Directed-Energy Weapons

Technologies, Applications and Implications

Executive Summary

After decades of research and development, directed-energy weapons are becoming an operational reality. Such weapons generate streams of electromagnetic energy that can be precisely aimed over long distances to disable or destroy targets. Two types of devices are currently being weaponized: high-energy lasers and radio-frequency weapons, commonly referred to as high-power microwaves. Lasers excite atoms to release photons in powerful bursts of coherent (single-frequency, single-phase) light that can be focused and aimed with mirrors. With sufficient power, lasers can quickly pierce or overheat a wide range of targets, including missiles, aircraft and artillery rounds. Radio-frequency weapons operate in the lower-frequency, longer-wavelength portion of the electromagnetic spectrum to generate bursts or beams capable of disabling electronic systems.

Directed-energy weapons have several advantages over conventional munitions. First, they transmit lethal force at the speed of light (about 300,000 kilometers per second). Second, their beams are not affected by the constraining effects of gravity or atmospheric drag. Third, they are extremely precise. Fourth, their effects can be tailored by varying the type and intensity of energy delivered against targets. Fifth, they have deep magazines and relatively low cost per shot. Finally, they are versatile in that they can be used both as sensing devices and kill mechanisms. However, directed-energy weapons also have drawbacks: laser beams are weakened by water vapor, dust and other obscurants, while radio-frequency emissions can be absorbed by any conductive material between the weapon and the target.

Directed-energy weapons are properly viewed as one facet of a broader "Revolution in Military Affairs" currently unfolding in the United States and elsewhere. Just as digital technology is greatly increasing the pace and precision of military information flows, so directed-energy weapons can enhance the speed and discrimination with which targets are engaged. Systems such as the Airborne Laser and various tactical lasers are potentially applicable to ballistic-missile defense, defense against air-breathing threats (manned and unmanned), suppression of enemy air defenses, interdiction of ground vehicles, and many other military missions. Radio-frequency weapons facilitate a wide range of information operations against both area and point targets. Over the longer run, directed-energy weapons may enable entirely new concepts of operation, such as "nonlethal" warfare.

Because directed-energy weapons are so new, there are few legal constraints on their development or use. However, without careful management and adequate resources, the warfighting potential of directed-energy technology may never be fully realized. The study recommends several steps to assure sufficient funding and focus, including creation of a joint program office and increased spending on basic research. It also recommends near-term emphasis on demonstrating the efficacy of first-generation directed-energy systems in realistic tests, exploration of a wider range of operational missions, and greater attention to potential countermeasures.

The principal investigator for this study was Dr. Loren Thompson. The study was written by Dr. Thompson and Dr. Daniel Goure of the Lexington Institute staff. All of the key participants in the research team's deliberations were given an opportunity to review the study prior to publication.

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I. THE GENESIS OF A DREAM

It is still a matter of wonder how the Martians were able to slay men so swiftly and so silently. Many think that in some way they were able to generate an intense heat in a chamber of practically absolute non-conductivity. This intense heat they project in a parallel beam against any object they choose, by means of a polished parabolic mirror of unknown composition, much as the parabolic mirror of a lighthouse projects a beam of light ... Whatever is combustible flashes into flame at its touch, lead runs like water, it softens iron, cracks and melts glass, and when it falls upon water, incontinently that explodes into steam.[1]

– H.G. Wells, *The War of the Worlds*

By the time H.G. Wells penned this fanciful description of a Martian "heat-ray" in 1898, human beings and their simian ancestors had been making tools -- including weapons -- for over two million years.[2] It was not until the eve of the twentieth century, though, that understanding of physics progressed to a point where directed-energy weapons could become a staple of popular fiction. In fact, use of the word "energy" in its modern sense barely predated Wells' birth in 1866.

However, the appearance of *The War of the Worlds* coincided with a series of scientific discoveries that provided the foundation for developing lasers and other directed-energy devices in the following decades. In 1895, Wilhelm Conrad Rontgen detected X-rays for the first time. In 1897 John Joseph Thompson demonstrated the existence of electrons and thus proved the divisibility of atoms. The following year Wilhelm Wien discovered the electron's positively-charged cousin, the proton. In 1899 Ernest Rutherford traced alpha and beta particles radiating from uranium, and a year later Antoine-Henri Becquerel showed that beta particles were in fact electrons. Every year seemed to bring important breakthroughs.[3]

The first decade of the new century provided the greatest breakthrough of all. In 1905 Albert Einstein published his "special theory of relativity," and thus began a revolution in theoretical physics that was to overthrow the prevailing Newtonian paradigm. Einstein's elegant equation, $E=mc^2$, revealed a universe in which the most prosaic items were bursting with energy. This insight demolished much of the received wisdom about energy and matter, setting the stage for innovations unimagined in earlier generations. Twelve years later, Einstein explained how atoms could be stimulated to emit energy at specific wavelengths, a discovery that led directly to the development of lasers at mid-century.[4]

Scientists now believe that four elemental forces shape the universe: the "strong" force that binds the particles in an atom's nucleus despite their mutual repulsion; the "weak" force that causes those particles to decay; the gravitational force exerted by any object with mass; and the electromagnetic force.[5] Thus far, only electromagnetism has proved highly malleable in human hands. This study is about how the electromagnetic force can be used as a tool of war. More specifically, it is about how certain forms of electromagnetic energy can be fashioned into powerful, precise beams capable of achieving a range of militarily useful effects, and what that capability may mean for the future of warfare.

Electromagnetism has played a continuously increasing role in warfare since the advent of telegraphs in the early nineteenth century. However, it is only since World War Two that the idea of using beams of pure energy to destroy or disable targets has become technically feasible. The most mature directed-energy weapon today is the high-energy laser (HEL), which generates an intense beam of monochromatic light. HEL's exist in several forms and are the main focus of the study. Another fairly mature concept is radio-frequency weapons, particularly the high-power microwave (HPM). HPM's are essentially high-frequency radio waves that can destroy or degrade electronic systems. Because radio-frequency weapons generally lack the versatility and precision of lasers, they receive less attention in the study. Other, more theoretical concepts such as particle beams are not addressed at all, since they offer little near-term prospect of weaponization.

