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The Airborne Laser from Theory to Reality: An Insider's Account

by Hans Mark

Introduction and Scientific Background

Albert Einstein spent World War I in Berlin, where he developed a theory that described electromagnetic radiation in equilibrium with atoms that could emit and absorb radiation. The innovation in Einstein's work, which was published in 1916 and 1917, was that he used the newly developed quantum theory to obtain his results. The most important result was not only that the atoms in the assembly could absorb and emit radiation spontaneously but also that atoms in certain excited states could be induced to emit radiation.[1] Einstein called this discovery the *stimulated emission of radiation.* Einstein's discovery provided the basis for the development of lasers, though the phenomenon would not be observed in the laboratory for many years.

The development of radar during World War II required intensive research in microwave radiation. The need for highly sensitive radar receivers led to isolating and observing for the first time Einstein's stimulated emission of radiation. In 1954, Charles H. Townes, J.P. Gordon, and H.J. Zeiger were the first to amplify a microwave signal by using stimulated emission.[2] They called their device the *maser*, which stood for *M*icrowave *A*mplification by the *S*timulated *E*mission of *R*adiation. This work led many to speculate about applying the same principles to radiation in other regions of the electromagnetic spectrum. This effort turned out to be successful, and 6 years later, a positive result was achieved with visible light.

The first *laser* (*L*ight *A*mplification by the *S*timulated *E*mission of *R*adiation) was developed by Theodore H. Maiman in 1960 at the Hughes Aircraft Corporation research laboratory.[3] To develop the laser, a material had to be found in which an assembly of atoms, most of which were in a higher energy state than the ground state (or lowest energy state) of the atom, could be created. Such a condition is called a *population inversion*. Where it exists, a light pulse can be amplified by stimulating the emission of radiation by the atoms in the higher energy state. Thus, a strong light pulse can be obtained using a small stimulus—hence the term *amplification*. Maiman found that a population inversion could be produced within certain atoms in an appropriately designed ruby rod by irradiating it with a strong pulse of light. The atoms in the higher energy states could be stimulated to emit radiation by a very weak light signal of the proper frequency, which would create a cascade that would stimulate the emission of light by all other atoms in the higher energy state, producing a strong pulse of red light.

About the same time, Ali Javan and his collaborators at Bell Laboratories discovered a way to create a population inversion in a mixture of helium, neon, and other gases.[4] The tube in which these gases were placed was irradiated continuously with light of the appropriate wavelength. A population inversion was created in the gas mixture, which created a tightly focused beam at a sharply defined wavelength. This tight focus bore out Einstein's 1916–1917 prediction. His calculations revealed that the light quanta or photons created by the stimulated emission are in exactly the same quantum state as the photon that initiated the stimulated emission. This means that all the photons in the process are moving in exactly the same direction, thus creating the tightly focused beam.

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Solid-state and gas lasers of the type described here are limited in terms of the energy that the laser beam contains because the population inversion is eventually destroyed by melting or other change in the state of the medium in which it is created. The best continuous energy both in pulsed and continuous wave beams is of the order of kilowatts. Lasers of this kind are useful for many purposes, including meteorology, bar-code scanning, and target designation. One of the most fascinating applications of a solid-state laser with energy in the kilowatt range is the lunar laser ranging experiment conducted for the past 30 years at the University of Texas McDonald Observatory. During the Apollo missions, the astronauts placed corner reflectors on the Moon that would later be used to reflect very short and intense laser pulses fired from Earth. The purpose of this experiment is to make precise measurements of the parameters of the lunar orbit. The laser can determine to within a few centimeters the position of the reflector with respect to Earth. Through these measurements, scientists have established that the Moon is receding from Earth at the rate of a few centimeters a year. What is remarkable about this experiment is that it illustrates how tightly focused a laser beam can be made so that it can traverse about half a million miles and still be intense enough for accurate measurements when the pulse returns.[5]

The lasers mentioned so far cannot be used as weapons because they lack the beam energy to cause material damage. Further innovation was required to produce laser beams with the requisite energy. Several research groups realized that producing a population inversion in a moving medium would create higher energy laser beams, because the energy generated by the process to create the population inversion (either by irradiation or combustion) could be dissipated rapidly. In 1967, Edward T. Gerry and Arthur Kantrowitz at the AVCO Everett Research Laboratory were the first to produce a good quality laser beam with a continuous wave energy in excess of 10 kilowatts. In March 1968, they succeeded in creating a laser beam at a wavelength of 10.6 microns in a supersonic flow of a nitrogen-carbon dioxide gas mixture with a continuous wave intensity of 138 kilowatts. This achievement made it possible to start thinking about the use of high-energy laser beams as weapons that would have military value.

