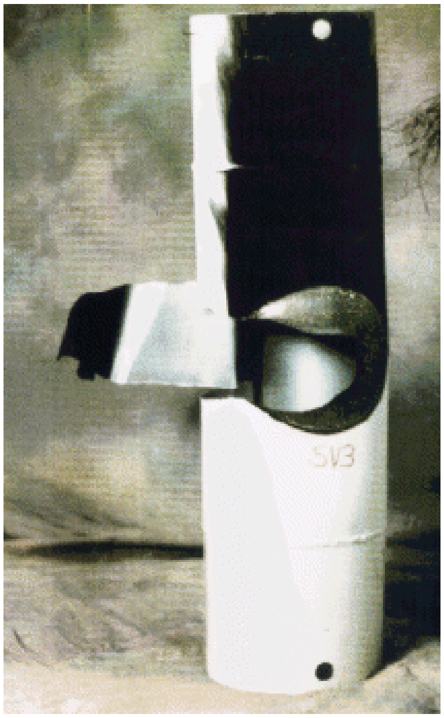

Figure 3. The ABL's missile kill mechanism has been studied in ground tests. Here, a steel vessel similar in dimensions to a SCUD fuel tank is shown after such a test. The laser beam first removed the paint covering the simulated missile. Soot from the paint is visible above the region of exposed metal. Then, the laser heated up the metal skin to the point where the internal pressure caused the tank to rupture. A vertical crack formed first, suggesting failure due to hoop stress. Immediately afterward, the flap, visible on the left, "unzipped." The laser has been dithered in a circular pattern to produce this large region of effected skin. In powered flight, the missile would almost certainly have collapsed after the laser produced such a large hole. Photo source: Phillips Laboratory.

The second possibility is having the axial compressive load collapse the missile. This kill mechanism results in the immediate destruction of the missile. There are two sources of this axial load. Atmospheric drag exerts a large force on the missile, particularly as it passes through the sound barrier. An Al Husayn missile typically passes through Mach one 30 to 40 seconds into its powered flight. This corresponds to five to seven kilometers in altitude. The second source is the inertial load originating from accelerating a large mass. Again using the Al Husayn as an example, the acceleration of the missile increases as it gains altitude. The acceleration of the single-stage Al Husayn reaches a maximum of seven G's just as it burns out. As will be seen below, these forces will make it possible to catastrophically destroy the missile if the laser weakens a sufficiently large arc on the missile's circumference.

Both these possible scenarios depend on the amount of absorbed beam energy. Bare metal with a smooth surface has a high reflectivity in the infrared. Theoretical calculations put the maximum reflectivity, depending on the metal, at more than 90%. However, a metal's reflectivity drops as the laser heats it, causing the electrical conductivity to decrease. Surface roughness also decreases the reflectivity. The calculations used in this study assume a constant 90% reflectance throughout the engagements. This approximates a worst-case scenario. The biggest variation in missile hardness arises from the rupture temperature. Steel, a material commonly used in third world theater missiles, requires almost five times the dwell time as a comparable thickness of aluminum.

One thing that is certain is that a metal-skinned missile will not explode when ruptured. There are several cases where missiles' fuel tanks have ruptured at high altitude. These suggest what would happen during an ABL engagement. The best-known case of fuel tanks rupturing during flight is the Space Shuttle Challenger disaster. As most people are aware, a rubber O-ring failed in a Solid Rocket Booster (SRB) during the Challenger's January 28, 1986 launch. Blow-through of hot combustion gases eventually burnt a hole 24" x 15" in the side of the steel booster. It also burnt a hole in the adjacent liquid hydrogen chamber of the large external tank. Far from causing the explosion of the spacecraft, the venting liquid hydrogen cooled the SRB plume. Liquid hydrogen continued to vent directly into the hot gases of this plume for at least twelve seconds before the Challenger disintegrated. The ABL's laser beam will not cause an explosion if the SRB's plume did not.