The study consists of four parts. The first part explains the basic physics of directed-energy weapons and describes various systems that are currently under development or active consideration. The second part examines the range of military missions to which directed-energy weapons might be applied, and assesses the operational implications of doing so. The third part reviews several related issues -- political, legal, philosophical -- that may have a bearing on how directed-energy weapons are used in future warfare. The fourth and final part offers recommendations for focusing development of this emerging technology and integrating its most promising manifestations into the nation's security posture.

II. UNIQUE FEATURES OF DIRECTED-ENERGY WEAPONS

In March of 2000 the Department of Defense issued a plan for developing high-power lasers that stated, "HEL systems are ready for some of today's most challenging weapons applications, both offensive and defensive." The plan provided a framework for increasing government investment in such systems, arguing that "HEL weapons offer the potential to maintain an asymmetric technological edge over adversaries for the foreseeable future."[6] A lengthy Defense Science Board study issued the following year came to similar conclusions.[7] The government is more circumspect about discussing its plans for radio-frequency weapons, but there are numerous indications of increasing investment in that area too.

One reason for the growing interest in directed-energy systems is that there has been considerable progress in developing relevant technologies over the past two decades, from power sources to beam-control concepts to pointing and tracking techniques. The more fundamental reason, though, is the one that visionaries like H.G. Wells recognized long ago: directed-energy weapons have unique characteristics that potentially enable new concepts of military operation. Explaining what those characteristics are is the logical starting point for any study of said weapons' military utility.

The first and most obvious point is that the beams generated by directed-energy weapons reach targets at the speed of light -- about 300,000 kilometers per second. Because every form of electromagnetic energy travels at this same speed (Einstein's universal constant in his famous equation), a weapon using directed energy as its destructive mechanism can traverse great distances almost instantaneously. Thus the challenge of tracking and intercepting a target is greatly simplified, and the target's capacity to evade harm is greatly diminished.

A second key feature of directed-energy weapons is that their beams are not affected by gravity or atmospheric drag. Although the bending of light by gravitational fields has significance for cosmologists, within the limited domain in which human warfare unfolds energy beams are essentially immune to gravity because they have no mass. This lack of mass also frees them from the kinematic and aerodynamic constraints to which more traditional weapons are subject. The complex calculations required to determine ballistic trajectories and other flight characteristics of conventional munitions -- a challenge that led to development of the first digital computer in World War Two -- are irrelevant in using directed-energy devices.

A third important aspect of directed-energy weapons is that they are extremely precise. The main beam of an Airborne Laser is only 1.5 meters wide, and yet it can hit targets that are 500 kilometers distant with pinpoint accuracy. In fact, with sufficient tracking and characterization, attackers employing directed-energy weapons can select the specific part of a fast-moving target that they wish to strike. This unprecedented precision makes it possible to accomplish surgical strikes with no collateral damage or fratricidal effects on friendly forces.

A fourth, related feature is that the effects of directed-energy weapons can be tailored to achieve a range of results, lethal or nonlethal, destructive or disruptive. This is achieved primarily by adjusting the amount of energy that is deposited on targets or the wavelengths at which the energy is delivered. For example, radio-frequency weapons can generate waves at particular frequencies and power levels to accomplish the temporary upset of certain types of electronic devices while leaving other types unscathed. In the words of former Air Force Chief of Staff Gen. Ronald Fogelman, an advisor for this study, "directed-energy weapons are the opposite of weapons of mass destruction -- they are the most promising precision nonlethal weapons we have."[8]

A fifth characteristic of directed-energy weapons is that they cost relatively little to intercept targets compared with conventional munitions. Although the beam-generating system may be expensive to build and maintain, the price of engagements is minimal because the system expends only energy. In the case of missile defense, interceptor rockets costing millions of dollars can be replaced with a directed-energy weapon costing only a few thousand dollars per shot to achieve equivalent or superior probability of kill.

A sixth important feature of directed-energy weapons is their capacity for repetitive engagements over protracted periods, constrained only by the availability of power and the need to vent the side-products of beam generation (heat, chemicals, etc.). Conventional weapons, especially those firing precision-guided munitions, are typically constrained in the number of engagements they can accomplish by a limited supply of rounds. Even when the rounds are cheap expendables, space and weight limitations place a ceiling on how many engagements can occur without replenishment. Directed-energy weapons are not entirely free of such considerations, but they have the potential for deeper magazines arising from the low cost and high energy potential of their power sources.

A final unique characteristic of directed-energy weapons is their versatility in also serving as sensing devices. Lasers can be used not only to attack targets, but also to detect, image, track and illuminate ("acquire") them. High-power microwaves operate in the same wavelengths as radars, giving them similar tracking potential in some applications. Thus, the distinction between weapons and sensors that prevails in traditional warfare begins to disappear in considering the military impact of directed energy. In fact, lasers (although not high-power ones) also are the most promising technology for eliminating bandwidth constraints in future command-and-control architectures.

However, not all of the unique characteristics of directed-energy weapons are positive qualities. Radio-frequency beams can be readily diverted by conductive material between their source and intended targets. Laser beams dissipate through interaction with water vapor, dust and atmospheric turbulence. And the highest-frequency, shortest-wavelength forms of electromagnetic energy, such as x-rays, are difficult to generate and condition into directed beams. These defects are addressed in greater detail below in the discussion of specific weapon systems. The degree to which they may detract from the military utility of directed-energy weapons is a key focus of the study.

Basic Physical Principles

The weapons discussed in this study generate electromagnetic waves that can be precisely aimed at intended targets. All such waves travel in a straight line at the constant speed of about 300,000 kilometers per second unless their movement is impeded by some intervening medium. The most elementary unit of electromagnetic energy is the photon, which is roughly analogous with subatomic particles in matter (photons sometimes behave like particles, and subatomic particles sometimes behave like waves).

Electromagnetic waves take many forms, but their intrinsic properties are defined by two characteristics other than speed: the length of their waves, and the frequency with which those waves vibrate ("oscillate"). Wavelength is measured as the distance between two adjoining crests or troughs in a wave. Frequency is measured as the number of vibrations per second, expressed in "hertz." A hertz is defined as one vibration per second, so kilohertz means a thousand vibrations per second and megahertz means a million.[9]

Because the speed of light is a constant, wavelength and frequency vary inversely. In other words, as frequency increases, wavelength decreases. Every form of electromagnetic energy can be defined in terms of this fundamental tradeoff. For example, radio waves have lower frequencies and longer wavelengths than visible light, which in turn has lower frequencies and longer wavelengths than X-rays. The full range of frequencies and wavelengths is referred to as the "electromagnetic spectrum."