Laser Weapons

As a result of a 1968 briefing about the high-energy laser program being carried out by the Defense Advanced Research Projects Agency and the U.S. Air Force under the code word *Eighth Card*, a subcommittee of the U.S. Air Force Scientific Advisory Board was established to study how this technology could be developed to create militarily effective weapons. In 1969 and 1970, the subcommittee (of which I was a member) met to consider possible applications of laser weapons. At one meeting, Edward Teller was particularly intrigued by the idea of what he called the *aerial battleship*—a large airplane equipped with one or more high-intensity lasers. A futuristic aircraft of this type could escort bombers to defend them from enemy attacks. The powerful airborne lasers would shoot down hostile interceptor airplanes as well as air-to-air and surface-to-air missiles, causing damage with energy traveling at the speed of light. This last point was deemed the principal advantage of laser weapons. Delivery of lethal energy with the speed of light would greatly simplify the fire-control problem. No complex calculations and guidance control solutions would be necessary to hit fast-moving targets. Since the optical system has little inertia compared to conventional guns or rockets, rapid slew rates were possible. Finally, lasers are capable of much more rapid firing rates than conventional guns or rocket launchers.

Our subcommittee began to consider Teller's idea seriously, and we looked at some concepts for a prototype. What eventually emerged from these discussions was a proposal to put a large carbon dioxide gas dynamic laser on a four-engine jet aircraft. However, lively debate developed among the subcommittee members over this proposal. One faction believed that the carbon dioxide laser would be the wrong one to use because of the known problems with atmospheric absorption for the 10.6-micron wavelength beam produced by the laser. They believed that it would be prudent to wait for the availability of a high-power laser producing a beam with a shorter wavelength and better atmospheric penetration than carbon dioxide. The other faction, to which I belonged, believed that it did not matter much what kind of a gas dynamic laser was used because the carbon dioxide laser would solve many system-level engineering and fire-control problems. Furthermore, it was not clear just when a large laser producing a short-wavelength beam would be available. Chemical lasers offered some promising candidates, but none could operate at power levels as high as a carbon dioxide laser. After some discussion, our subcommittee recommended to the Scientific Advisory Board in April 1971 that we initiate a program to put a large carbon dioxide laser on an airplane. The Board approved the recommendation, and the airborne laser laboratory (ALL) program was born.

The Airborne Laser Laboratory

While the Air Force Scientific Advisory Board was discussing the aerial battleship proposal, the Air Force itself took some action to preempt the Board. On February 3, 1971, Air Force Headquarters issued a directive calling for an accelerated demonstration program to create an airborne laser laboratory. This directive, together with the positive recommendation of the Board, provided the push necessary to get started. The proposal that eventually emerged was to modify a Boeing KC–135 tanker aircraft to accept a large carbon dioxide laser that would produce a beam with a continuous wave energy of about 500 kilowatts. The airplane would also be equipped with a fire-control system that would be sufficiently accurate to perform the proof-of-concept experiments that we had in mind.

Several large and complex technical problems had to be solved:

- The airplane had to be modified to carry the large carbon dioxide laser, and a method had to be established to mount the optical train in a flexible aircraft in such a way that the properties of the various laser beams in the system were preserved.
- An appropriate optical system had to be built to transport the high-intensity laser beam to the turret in which the large mirror of the airborne pointing and tracking (APT) system was mounted.

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■ A window through which the high-intensity laser beam would pass from the inside to the outside of the aircraft had to be developed.

■ The safe operation of the airplane with the APT turret in place had to be established.

■ A flight-weight, high-intensity carbon dioxide laser had to be built and tested and then mounted in the aircraft.

■ Perhaps most important, all of these components had to be integrated so that everything would work as a system.