The final destruction of the Challenger, at approximately 14 km altitude, resulted when the SRB burned through its aft support structure. This freed it to bodily crash through the liquid oxygen vessel at the top of the external tank. After this, both solid fueled rockets continued in separate stable flight for approximately thirty seconds until the range safety officer issued their destruct commands. The presence of a large hole leading directly to the combustion chamber did not cause this unguided rocket to become unstable.

Another accident involving the rupture of a missile occurred on August 2, 1993. A Titan IV developed a hole in the side of one of its two SRBs at approximately 28 km altitude. This accident was unrelated to O-rings. The hole widened over a two-second interval enough to considerably weaken the structure. Automatic range-safety charges detected the bowing of the booster and exploded. In this case, the hole must have been big enough to start the column collapse of the missile under the compressive loads present only during powered flight. This represents the best possible outcome for an ABL engagement. The collapse of the missile dramatically changed its aerodynamic characteristics. It is very likely that the missile will break up after this collapse. This is another example of where boost-phase defenses differ from terminal phase ones such as the Patriot. Missile breakup during the boost assures that the pieces will fall to earth close to the launch site, because the effects of atmospheric drag are magnified on the bulky debris. Also, far from complicating the tracking problem for the missile defense system, as they would in terminal defenses, the debris is a clear indication of a successful engagement. However, the likelihood of achieving the collapse of the missile depends on how large an arc across the missile's circumference is heated. A battle management officer deciding to try to collapse the missile will need to swing the beam back and forth across this arc. This reduces the average peak beam intensity and therefore increases the required dwell time to heat the larger area to the critical temperature. A lowered peak intensity implies a reduced range for this kill mechanism.

Even rupturing a simple hole in a fuel tank can greatly affect the missile's range. There will be a considerable loss of fuel out the side of the missile with a resulting decrease in range. The loss of pressure also means that the turbopump will not be efficient in pumping the remaining fuel to the engine. Additionally, if it is the fuel tank—as opposed to the oxidant tank—which is ruptured, the engine could run hotter and eventually melt. There was evidence of this occurring in the Challenger main engines.

The Bottom Line

In a typical engagement the ABL starts firing its main laser horizontally and follows the missile upward. It must inflict damage on the missile while the missile is still under power. Typically, it will have 20 to 30 seconds to do this. The ABL is imaging the missile as it is firing the main laser at it. Catastrophic collapse of the missile, possible at reduced ranges, will be easily recognizable. Battle management officers will have a harder time assessing engagements that rupture the fuel tanks. It seems likely that in these more ambiguous engagements the ABL will continue to fire at a missile until it burns out. Failure to at least rupture the fuel tanks during this limited time will not affect the missile's range. This stringent timing requirement restricts the range of the ABL because of the curvature of the earth.

Missiles launched from sites far from the ABL spend more of their time under power below the ABL's engagement plane. This plane is an imaginary sheet spreading out horizontally from the position of the ABL. It represents the lowest point that the ABL can start to fire its main laser, either because of clouds or atmospheric dispersion of the beam. The earth's surface curves away from this plane as the ground distance increases. Consider for instance an Al Husayn missile launched in the most favorable geometry with the missile approaching the ABL. In this case, an Al Husayn launched from a distance of 720 km from the ABL crosses the engagement plane just as it burns out. This phenomenon sets an upper limit on the ABL's range, even if one that is dependent on the type of missile engaged.

In practice the ABL's range will be considerably shorter than this maximum because the beam intensity drops with distance. As the distance between the ABL and missile increases, unavoidable diffraction effects increase the minimum size of the beam spot on the missile's surface. In the example mentioned above, the diffraction limited beam spot size on the Al Husayn launched 720 km from the ABL is 71 cm. Beam jitter from pointing and tracking errors plus atmospheric effects will make the actual beam spot larger than this value. Thus diffraction lowers the power density at the missile's skin and increases the required dwell time. Atmospheric transmission effects discussed above also lower the beam strength. Such beam quality degradation further increases the required dwell time. The maximum range is reached when the increasing dwell time equals the decreasing time the missile is under power above the engagement plane. Firing times on the order of 20 seconds are not atypical for the longest-range engagements. These engagements will not occur over the theoretical maximum distance of 720 km but at the range where the dwell time equals the missile's time above the engagement plane. Experience with the ALPHA high-energy laser, operated by Science Applications International Corp. (San Diego, CA) at the San Juan Capistrano range, suggests that the optical train can withstand the heat associated with such long operations. The ALPHA laser is a Hydrogen Fluoride chemical laser operating at wavelengths between 3.6 and 4 microns. This difference in wavelength is not a factor when comparing the heating of the optical trains for these two different systems.