There is an infinite number of specific wavelengths and corresponding frequencies, so scientists have divided up the electromagnetic spectrum into a series of sub-ranges defined by certain shared characteristics of the waves generated within those ranges. At the low end of the spectrum, ranging from wavelengths of 10,000 meters to one millimeter, are radio waves. Radios, televisions and integrated circuits all operate at these relatively low frequencies and long wavelengths. The highest-frequency, shortest-wavelength radio waves are called microwaves, which are used in radar transmissions.[10]

Radio-frequency weapons propagate intense bursts of energy at microwave or lower frequencies that disable or destroy electronics. Such bursts can be generated by both nuclear and conventional explosives, but since these mechanisms result in omnidirectional, wideband releases of energy, they cannot properly be called "directed" energy. Radio-frequency devices producing directed energy would typically resemble radar transmitters, with steerable antennas for aiming their beams.[11] It could be argued that radio-frequency weapons transmitting omnidirectionally but on tightly restricted frequencies are a form of directed energy; however, this study follows the customary practice of defining directedness in spatial rather than spectral terms.

The rest of the electromagnetic spectrum operates at higher frequencies and shorter wavelengths than radio waves. Immediately adjacent to the microwave portion of the spectrum is the infrared range, followed by the relatively narrow slice between wavelengths of 400 and 770 nanometers occupied by visible light. Above that is the ultraviolet portion of the spectrum, followed by x-rays. The highest-frequency form of x-rays, known as gamma rays, vibrate at the rate of 10 to the 20th power per second.

Lasers operate in the infrared, visible and ultraviolet sub-ranges of the spectrum. The term laser is an acronym, standing for "light amplification by stimulated emission of radiation." Exploiting a principle discovered by Einstein, lasers organize the light radiated by excited atoms into intense, monochromatic beams. First, atoms must be excited to a high-energy state (usually using heat), so that they will emit light as they return to their initial state. When an emission is stimulated, it serves as a source stimulating other atoms to emit light matching its phase and wavelength. The powerful output that results is then refined into a tightly focused beam of pure (single-frequency), coherent (single-phase) light using mirrors.[12] The same effect can be achieved with microwaves, in which case the mechanism is called a maser.

III. LASER TYPES AND TECHNOLOGIES

Lasers are the most versatile type of directed-energy weapon likely to be operationally deployed during the first two decades of the new century. They trace their origin to the late 1950s, when two Americans, Charles Townes and Arthur Schawlow, published a paper explaining how the stimulated emission of radiation from excited atoms and molecules could be used to produce beams of coherent light. Within two years physicist Theodore Maiman had built the first working laser. Maiman's device used a high-power lamp to excite atoms in a ruby lasing rod -- in effect, the first optically-pumped solid-state laser.[13]

A number of different approaches to laser design were subsequently developed. The three concepts that have greatest relevance for weapons applications (at least in the near term) are chemical lasers, solid-state lasers, and free-electron lasers. Chemical lasers employ chemical reactions to excite atoms, and then organize the resulting light into beams through the use of mirrors. An example is the Mid-infrared Advanced Chemical Laser (MIRACL), a deuterium fluoride device that has successfully downed target drones and missiles using a megawatt-class beam operating at a wavelength of 3,800 nanometers. All of the high-power lasers likely to see deployment in the current decade are chemical types.

Solid-state lasers employ Theodore Maiman's original concept of optical pumping -- an intense light source -- to excite atoms in a lasing rod made up of rare-earth materials such as synthetic ruby or sapphire. Because they rely on electrical power, solid-state lasers may impose less of a logistical burden than chemical lasers, which require large quantities of various chemicals to sustain lasing action. On the other hand, solid-state lasers are relatively inefficient, and to date have only managed to achieve beam intensities in the kilowatt range. Megawatt-range intensities are required to destroy aerospace vehicles such as ballistic missiles.

Free-electron lasers generate streams of electrons from a particle accelerator or some other source that are then passed through a linear array of electromagnets. The magnetic field accelerates the electrons so that they emit radiation that can be fashioned into a beam. By varying the magnetic force, the wavelength and duration of the beam can be altered to accomplish different effects. In principle, free-electron devices should be able to efficiently produce megawatt-range beams while consuming only water and electricity. However, the engineering challenges of such systems are considerably greater than those for solid-state or chemical lasers, so despite 20 years of development they are not yet ready for weaponization.

Dr. Paul Kaminski, a former Under Secretary of Defense and advisor on this study, compares the current state of laser development to radio technology during the era of vacuum tubes. He believes that the most useful military breakthroughs will probably occur in developing solid-state devices, but argues that all three types of high-energy laser technology require increased and stable funding if they are to achieve their full operational potential.[14] In addition to the further advances required in technical areas such as power sources and optical coatings, much is still unknown about the mechanics of laser propagation and lethality under various conditions.

Although there are several different methods by which high-energy lasing can be accomplished, the generic components of a laser weapon are always the same. There must be a power source with adequate fuel; there must be a chamber in which coherent light is generated; there must be optical mechanisms for forming and focusing a beam; there must be sensors for tracking intended targets and characterizing the space between the laser and the targets; there must be beam-control techniques for shaping the beam and directing it so it traverses the intervening space with maximum efficiency; and there must be some method of assessing whether the energy deposited on the target has had the desired effect.

Assuming a specific degree of pointing accuracy, the lethality of the laser against any class of targets will be determined by power level, wavelength and optical dimensions. These factors are typically traded off in designing an integrated system. Shorter wavelength enables designers to use less power or smaller optical dimensions and still achieve desired lethality, although the effects of atmospheric turbulence are more pronounced at shorter wavelengths. Higher power or larger optics enables the same effect to be achieved at longer wavelengths with less degradation from turbulence. However, there are limits on each of these parameters dictated by physical laws. For example, a laser operating at any given wavelength in the atmosphere will have a "critical power level" that defines its maximum lethality; at higher power levels, beam degradation resulting from interaction with the atmosphere will actually diminish energy deposited on the target. High power output can also exceed the tolerances of optical systems, leading to system failure.[15]

Considerable progress has been made over the last 20 years in advancing every facet of laser-weapons technology. Power levels have been boosted for the first time to megawatt ranges, a necessary step since three megajoules of energy -- the equivalent of three megawatts of power per second -- are needed to kill moderately hard aerospace vehicles (one pound of high explosives generates four megajoules of force). Optical coatings have been devised that can protect sensitive mirrors from these higher power levels without reducing beam efficiency. Sensing and tracking mechanisms have seen huge improvement, due primarily to the application of new information technologies.