The Air Force assembled an excellent team of people to manage and execute this program.[6] In addition, an extremely competent group of contractors was assembled to carry out the development, construction, and integration of the ALL system. The General Dynamics Company was engaged to modify the KC–135 aircraft and to build the turret; the optical train and APT system were built and assembled by the Hughes Aircraft Company. This job required the solution of very difficult technical problems, and several setbacks were encountered. A primary mirror broke when it could not sustain the heat load delivered by the high-intensity laser beam, and finding an appropriate material from which to manufacture the mirror was difficult. The carbon dioxide laser was built by Pratt and Whitney and thoroughly tested on the ground at an optical range near the Air Force Weapons Laboratory at Kirtland Air Force Base. The entire system was integrated and eventually operated by an Air Force team at Kirtland.

In addition to the Air Force team and the contractors, other Federal agencies made significant contributions to the program. The National Aeronautics and Space Administration (NASA) was crucial, and the NASA–Ames Research Center was in a good position to help. Ames housed test facilities that could be used to solve the turret problem and to establish the fact that the laser beam could be successfully propagated through the turbulent boundary layer that surrounds the aircraft. One of the large wind tunnels at Ames with a test section 14 feet in diameter was activated and dedicated to the program.[7] A great many turret configurations were considered, and it was determined that a fairing would be required around the turret to prevent turbulent flow that could lead to harmful vibrations. The configuration that was finally selected performed successfully throughout the test program. Another very encouraging result of the tests at Ames was that it proved possible to send the carbon dioxide laser beam through the turbulent boundary layer that surrounded the aircraft without any significant distortion. The tests performed in the 14-foot wind tunnel at Ames contributed significantly to the ultimate success of the ALL program.

When the aircraft modifications were completed in January 1973, an extensive series of test flights were conducted at Edwards Air Force Base that confirmed the wind tunnel tests performed at Ames.[8] Once the fundamental aerodynamic tests were completed, tests that involved the laser system were initiated. These involved both the ALL aircraft and target aircraft that would be used to measure the properties of the laser beams emitted by the ALL. At first, a small T–39 aircraft was used, and later another KC–135 tanker aircraft was modified to serve as the target aircraft.

The laser tests were conducted in a series of cycles beginning in May 1973 with a low-power carbon dioxide laser installed in the ALL aircraft. The first fire-control tests were completed in November 1973. Each of the cycles involved more complex tests and at the end of each cycle, progress was reviewed before the next cycle was initiated. At the completion of the second cycle, in June 1976, the Air Force High Energy Laser Review Group performed a very thorough review of the program and authorized proceeding with the remaining cycles in the program. The methodology of using periodic milestones to manage the program and then to review the results has proven to be successful in complex programs such as this one.

The ALL program culminated in May 1983 with a test series that resulted in the disabling of five Sidewinder AIM–9B missiles by the airborne lasers at a range of 3 miles. In September 1983, the ALL disabled two Navy drone vehicles (BQM–34A). These tests were proof-of-concept experiments that demonstrated that airborne lasers could bring down surface-to-air or air-to-air missiles. With the successful completion of the ALL experiments, the aircraft was flown to the Air Force Museum at Wright-Patterson Air Force Base in Ohio, where it is on static display.[9]

The Airborne Laser Program

Two technical developments revived interest in the airborne laser in the early 1990s. The first was the development of a chemical laser that could produce intense laser beams with a wavelength of about 1.3 microns. Unlike the carbon dioxide laser, which has a wavelength of 10.6 microns, the chemical laser beam is not strongly absorbed by the atmosphere. This laser works using a chemical reaction triggered by a hydrogen peroxide mixture between oxygen and iodine. The chemical oxygen iodine laser (COIL) can deliver beams of continuous-wave energy in the megawatt range. Also, at the short operating wavelength, the COIL would have a range of clear military interest.[10]

The second technical innovation since the ALL program was concluded in 1983 was the development of adaptive optics. Adaptive optics is a method for neutralizing the adverse effect that atmospheric turbulence has on the image of an astronomical telescope. The idea is to build a mirror for the telescope that is made not of a monolithic piece of glass but rather of segments that can be moved quickly by piezoelectric actuators to compensate for atmospheric turbulence. The atmospheric turbulence is measured by a pulsed laser that uses the same optical train as the telescope itself. The reflected laser signal from various segments of the path in the atmosphere is analyzed by a computer that drives the actuators to reshape the mirror to compensate for the effect of atmospheric turbulence. This method, first developed for astronomical telescopes, has been adapted for the airborne laser.