The amount of time a missile type spends above the engagement plane depends on the characteristics of its trajectory. For instance, engines for both the SCUD-B and Al Husayn are believed to deliver the same thrust of 35 kN. Time spent above the engagement plane will, however, be different for the two missiles. Before the Gulf War, the Iraqis modified the Al Husayns to carry more fuel and therefore have a longer burn time. A typical SCUD-B has a powered flight time of 75 seconds while the Al Husayn has a 90-second burn time. The Al Husayn burnout altitude of 50 km is also higher than the SCUD-B's burnout altitude of 32 km. Both factors contribute to the greater range of the ABL against Al Husayn missiles as opposed to SCUD-Bs.

There is a tradeoff between the ABL's maximum range and how effective the laser is at stopping the missile. As discussed earlier, it is possible to cause the collapse of a missile by weakening enough of its circumference. Unfortunately, the uncertainties associated with exactly how much of the surface to illuminate are very large. If the missile has no internal structural support then heating an arc of 45° to the rupture temperature should cause the missile to collapse. This involves swinging the beam across the missile's diameter more than natural jitter or beam spread would normally cause. Required dwell time increases with the consequent decrease in range. *(Figure 4)* Furthermore, the increase in dwell time is missile-specific. Missiles with larger body diameters will require more dwell time than thinner missiles at the same range. This is because the beam spot size is the same but must heat up more material for the same fraction of the missile's circumference. The calculations presented here assume that the ABL must heat a 45° arc on the missile's circumference to the rupture temperature before the missile will suffer a catastrophic failure.

The start of a ballistic missile's powered trajectory consists of a brief near-vertical rise. After the missile has gained sufficient speed its thrust is directed to one side, initiating its gravity turn toward its destination. A theater ballistic missile's powered trajectory typically extends 40 to 50 km down range. This will affect the laser beam's delivered power density since the distance between the missile and the ABL is changing. The importance of this effect is smaller than other factors that also depend on the engagement geometry. An example of one of these factors is the increased aspect angle the missile presents to the ABL when engaged from the side. Tail-chase geometries, where the missile is fired away from the ABL, have factors compensating for the increasing range: the apparent angular velocity of the missile is lower in these engagements, which helps in turbulence compensation. The author's calculations show that as a result, the ranges associated with theater missile engagements are the same in all directions to better than 10%.

Strategic missiles, on the other hand, can travel 600 to 700 km down range while still under power. This will have substantial effect when the ABL is down range from the ICBM launch site. The author has studied engagements between an ABL and an SS-18, assuming a