One of the most important technological developments is adaptive optics, a method of adjusting laser beams to compensate for distortions that reduce the energy deposited on targets. Several extraneous factors can interfere with beam propagation through the atmosphere, including scattering, thermal blooming (heat-induced spreading), and defocusing due to turbulence. In addition, performance factors intrinsic to the laser device itself can diminish the energy of the beam at its point of destination. Adaptive optics measures these sources of distortion and deforms the beam at its point of origin so that it achieves maximum lethality after encountering such influences. In other words, the beam is actually more lethal when it reaches the target than where it began, because it is distorted in an amount and manner at the source equal and opposite to the various contaminating influences that will be encountered en route to the target.

When operating in the atmosphere, as most laser weapons do, adaptive optics can make as great a contribution to ultimate lethality as factors such as power output and optical dimensions. In applications requiring atmospheric propagation, further refinement of the beam through rejection of distorting influences may be the main avenue open for increasing weapon efficiency.

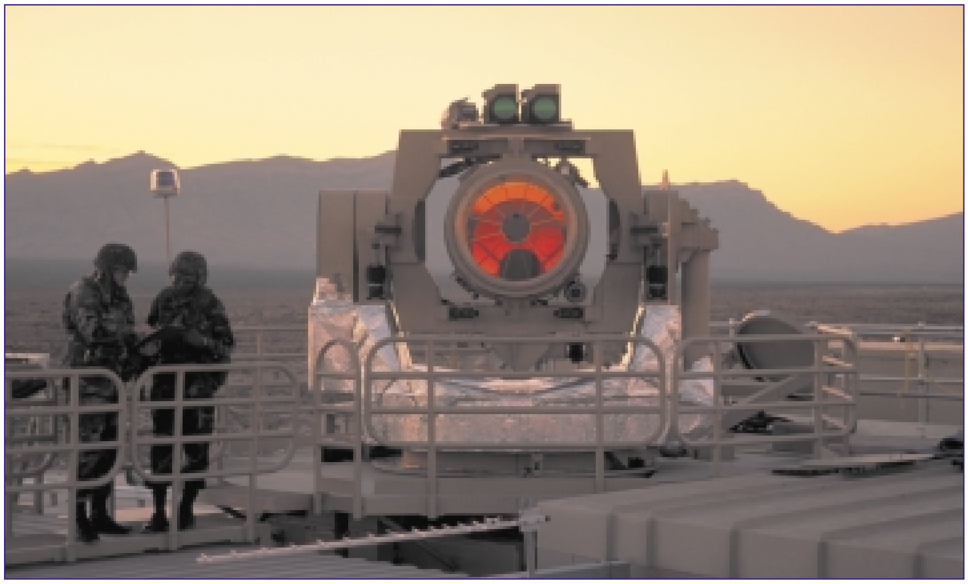
The biggest engineering challenge in fielding laser weapons with military utility no longer resides at the subsystem level -- power sources, beam control, pointing mechanisms, etc. -- but at the integration level. The skills required to combine all of the components of a laser weapon in a functioning and reliable system are still in their infancy.[16] However, it is a measure of how far high-energy laser technology has progressed since the advent of the Strategic

The final configuration of the Airborne Laser will deploy four different laser systems on a modified Boeing 747 transport.

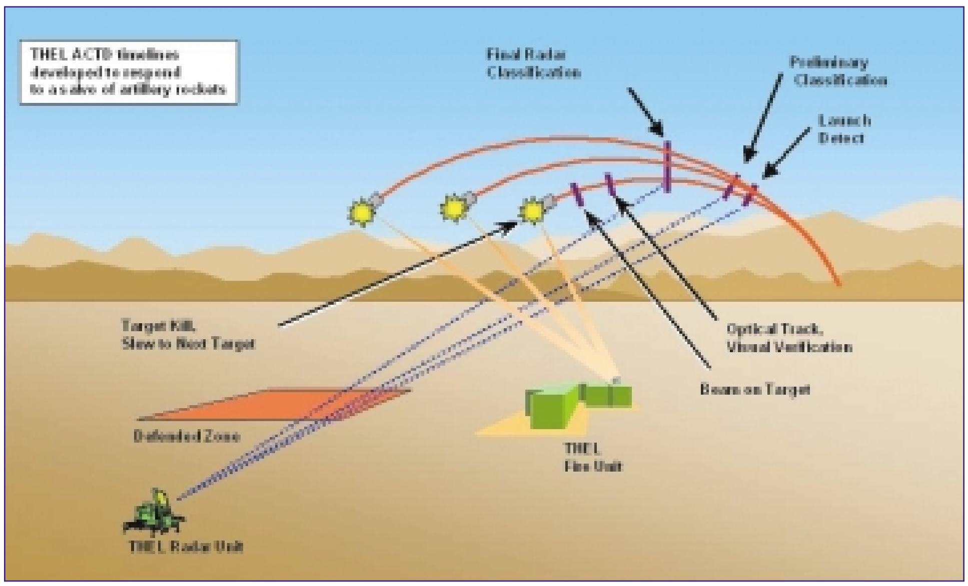
Construction of the Airborne Laser entails integration of several complex subsystems on a commercial airframe.

Once operational, the Airborne Laser will offer a rapidly deployable response to theater-range ballistic missiles.