These technical developments persuaded the Air Force leadership to initiate planning for an airborne laser in 1991. In 1994, the Airborne Laser (ABL) Program was formally initiated, and in 1996, Air Force Chief of Staff General Ronald R. Fogleman announced the selection of contractors to develop the ABL weapon. The program plan called for the modification of a commercial Boeing 747–400F cargo aircraft to carry an advanced COIL. The continuous wave energy of the laser would be in the megawatt range delivered at a wavelength of 1.3 microns.

The TRW Company built and tested a flight-weight COIL in 1997. In addition, positive developments were made in the technology of mirrors and windows for the high-energy laser beam. However, the

The Airborne Laser (ABL) Program

The first ABL aircraft recently completed 21 months of major structural modifications at the Boeing facility in Wichita, Kansas. In 2002, the aircraft will make its first flight and will begin an incremental testing phase. Each individual segment of the weapon system will be tested first on the ground and then in the air. The aircraft's sophisticated battle management system will be the first to be tested. The battle management suite will enable the 747–400 freighter aircraft to detect and track boosting missiles from hundreds of kilometers away. The ABL will hand-off missile tracks to other missile defense systems or to the aircraft's beam control/fire-control system in preparation for engagement with the high-energy laser. While these airborne tests are taking place, the beam control/fire-control system and the high-energy laser will be completely checked out on the ground. The entire beam control/fire-control train is being constructed on the ground at Lockheed Martin's facility in Sunnyvale, California. At the same time, a system integration laboratory is under construction at Edwards Air Force Base, where six laser modules will be linked and tested. These systems will be integrated onto the aircraft and full system flight-testing will occur against a series of target boards on aircraft and dropped from balloons. The ABL test program will culminate in the shootdown of a boosting ballistic missile in late 2004.

Upon completion of the test program, the ABL will be available for emergency use as part of the U.S. ballistic missile defense system. Additional ABLs will be built with incremental improvements as the technology matures, exploiting developments in adaptive optics, light-weighting, chemical efficiency, solid-state lasers, and other sensors. ABL will provide a unique capability to intercept missiles during boost phase to complement the emerging U.S. capability to intercept missiles in mid-course and the existing capability in the terminal phase. As such, ABL is a critical element to a layered missile defense capability to protect forward-deployed troops and civilians.

Current program plans are to provide seven ABL aircraft that will be organized into a single squadron based in the United States. In a contingency or war, five ABL aircraft will be deployed at a single forward operating location. Once deployed, these aircraft will be capable of maintaining two simultaneous, near-continuous combat air patrols and defend against boosting ballistic missiles. ABL also will provide theater-wide surveillance against ballistic missiles and provide impact and launch point data to support active and passive defense, as well as attack operations.

The ABL role in missile defense is only the beginning for applications of this speed-of-light weapon. The Air Force is already exploring future missions for ABL and high-energy lasers. Two potential applications are protection against high-flying cruise missiles and air-to-air missiles. In addition, the Air Force Research Laboratory is exploring partnering the airborne laser with satellite mounted mirrors. Using these mirrors to relay ABL's powerful laser beam has the potential to dramatically improve ABL range.

The 30-year-old vision of Edward Teller is on the threshold of becoming a reality. A concept born in the Air Force research laboratories in the early 1970s and nurtured through two to three generations of technology evolution, is close to reality today. The Airborne Laser aircraft and its technology have been demonstrated. The remaining challenge is to integrate all the pieces into an effective weapon. Once this challenge is met, ABL will usher in a new era of weaponry for U.S. defense.

—Colonel Ellen Pawlikowski, ABL Program Director

airborne laser, like any complex development program, also experienced problems and delays. Most of these involved cost increases and the fact that developing some of the hardware components took longer than originally estimated. Perhaps the most persistent technical question was the calculation of the range of the airborne COIL at which it would have military value. The exact numbers are classified, but the issue was clear: At what range could the ABL aircraft flying at 40,000 feet destroy an ascending ballistic missile?

To support the complex range calculations, the Air Force has performed a variety of experiments on atmospheric turbulence. These included measurements performed using aircraft and high-altitude balloons, as well as experiments on the ground. Measurements were taken at many locations around the world to determine whether geographic effects could influence the effectiveness of the ABL aircraft. When these experiments were completed, the decision was made to conduct a critical examination of what was known about atmospheric turbulence in order to validate the range calculations that have been made. In November 2000, a report was issued in which some range curves were presented based on the data available from experiments at the time.