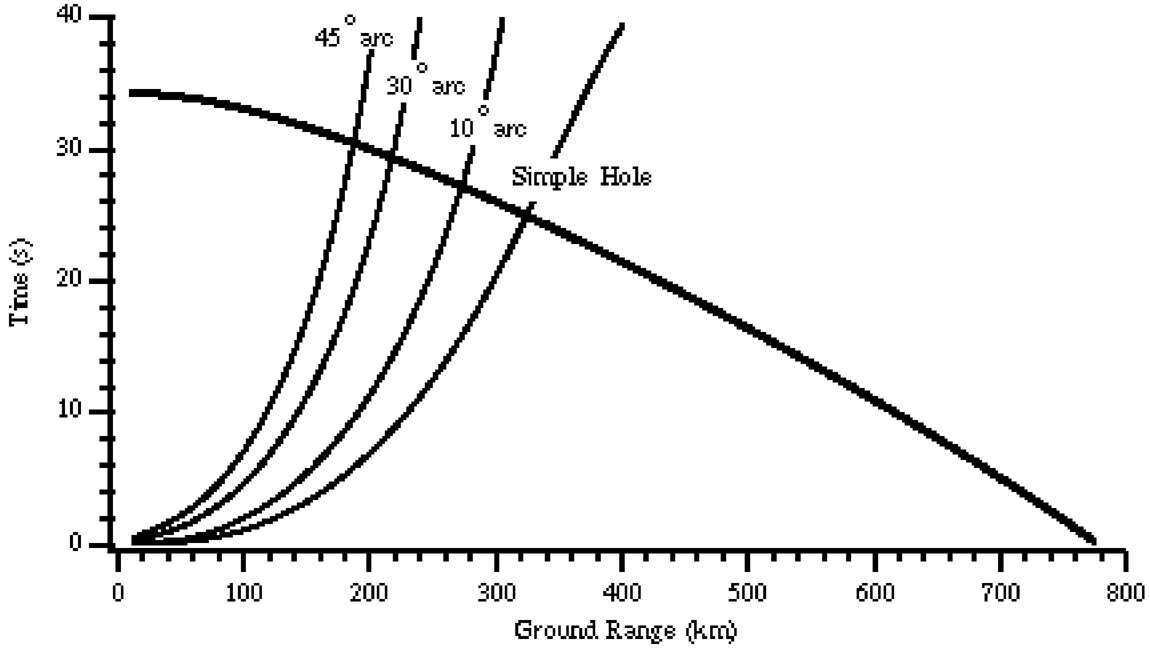

Figure 4. The time a missile (in this case, a Nodong-1) is visible to the ABL under power, dark line, decreases as a function of the distance between the ABL and the launch site. Concurrently, the dwell time required to heat the missile skin to the rupture point increases with distance. Maximum range of the ABL, when these curves cross, will depend on the amount of the missile's circumference that must be heated to the rupture point. Four possible requirements are shown, including the rupture of a simple hole, a 10^0, a 30^0, and a 45^0 arc of the missile circumference.

trajectory similar to a Titan II missile and two mm thick aluminum skin. Based on these studies it appears that the ABL can shoot down an SS-18 launched from over 1000 km away in eight seconds or less dwell time. It would appear that the best strategy for the ABL is not to try to cause catastrophic failure of the ICBM because of the missile's internal support structure. Presumably, the ABL would try to terminate the SS-18's thrust early by simply rupturing its fuel tanks. It is extremely doubtful, however, that the large 747 carrying the ABL could penetrate the air defenses and remain on station within 1000 km of an SS-18 launch site.

Theaters of Operation

Various ABL theaters of operation are possible including North Korea, Libya, Iran, and even Iraq. The North Korean example is particularly interesting considering the recent information filtering out to the West about possible production of weapons of mass destruction. Ballistic missiles would represent both tactical and strategic assets in a Korean conflict.

Tactically, North Korea could use its SCUD-C (roughly equivalent to the Al Husayn) to attack airfields in the South. A biological or chemical attack against these airfields would considerably reduce the air sorties the U.S. and South Korean Combined Forces Command (CFC) could launch against tanks moving south. A single ABL flying over the Sea of Japan could rupture the fuel tank of a SCUD-C launched from anywhere in North Korea, while it could cause catastrophic failure of a launch over most of North Korea.

North Korea could also use its long-range Nodong-1 to threaten Japan. Such a threat would possibly deter Japan from allowing the CFC use of air bases on Japanese soil. Two ABLs flying over South Korea and the Sea of Japan can rupture the fuel tanks of a Nodong-1 launched from most sites in North Korea. (*Figure 5)* They would not be able to cause a