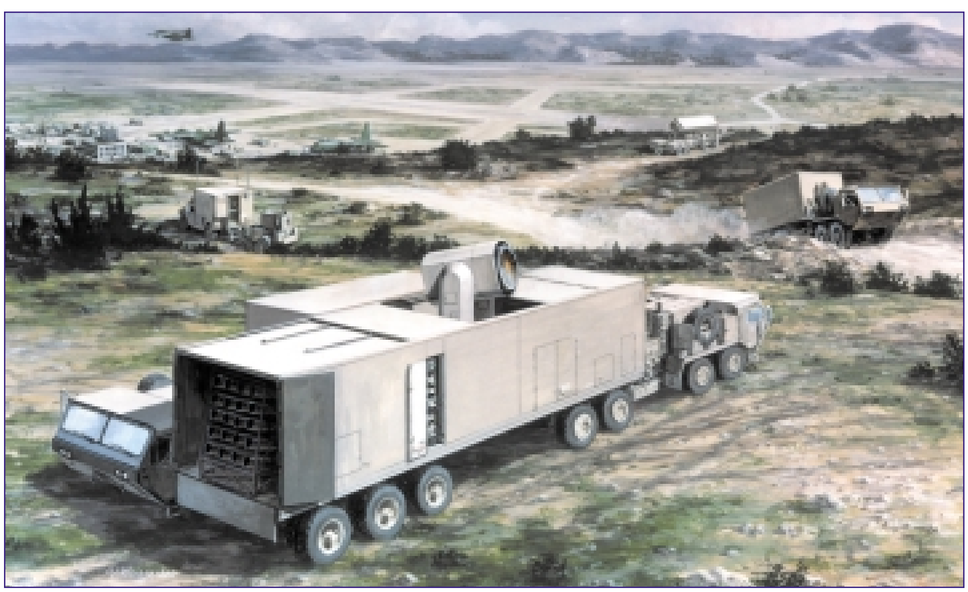
The Tactical High-Energy Laser has successfully engaged dozens of rockets and artillery rounds.



In order to operate effectively on the battlefield, tactical lasers must track and engage threats within a few seconds.



The Mobile Tactical High-Energy Laser (MTHEL) combines laser lethality with rapid mobility.



Defense Initiative 20 years ago that integration now is viewed -- at least in the case of chemical lasers -- as the last remaining obstacle to an operational weapon.

Tactical Laser Weapons

The design specifications of laser weapons tend to be proportional to their range and effects. As the distance to intended targets or the desired level of energy delivered against them grows, so must the size of power sources, the dimensions of optical systems, and the precision of tracking mechanisms. This tendency to "linear scaling" means that it is much easier to develop laser weapons that operate on the ground over short distances than in the air or space over longer distances. Not surprisingly, the most mature laser weapons currently in development are those intended for tactical applications.

One such system is the Tactical High-Energy Laser (THEL), a U.S.-Israeli technology demonstration effort begun in 1996. THEL is a chemical laser designed to intercept short-range rockets from a surface location at ranges of about ten kilometers. At the time it was conceived such rockets were a major security concern for Israel on its northern border, and the U.S. Army had a growing interest in low-cost approaches to defeating maneuvering short-range threats requiring rapid response.[17]

The THEL system consists of a transportable deuterium-fluoride laser and fuel source integrated with a pointing and tracking subsystem. The system is linked to a mobile fire-control radar and command shelter, and thus comprises the first complete directed-energy demonstrator with an autonomous fighting capability. In tests, THEL's chemical laser has successfully intercepted dozens of rockets and artillery shells, including two simultaneously-launched Katyusha rockets. The system can track up to 15 targets simultaneously, requiring a laser dwell time of about five seconds to kill a typical rocket.[18]

The baseline THEL system has drawbacks. Like all lasers operating in the lower atmosphere, its beam energy can be rapidly attenuated by dust, fog, smoke or other battlefield obscurants. Furthermore, because it was assembled quickly as a technology demonstration, it is not truly mobile, but merely transportable with considerable effort. The U.S. and Israeli Army have decided to pursue development of a mobile THEL (MTHEL) that will reduce the size of the system 80% without diminishing laser performance. The basic goal is to create a modular, easily deployable tactical laser that will fit within the dimensions of a C-130 transport. Assuming the program stays on track, it will yield an initial prototype in 2008.

The U.S. Army's Space and Missile Defense Command is also pursuing development of a solid-state laser weapon that would not impose the unique logistical burdens of a chemical laser. Because solid-state lasers utilize electrical power rather than chemical reactions to generate their beams, the same diesel fuel used in Army tactical vehicles could be used to run the laser's generator. Ideally, the Army would like to develop a solid-state device generating at least 100 kilowatts of power that is deployable on a light vehicle.

A 2001 survey of high-energy laser technology by the Defense Science Board noted that laser weapons might be useful in a number of missions planned for the Army's Future Combat System, including air defense, protection from precision munitions, mine clearance and countering adversary surveillance sensors. The same study expressed a preference for solid-state lasers over chemical lasers in ground-combat environments, due to the superior mobility and sustainability electrically-driven weapons are expected to exhibit. However, the study also called for increased analysis of target vulnerabilities in ground combat, given the numerous influences that might impede beam propagation in a battlefield environment. Some of these influences, such as smoke and aerosols, could be readily employed by resourceful adversaries as laser countermeasures.[19]

The Defense Science Board expressed similar concerns about using tactical lasers on naval vessels. The Navy has investigated laser-weapons technology for many years, and faces fast-reaction defensive requirements against sea-skimming cruise missiles analogous to those faced by the Army with regard to precision munitions. Moreover, future warship designs may provide sufficient electrical energy to power laser weapons without adversely affecting other combat systems. However, the atmosphere at sea level is a difficult medium through which to operate lasers, causing scattering and absorption of energy. The Defense Science Board recommended free-electron lasers for maritime self-defense, since their wavelength could be adjusted to cope with changing atmospheric conditions.[20]

Deployment of tactical laser weapons on aircraft is likely to occur before deployment on ships. The Boeing Company is developing a palletized chemical laser that can be rolled on and off of cargo aircraft such as the C-130 transport. TRW Corporation is developing a modular chemical laser for transport on C-130 class airframes. And a Lockheed Martin-Raytheon team is developing a compact solid-state laser for integration into the F-35 Joint Strike Fighter. Such weapons could potentially be used in a wide range of missions, including cruise-missile defense, ballistic-missile defense, air-to-air combat, suppression of air defenses and noncooperative identification.[21]

Solid-state devices are a promising option for near-term deployment of tactical lasers on aircraft, because they can be operated using power generated by engine driveshafts. It may be feasible within a few years to continuously generate one megawatt of electrical energy in this manner. Once the power source is supplied, the other parts of the weapon can be integrated into a compact package small enough to fit within a fighter fuselage.

However, there are major engineering challenges associated with this concept. The power output of current solid-state lasers seldom exceeds ten kilowatts, and at least 100 kilowatts would be needed to successfully accomplish missions. Even at the higher level, it would be difficult to achieve damage of most targets beyond a range of ten kilometers. Moreover, operation of directed-energy devices from fast-moving aircraft presents special beam stabilization and control problems caused by vibration, g-forces, and turbulence around the airframe. To be effective, an airborne tactical laser would have to overcome the generic challenges of atmospheric propagation such as scattering and thermal blooming, plus additional difficulties unique to the operating regime of the host platform. While there is little doubt these issues can be successfully addressed, it remains to be seen whether the military utility of airborne tactical lasers justifies the efforts required to make them work.