Figure 1 shows the results in terms of the ratios of the range divided by the classified range requirement in the operational requirement document (ORD) for the ABL and the ratio of the beam intensity to the kill intensity required for the classified designated target missile in the ORD. The horizontal lines across the graph indicate the exposure time necessary to achieve the kill. The four curves show what happens with no atmosphere (which follows the inverse square law), for an atmosphere with average turbulence, and for atmospheres having half and twice the average turbulence levels as determined by the experiments. What this picture shows is that at the ORD range, the ABL aircraft could kill the missile defined in the ORD with an exposure of a little more than 1 second under average conditions of atmospheric turbulence. The actual numbers are still classified, though they clearly are of military interest. These results would not have been possible without the existence of adaptive optics and the COIL.

Another important series of experiments has just been concluded at the White Sands Missile Range. An optical range there has a 30-mile path length and a low-power, solid-state laser situated on a mountain (North Oscura Peak) that can be aimed at aircraft with appropriate measuring devices flying within the range. The laser has a simplified adaptive optical system similar to the one that will be installed in the ABL aircraft. Two important experiments were performed in the past 3 years at this facility. One was to demonstrate that the fire-control system intended for the ABL can find and track an uncooperative target aircraft. The second was to measure the effect of various levels of atmospheric turbulence on the laser beam to see how adaptive optics improves the situation (figure 2). The measurements have a large standard deviation for two reasons: the turbulence level at the altitude of North Oscura Peak (7,000 feet) is much higher than it is at the altitude where the ABL aircraft will operate, and some systematic errors in the experimental equipment contributed to the statistical errors.

Other significant progress has been made in the area of component development. The most important is the development of a very high-capacity pump to supply the oxidizer (hydrogen peroxide) for the combustion chamber of the COIL. This was a difficult problem to solve because the effervescent properties of hydrogen peroxide make pump cavitations more likely. Although so far this is an example of a success story, the major problems in complex programs such as this one almost always arise in the integration phase of the program, when successfully tested components are assembled as a system. Thus, more problems probably will arise before the first missile shootdown is demonstrated in 2 or 3 years.

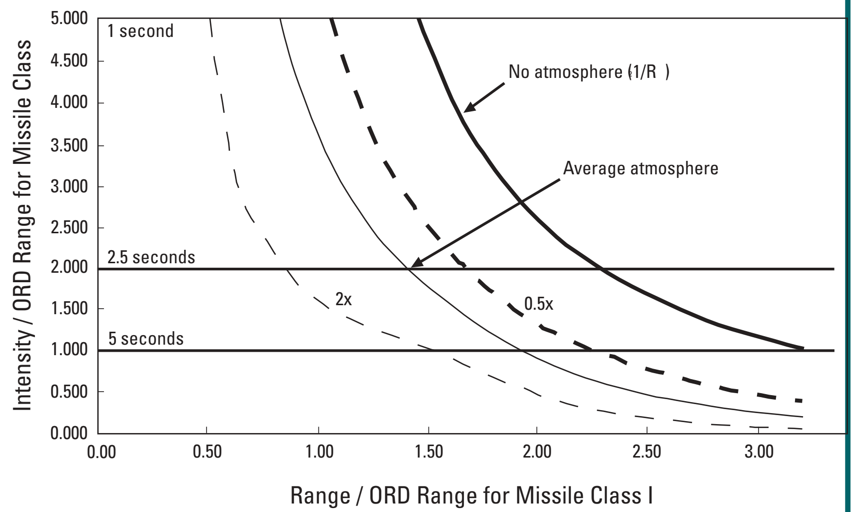
Operational Concepts

The initial idea was for an aircraft armed with an airborne laser to act as an escort for other warplanes. The capability to disable air-to-air missiles demonstrated in the 1983 tests constituted a proof-of-concept test for missions of this kind. These experiments were carried out in the same spirit as the bombing tests against warships conducted by General Billy Mitchell in 1921. What was accomplished was to prove that a large laser could be mounted on an airplane and that the fire-control problem could be solved. A laser-armed aircraft could be built that could shoot down hostile air-to-air or surface-to-air missiles threatening a group of aircraft. The laser weapon could also be used to shoot down hostile aircraft threatening to attack the formation escorted by the ABL aircraft. Both air-to-air missiles and interceptor aircraft are fairly soft targets for the airborne laser weapon, so kills could be performed at relatively long ranges. The scenarios described so far are essentially offensive ones that call for the protection of aircraft flying into hostile territory. Defensive applications also might be considered. Airborne laser aircraft could be deployed to prevent the overflight of hostile aircraft. Patrols by ABL aircraft over friendly territory would provide an effective defense. Thus, Edward Teller's vision of an aerial battleship would be realized.