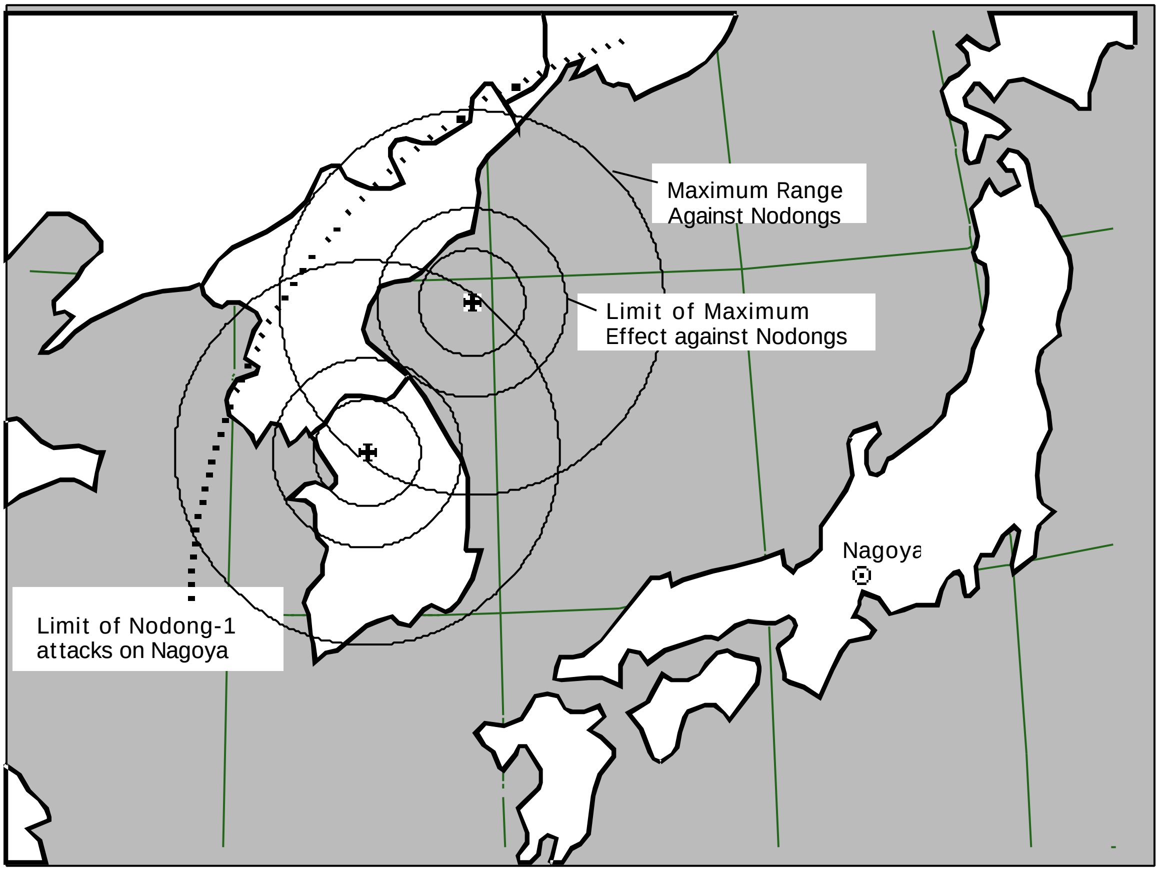

Figure 5. The Korean peninsula represents the optimum geography for using the ABL missile-defense system. North Korea is a small country accessible on three sides. A two-ABL defense deployment against possible Nodong-1 attacks of Nagoya, Japan is shown. Each billion-dollar aircraft is positioned outside the range of surface-to-air missiles. Most of North Korea is covered at a level sufficient to rupture the Nodong's fuel tanks and terminate its thrust early. However, only launches from a very limited region near the coasts would allow the missile's catastrophic failure.

catastrophic failure of a Nodong except in those rare cases when the launch occurred very close to the North Korean border. With its thrust terminated prematurely, the Nodong would most likely crash in the Sea of Japan.