The Airborne Laser

Over the last twenty years the Department of Defense has spent billions of dollars developing high-energy lasers with operational ranges in excess of 100 kilometers. Most of that funding was associated with efforts to provide active defense against ballistic missiles. The largest such undertaking was the Strategic Defense Initiative begun in 1983, which investigated numerous concepts for space-based, sea-based, ground-based and airborne lasers capable of negating intercontinental ballistic missiles. Although the main focus of research on longer-range lasers has been missile defense, any weapon capable of defeating ballistic vehicles also has potential to accomplish other missions such as countering hostile aircraft or low-orbit satellites.

The United States until recently had two programs underway that could have produced deployable laser weapons with long operational ranges by 2020. One of those efforts, the Space-Based Laser, is now being dismantled following congressional cutbacks in funding. The other effort is the Airborne Laser, an Air Force program that continues to make progress toward deployment of an operational capability at the end of the current decade.

The Airborne Laser (ABL) program is integrating a multi-megawatt chemical laser with a modified Boeing 747-400 transport so that theater ballistic missiles can be intercepted in their boost phase. Boost phase is the initial stage in a ballistic trajectory, when missiles present large and vulnerable targets that can be easily tracked. The basic operational concept of ABL is to fly at 40,000 feet and intercept boosting missiles after they have exited cloud cover, but before they can escape enemy air space or release warheads and penetration aids. In a tiered defensive architecture, ABL would substantially thin out attacking missiles near their source, leaving a less challenging threat for defenders to address during the later midcourse and terminal phases of trajectory.[22]

The lethal range of ABL against typical ballistic targets is 500-700 kilometers. It achieves this reach by fusing the energy from fourteen kilowatt-rated laser modules into a single, multi-megawatt beam operating at a wavelength of 1.3 microns. Each module mixes hydrogen peroxide and sodium hydroxide to excite oxygen atoms, and then collides those atoms with iodine atoms in a resonator chamber to sustain lasing action. The total weight of the modules, fuel for twenty shots, optics and associated subsystems is about fifty tons, close to the maximum load for a 747-400 freighter flying at 40,000 feet.[23]

In its final configuration, ABL would carry six infrared search-and-track seekers to provide 360-degree passive detection of any missile plume. When a plume is detected, a low-power laser is used to calculate range. A second low-power laser tracks and illuminates the target, and a third device called the "beacon illuminator laser" then samples the intervening atmosphere to determine how the main beam must be adjusted to compensate for distortions. When the main beam is fired at the hostile missile, deformable mirrors employ adaptive-optic techniques to assure it will arrive at its point of destination bearing the maximum feasible energy. With sufficient atmospheric compensation, the beam can disable most ballistic missiles in one second. Thermal energy -- heat -- is the principal kill mechanism.[24]

The Airborne Laser is an extremely complex system that must be engineered to very fine tolerances. Dr. Robert Cooper, an advisor for this study with long experience in high-energy laser technology, detects only low to moderate risk of failure in any of the key subsystems. However, he sees integration of so many advanced technologies in an operational architecture as highly challenging, in part because no similar integration challenge has been undertaken in the past. Some of the uncertainty arises from the fragility of a very specialized industrial base for items such as optical coatings. Cooper believes ABL will ultimately work as advertised, but says no final judgment can be made on that score until the system is fully integrated and tested in an operational environment.[25]

A prototype of the Airborne Laser is scheduled to conduct test engagements against three live missiles in 2004-2005. If those engagements are successful, the program will probably proceed to initial operational capability at the end of the decade. As currently structured, the program will acquire a total of seven airframes to support continuous coverage of overseas theaters, with all seven eventually upgraded to the highest performance standard.

The Defense Science Board has recommended that the Air Force investigate the use of solid-state rather than chemical lasers in some future variant of ABL. The Air Force has no plans at present to pursue that option, which would require extensive changes to the system design. A solid-state main laser potentially could be powered with electricity generated by the aircraft's four engines, eliminating the need to transport and vent toxic chemicals. Chemical fuel supplies represent about 40% of the weight in the baseline ABL system. However, solid-state devices have not yet progressed to a point where they could match the energy output of large-scale chemical lasers.

Space-Based Laser Weapons

Deployment of high-energy lasers in space could provide unique military leverage across a range of missions, but it also poses unique technical challenges. The Department of Defense has been investigating the feasibility of space-based lasers since 1977, and is still decades away from deploying a first-generation system. Three generic constellations have been considered, all with the primary mission of intercepting intercontinental ballistic missiles. The least challenging but most expensive concept would require dozens of lasers in orbit to achieve global coverage. A less expensive but considerably riskier option would employ fewer space lasers whose reach is extended through the use of orbiting relay mirrors. A third concept would use ground-based or airborne lasers in conjunction with space-based relay mirrors.

A combination of ground-based lasers and space mirrors might incur the lowest life-cycle costs because many of the problems associated with launching and operating orbital platforms would be mitigated. Unlimited power would be available if optics could be developed to manage the resulting beams, and there would be few constraints on the weight or configuration of the ground segment. One concept considered by the Strategic Defense Initiative Organization in the 1980's would have deployed very powerful free-electron lasers at widely scattered, high-altitude locations. If sites with minimal cloud cover are selected, there is high probability that at any given time some of the lasers will be capable of delivering lethal energies through the atmosphere and into space.[26]

However, the viability of this concept depends upon extremely precise and durable relay mirrors in orbit, and most of the discussion surrounding such mirrors at present is conjectural. Use of relay mirrors greatly increases the challenge of aiming and controlling laser beams over long distances, because optics must be exactly aligned not only with intended targets but also with the remote source of the beam. Basic questions such as how much energy would be lost on each mirror "bounce" -- there might be several per shot -- cannot today be answered with any certainty. In fact, every facet of this option from laser sources to beam control to launch capacity to mirror performance involves major uncertainties. Since these uncertainties essentially preclude operational deployment of any system requiring space mirrors during the early decades of the current century, no further treatment of such concepts is necessary here.