Another mission that has been proposed for an airborne laser is to shoot down ballistic missiles in the boost phase. In 1981, I proposed that a fleet of ABL

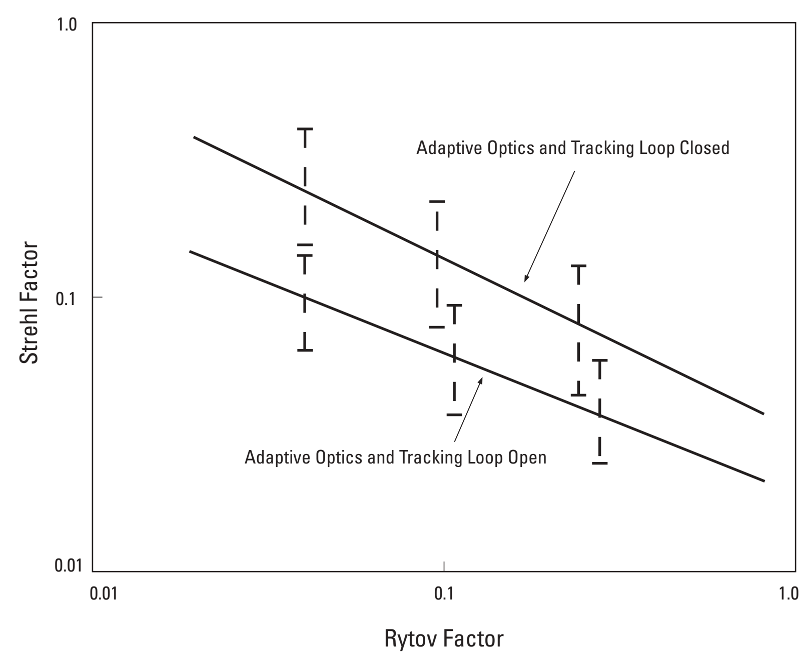
Figure 1. Target Irradiance vs. Range

(3 degree elevation angle)



Range curves for the COIL mounted on the ABL. The solid curve shows the range with no atmosphere, an inverse square of the distance. The other three curves indicate the ranges for various levels of atmospheric turbulence. For reasons of classification, the numbers cannot be included. Thus, ratios with respect to the operational requirement document (ORD) are used.

Figure 2. Oscura Peak Experimental Results



Effect of adaptive optics on the laser beam derived from a large number of measurements performed at the Oscura Peak facility at White Sands Missile Range. The Strehl factor is a measure of the laser beam width at the target; the Rytov factor is a measure of atmospheric turbulence.

aircraft patrol ocean areas where Soviet submarines were known to be located.[11] Sensors would pick up a submarine-launched missile as it broke water, and the high-intensity laser would shoot it down. Because of the rapid slew rates possible with the laser weapon, the aircraft would be capable of shooting down several missiles launched in succession. (This capability has recently been demonstrated by the tactical high-energy laser at the White Sands Missile Range. In September 2000, this laser shot down a salvo of two Katyusha rockets launched within a second of each other.)

The scenario I described was appropriate during the Cold War when the Soviet Union was the principal adversary. Given our ability to locate Soviet submarines, a long-range laser would be required to do what I suggested, and the carbon dioxide laser on the aircraft did not have the range capability to execute the mission. It would be some years before the technology necessary to extend the range of high-intensity lasers was ready for application.

Iraqi use of short-range ballistic missiles during the Gulf War in 1991 renewed interest in solving the problem of shooting down ballistic missiles. For the first time since 1944, when the Germans used V–2 rockets to bombard London, ballistic missiles were used in combat. The Iraqis used a modified Soviet Scud missile to bombard targets in Israel and in Saudi Arabia. The United States deployed Patriot missiles to shoot down the Scuds in Israel and Saudi Arabia but achieved only limited success. However, the fact that ballistic missiles were used triggered a strong and successful effort to upgrade the Patriot with the Advanced Capability Program to create the PAC–3 missile. This weapon, which has been tested successfully a number of times, is now being fielded by the U.S. Army.