North Korean geography is very favorable for ABL use. It is a small country on a peninsula. This makes it potentially possible to station ABLs on three of North Korea's borders. Other, larger countries have geometries less favorable for this airborne missile defense system. There are reports that Iran is interested in purchasing the Nodong-1 missile from North Korea. Iran could launch Nodong attacks against Tel Aviv from its far western edge. Here the ABL would be a completely ineffective defense when stationed over either Turkey or the Persian Gulf. The Iranian launch sites are out of range of both positions. *(Figure 6)*

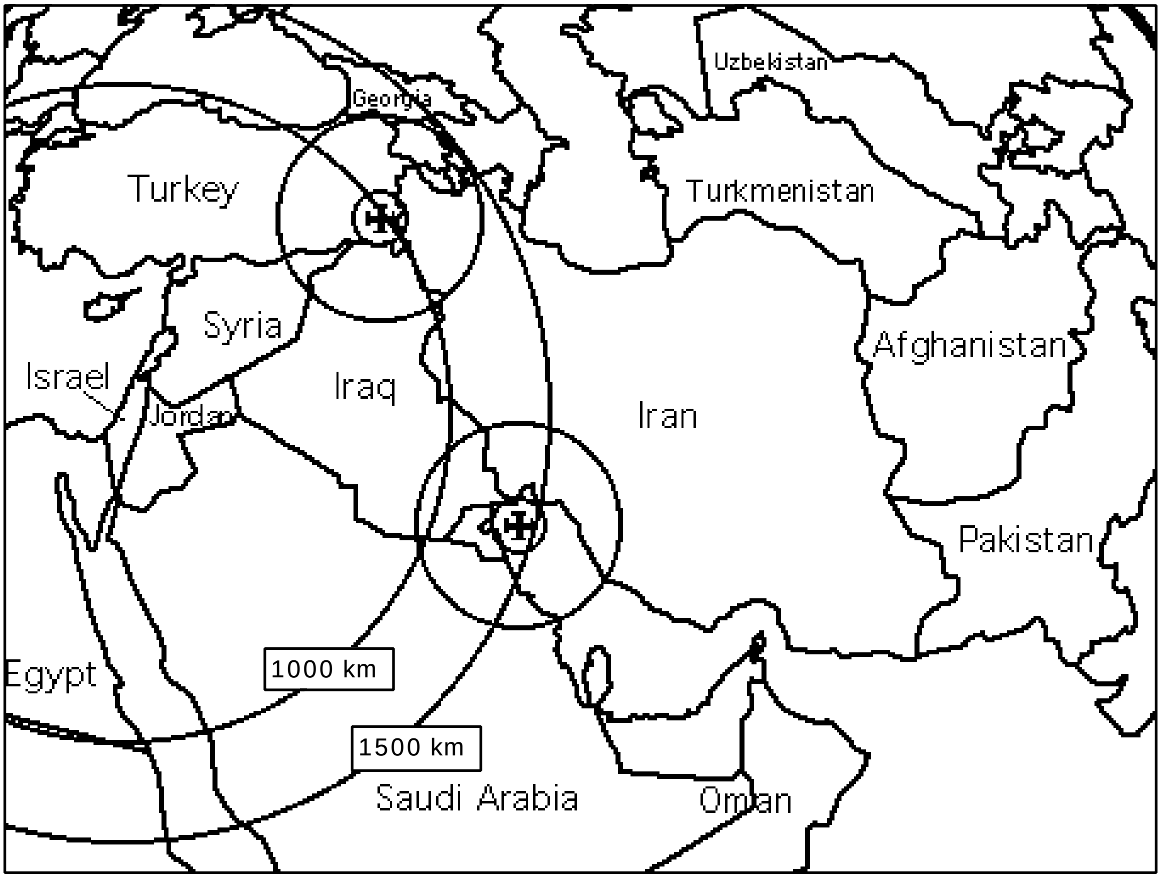

Figure 6. Recent reports suggest Iran might be trying to purchase Nodong-1 missiles from North Korea. Iran could launch these 1000 km-range missiles at Tel Aviv from its the western borders. Simulated engagements between the ABL and the Nodong showed that a laser defense system flying over either Turkey or the Persian Gulf could not prevent these attacks. Longer-range missiles provide even more sites inside Iran that would be safe for launching.

So far, only engagements between the ABL and current Third World missiles have been considered. There are countermeasures that unstable nations could take and possible counter-counter-measures. It is important not to fall into the fallacy of the last move. The ABL, as it currently is envisioned, is an effective defense against today's limited ballistic missile threats. *(Table 1)* Threats developing in the future, from Iran or Libya for instance, will require different platforms for a laser defense. The most likely is a space-based laser system with all the ABM treaty implications that entails.