Once the near-term possibility of employing orbital mirrors is dismissed, the budgetary and logistical burdens of operating a constellation of laser weapons in space becomes quite imposing. A study of space-laser affordability conducted by three aerospace companies in 2001 found that constellation size -- the number of satellites -- is the main factor determining life-cycle costs for any architecture providing global coverage against missile attack. Without mirrors, the number of satellites in the constellation increases and so does the cost of sustaining each one, because every satellite will be a weapon requiring fuel for its laser and other forms of replenishment.[27]

In theory, a handful of very bright lasers operating in geosynchronous orbit could protect most areas of interest on the earth's surface from ballistic-missile attack. In practice, though, the scale of required optics and power sources combined with the degree of precision needed to accurately aim the weapons will preclude such as approach for the foreseeable future. Even if all the necessary technology were available, the cost of the launch capacity required to deploy and sustain such a system would be prohibitive.

In order to be feasible within the constraints of near-term technology, the laser constellation would have to be placed in orbits much closer to the earth. But satellites in those lower orbits will have a diminished field of view and be moving relative to the earth's surface, so even with lethal ranges of over a thousand kilometers numerous weapons would be needed to assure continuous protection of any given location on the surface. To provide continuous global coverage against missile attack (and most other addressable forms of aggression), a constellation of a hundred or more orbiting weapons might be needed.

Until recently, the Defense Department had a focused effort under way to investigate the feasibility of building such lower-orbit laser constellations. The effort was designed to culminate in an "Integrated Flight Experiment" (IFX) during 2013 that would deploy and test in orbit a megawatt-rated hydrogen-fluoride chemical laser against ballistic targets. Even though the IFX demonstration would not have produced a working prototype weapon, it would have resolved many of the uncertainties regarding generation, propagation and targeting of high-energy lasers in space. However, Congress reduced funding for the program in its fiscal 2002 budget to less than a third of the amount requested, effectively ending the quest for a first-generation space laser.[28]

In its 2001 assessment of high-energy laser weapons, the Defense Science Board noted several drawbacks to the Integrated Flight Experiment. First, it was a very complex undertaking since it sought to resolve a dozen different technical issues in a single demonstration; the science board suggested that a series of less complicated experiments were more likely to be successful. Second, even if it were fully successful, the IFX system would have provided only a fraction of the performance needed from an operational weapon in key areas such as laser power, beam quality, jitter control and wavefront error (correction of beam aberrations). Third, IFX did not address the issue of optics for an operational weapon, which the Defense Science Board estimated would have weight and dimensions far in excess of available launch capacity for a chemical laser functioning at the specified wavelength.[29]

Although the science board offered possible solutions for the deficiencies it noted -- a new class of launch vehicles, segmented mirrors more easily deployed in space, shorter-wavelength lasers -- its findings underscored the fact that operational space lasers are still many years from fruition. The subsequent congressional reduction in funding for IFX further delayed developmental research, in effect putting space-based laser weapons beyond the planning horizon of current-generation policymakers. The laser affordability study prepared the same year as the Defense Science Board assessment stated that, "the integration of a high power laser with a large optical system and the demonstration of sufficient control of the large expected vibrations to point and hold the laser on a moving target is crucial to the development of the HEL Operational System regardless of which concept is finally selected."[30] With the main effort to accomplish those objectives now being dismantled, the possibility that any nation will deploy a working space-based laser weapon during the early decades of the current century -- with or without mirrors -- must be regarded as remote.

IV. HIGH-POWER MICROWAVE WEAPONS

High-power microwaves (HPM's) are another type of directed-energy weapon likely to see operational deployment in the near future, probably during the present decade. Although not as versatile as lasers, they share some of the same operational virtues -- speed-of-light transmission, deep magazines -- while offering additional advantages such as being able to propagate in any weather and requiring only modest logistical support. HPM's basically operate like steerable radio transmitters, generating intense bursts of electromagnetic energy that can disable or destroy electronic systems, cause explosions, and lead to a variety of more subtle effects.[31]

The term "microwave" technically only applies to the highest-frequency radio waves, those operating in the gigahertz (billions of vibrations per second) range. However, it has become commonplace to refer to all directed-energy weapons operating at radio frequencies as "high-power microwaves," in much the same way that weapons operating at infrared or ultraviolet frequencies are called "lasers" even though they do not generate visible light. The tendency to semantical imprecision is presumably increased in the case of radio-frequency weapons by the fact that so much of the government's research on those systems is secret.

Unfortunately, such looseness can foster misconceptions about the physical properties of high-power microwaves. For example, it is sometimes assumed that hardening techniques developed to cope with the electromagnetic pulse generated by nuclear blasts can also shield electronic systems from microwave bursts. In fact, nuclear pulses occur at the low end of the radio-frequency spectrum -- in the megahertz range in which televisions and integrated circuits operate. Microwaves occur at the high end or gigahertz range of the radio-frequency spectrum, where most radars operate. Defensive techniques that cope well with megahertz-frequency threats may be useless against the gigahertz-frequency pulses of high-power microwave weapons.

The advent of solid-state electronics and the continuous trend toward greater miniaturization, density and power efficiency in such devices has made radio-frequency weapons an attractive option for waging information-age warfare. All digital systems are potentially vulnerable to damage or destruction by electromagnetic pulses, and that vulnerability grows as the size of the circuitry shrinks to sub-micron dimensions. The susceptibility of military equipment to radio-frequency weapons has been further increased in recent years by the use of relatively fragile "commercial-off-the-shelf" systems, and by the replacement of metal packaging with plastic or composite materials (metal exteriors provide partial protection against electromagnetic intrusions by absorbing incoming radiation before it can reach interior components).[32]

High-power microwaves can cause three levels of destructive effect in electronic devices: temporary upset, permanent upset or burnout. Temporary upset is a transient effect similar to the electromagnetic interference caused by jamming equipment or lightning. Permanent upset occurs when magnetic memories or processor logic is erased. Burnout is physical damage to components resulting from power overloads and resulting heat. The level of effect against a given target will depend on the amount of energy coupled to the target and the characteristics of the transmission -- frequency, pulse duration and so on. If a transmission is "in-band" (matches the operating frequencies of targets), it can couple efficiently to antennas or cables and potentially cause considerable damage. If it is not in-band, it will couple less efficiently and damage levels will be correspondingly diminished.[33]