Although the range of the airborne laser is classified, some general statements about applications can be made. Airborne lasers would clearly be useful in any conflict near the Korean Peninsula, essentially because overflight of hostile territory is less necessary in this region than it is elsewhere for effective use of this weapon. Airborne lasers also would be effective weapons in some parts of the Middle East and Europe. One could construct operational orbits for ABL aircraft above the Mediterranean, the Arabian Sea, and the Black Sea that would be effective in various possible engagements.

The operational concepts for the ABL aircraft would be to deploy them in areas where potentially hostile actions by aircraft and missiles (including ballistic missiles) are likely. Such deployment could be a deterrent as well as a militarily effective weapon. A good model for the deployment of ABL aircraft is the airborne warning and control system (AWACS) aircraft as used in various situations around the world since the aircraft were introduced 20 years ago. AWACS aircraft are designed to control air combat operations. Thus, the mere deployment of AWACS aircraft signals serious interest in a region. Because laser-armed aircraft are valuable assets, they would have to be escorted, just as the AWACS aircraft are protected by fighter aircraft when they are deployed. The employment of AWACS during the past 20 years is a model of what can be expected from the airborne laser. When AWACS aircraft were first developed, the program called for the deployment of seven aircraft. At present, about 30 AWACS aircraft are in service around the world. A similar increase in demand is likely in the case of the ABL aircraft.

Although many problems remain to be solved, the ABL program probably will be brought to a successful conclusion. The first shoot-down of a ballistic missile is scheduled for late 2004. This objective almost certainly can be achieved. The United States is very good at this kind of thing, having done it many times before with radar, nuclear weapons, stealth aircraft, and smart weapons. The most important fact is that the airborne laser is a truly new weapon—the first directed energy weapon to fulfill an important strategic mission. For this reason alone, it is important that the ABL program be completed. Once a new weapon is fielded, it always leads to important applications not even considered during the development program. These applications often turn out to be the decisive ones. There is good reason to believe that the same will be true for the airborne laser weapon.

Notes

[1] Albert Einstein, *Verhandlungen der Deutschen Physikalischen Gesellschaft,* vol. 18 (1916), 318, and *Physikalische Zeitschrift*, vol. 18 (1917), 121.

[2] J.P. Gordon, H.J. Zeiger, and Charles H. Townes, *Physical Review* 95 (1954): 282, and 99 (1955): 1264 .

[3] Theodore H. Maiman, "Stimulated Optical Emission in Ruby," *Nature* (August 6, 1960): 493–494.

[4] Ali Javan, W.R. Bennett, and D.R. Herriott. "Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing a He-Ne Mixture," *Physical Review Letters* (February 1, 1961): 106–111.

[5] A Neodymium-Yag solid state laser was used to produce the intense pulses.

[6] Colonel Donald Lamberson, USAF, was the overall program leader and Colonel Demos Kyrazis, USAF, served as the project manager during most of the duration and was in charge of making the airplane work. Both of these officers had first class technical ability as well as outstanding managerial and leadership capacities. In addition, there was a galaxy of brilliant younger Air Force officers, enlisted people, and civilians who worked on the Airborne Laser Laboratory with great intelligence and dedication. The intellectual sparkplug was Dr. Petros Avizonis, who began his career as an Air Force officer and later became Chief Scientist of the Air Force Weapons Laboratory for an extended period.

[7] An experienced Ames researcher, Mr. Don. A. Buell, was put in charge of the aerodynamic experiments to be performed using the facility. Colonel Kyrazis spent much time at Ames working on the turret and boundary layer problems. He was joined soon by First Lieutenant L. John Otten, USAF, who became a key member of the ALL team. Eventually, as a Colonel, he headed the Air Force Laser program.

[8] The tests were performed by by Don Buell, Demos Kyrazis, and John Otten.

[9] All of the events that I have described in this section are the subject of Dr. Robert W. Duffner's excellent book *Airborne Laser: Bullet of Light* (New York: Plenum Trade, 1997), which is a comprehensive history of the ALL program.

[10] Alan I. Lampson, Richard C. Buggeln, Peter G. Crowell, James A. Rothenflue, and Gordon D. Hager, U.S. Air Force Weapons Laboratory, 1977, accessed at <http://de.afrl.af.mil>.

[11] In May 1981, shortly after I left my position as Secretary of the Air Force, I delivered the annual Charles H. Davis Lecture, "Technology and the Strategic Balance," at the U.S. Naval War College. The lecture was reprinted in full in *Technology and Society* 4 (1982), 15–32.

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