Missile Name	Missile Range	Missile Burn Time	Missile Diameter	Missile Skin Type/ Thickness	ABL Range for Decisive Engagement	ABL Maximum Range
SCUD-B	300 km	75 s	0.84 m	1 mm/Steel	240 km	320 km
Al Husayn	650	90	0.84	1 mm/Steel	320	470
Nodong-1	1,000 (?)	70 (?)	1.2 (?)	3 mm/Steel (?)	185	320
ICBM (SS-18 like)	10,000	324	3	2 mm/Al	_____	> 1,000

Table 1. This table lists the results for engagements between an ABL and four types of missiles together with the relevant missile parameters. Decisive engagements require a 45^0 arc of the missile's circumference to be heated to the rupture point.

Appendix

Adaptive Optics

Adaptive—or active—optics is a new discipline designed to improve the performance of a wide range of optical devices in real time. This real-time requirement separates it from image processing, whose goal is to improve an existing image's quality. Two examples make this difference clear. Early images taken by the Hubble Space Telescope, before it was repaired, can be processed to partially correct for the imperfect optical elements. This is possible to do here on earth after careful study of the distortions produced on a number of point sources of light. These determine the proper mathematical corrections to be applied to all the other digitized images. On the other hand, active optics on ground-based telescopes has been used to correct the constantly varying random fluctuations induced by the atmosphere. The key to making these real-time corrections is having a reference source of light.

The light radiated from an ideal point source can be characterized by concentric spherical surfaces. Each shell, or wavefront surface, represents a region in space where the electromagnetic radiation has the same phase. A line drawn perpendicular to the wavefront at any given point represents the axis of propagation for the light wave. This is true for spherical wavefronts and wavefronts of light distorted by passing through a nonhomogeneous medium. Small scale turbulence in air, arising from slight random variations in temperature, leads to varying indices of refraction.

Two spatially separated, parallel light rays will experience different variations in the index of refraction as they travel over hundreds of kilometers through the atmosphere. At the end of their journey, the phases of the two rays will be slightly shifted. The shifted phases define a wavefront that is slightly tilted from its original direction. Consequently, the "wave" these two rays form will start to propagate along a new, randomly shifted direction. Additional adjacent waves will diverge in other directions. This causes either a blurring of the image, if the device is a telescope, or a broadening of the beam spot from a high-energy laser.

In the worse cases, a beam may be totally broken into hundreds of separate spots. Phase-only adaptive optics cannot correct this extreme process, known as "scintillation." If, on the other hand, the dispersion is mild, then reflecting the light off a purposely distorted mirror can remove a large fraction of the distortion. This is possible because differences in phase arise not only from variations in the index of refraction but also from differences in path lengths. A properly distorted mirror can allow a ray whose phase is lagging behind to catch up by causing other rays to travel longer path lengths. A telescope using adaptive optics will receive an irregular wavefront and reflect it off a "flexible" mirror. The result will closely approximate the ideal spherical surface. A high-energy laser pre-distorts the outgoing beam and lets the atmosphere "correct" it to produce a well-focused spot at the target.

Again, the key to real-time corrections is having a reference beam travel the same optical path the light from the image or laser will traverse. The ground-based telescope creates its own artificial point sources, or guide stars, by reflecting a monochromatic laser beam off the sodium layer high in our atmosphere. These guide stars are essentially point sources that should, in a vacuum, have a spherical wavefront. A special sensor, such as a Hartmann sensor, breaks up the received wavefront into small segments and determines the local “tilt” of the beam in each. The complete wavefront is then reconstructed and used to determine the shape of the mirror surface that would compensate the phase differences. The time scale of changes in the atmospheric turbulence is long enough to allow old corrections to be used while the new ones are being determined. The wavelength of the laser guide star is filtered out of the astronomical image. A similar technique is used for the high-energy laser. But instead of reflecting light off part of the atmosphere a pulsed laser is focused on the missile’s body.

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