Because the location and vulnerabilities of targets are often unknown, HPM weapon designs must tradeoff key performance parameters such as power output, bandwidth and pulse duration. Assuming a static power source, a narrowband transmission will be less likely to couple efficiently to targets but more likely to achieve significant damage when it does. A broadband transmission will be more likely to couple, but will deliver less energy at relevant frequencies. Technical literature distinguishes high-power microwaves from "ultra-wideband" (UWB) devices, with the former said to generate more powerful, narrowband pulses, but this distinction is frequently lost everyday usage.[34]

Since research on microwave weapons first began in the 1970s, there has been considerable progress is developing power sources, beam conditioners, and antennas for aiming the resulting energy. Compact, explosively-driven HPM's reportedly can generate gigawatt-level pulses of a few nanoseconds duration, far exceeding the daily output of a major hydroelectric facility. Pulsed-power sources capable of producing terawatt energy levels are commercially available, which at a modest 10% extraction efficiency suggests the potential for microwave weapons transmitting pulses in excess of 100 gigawatts (billions of watts).[35]

Obviously, any weapon emitting that much energy has potential to do great damage to the military sensor and communication networks of an adversary, not to mention its civilian infrastructure. Even at considerably lower power levels, microwave weapons could be used to disable the avionics of aircraft in flight, disrupt the command links of surface forces, and even heat the skin molecules of enemy personnel -- a painful effect potentially applicable to nonlethal weapons. However, because the energy threshold at which radio waves begin to disrupt digital electronics is far below levels at which radiation would be perceptible to humans, most employment scenarios involve discriminate attacks against electronics in which there are few collateral effects on people or physical infrastructure.

In theory, it might be possible to generate graduated effects against enemy electronics by varying the power output, frequency, and pulse duration of microwave weapons. The “tunability” of microwave effects should not be exaggerated, since it will often not be feasible to determine in advance precisely which targets are effected and in what manner. Nonetheless, high-power microwaves may offer unprecedented opportunities for precision targeting of effects, while leaving many adversaries in the dark as to what caused their sudden loss of capability.

It should be noted, though, that all of the operational virtues of radio-frequency weapons have equal or greater appeal to potential adversaries. Unlike high-energy lasers, the technology for generating high-power microwaves is neither arcane nor expensive. Other countries have developed powerful HPM devices, and the growing emphasis on “network-centric” operations may make U.S. forces uniquely vulnerable to their effects. More broadly, the introduction of digital technologies into every facet of national commerce and culture may make Americans susceptible to radio-frequency aggression by technically-proficient terrorists. The federal government has only recently begun to investigate the full range of microwave-weapon effects, in order to more fully grasp the danger they may pose to U.S. interests in the future.[36]

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Chapter Two

For more than forty years, the Department of Defense has pursued the goal of using directed energy for military purposes. This effort has been part of a broad-based strategy of investing in science and technology in order to maintain decisive military advantage over prospective adversaries. Such advantages were particularly important during the Cold War when the United States and its allies sought qualitative superiority in their military systems as a way of offsetting the Soviet Union's quantitative superiority. Over this period, advances in a wide range of disciplines from physics and electronics to computing and chemistry resulted in a series of so-called "Revolutions in Military Affairs" (RMAs).

The most recent, and potentially powerful, of these RMAs is that often referred to as the "Revolution in Information Warfare." This RMA centers on the collection, processing, transmission and management of information relevant to the conduct of military operations. It is part of a broader information revolution. The U.S. military now considers the battle with an adversary for information superiority to be as important to the outcome of a conflict as any engagement involving the exchange of fires. Based on continuing advances in sensor technologies, computing power and high-speed communications, the Revolution in Information Warfare has resulted in orders-of-magnitude improvements in the ability of U.S. forces to locate and target with precision an adversary's forces and supporting capabilities.

The United States may well stand on the verge of yet another RMA, this one associated with the exploitation of directed-energy weapons in conjunction with the Revolution in Information Warfare. This latest RMA has reduced the time needed between finding and engaging a target to a matter of minutes. That is because the new RMA is based on the speed of photons or electrons in sensors, computers and communications systems. Increasingly, the slowest part of the kill cycle is the penultimate step, putting energy on a target sufficient to kill or disable it. The delay is due to the dependence of the military on delivery platforms and weapons systems limited to the speeds of jet engines or rocket propulsion. Directed-energy weapons enable the user to place energy on a target at the speed of light, matching the speed of the other parts of the kill chain.

I. OPERATIONAL CHARACTERISTICS OF DIRECTED ENERGY

The Defense Department recognized the potential for directed-energy weapons to transform warfare more than forty years ago when it first began to conduct research in this area. Speed of light was clearly one characteristic of directed-energy systems that appealed to the military (and in some fields to civilians, as well). But it was more than that. The ability of the directed-energy system (principally lasers, but in some instances microwave and particle devices, as well) to interact with its target in a unique way excited the imagination of scientists and military leaders alike. At low power levels, directed energy held forth the promise of high speed, extremely accurate targeting and also of instantaneous, high data-rate communications. At high power, it could be the "death ray" of science-fiction fame. If the energy output could be adjusted, then it might be possible to create the all-purpose weapon, able to be employed coercively, not fatally, on human beings but also at higher power, able to melt through the skins of aircraft and missiles or the armor of tanks and battleships.

At the time that research first began on directed-energy technologies, it was impossible to anticipate how profoundly they would come to impact both the military and civilian worlds. The world is entering an era of what might well be termed "ubiquitous" directed energy. U.S. smart weapons, which constituted some 60 per cent of all weapons employed in Kosovo and Afghanistan, are dependent on lasers, either to illuminate their targets, or in the case of the GPS-guided Joint Direct Attack Munitions (JDAM), on the use of laser range-finders to precisely locate a target's coordinates. Laser range-finders are key to the operation of virtually all modern, direct-fire weapons systems such as main battle tanks and attack helicopters. Ring-laser gyroscopes are the basis for extremely accurate guidance systems on aircraft and missiles.[1]

Communications systems based on directed energy, specifically lasers, may provide the solution to the military's growing problem concerning the availability of bandwidth needed to support an increasingly network-centric, information-dependent force structure. Certain frequencies also have unique properties. Blue-green lasers have been of particular interest to submarine services because of their ability to penetrate well below the surface without attenuation. In general, laser-based communications can provide high-capacity, reliable, and secure communication between widely distributed, mobile military platforms.[2]

Directed energy is even more pervasive in the civilian and commercial worlds. We are surrounded by directed-energy systems from the microwave oven in our kitchens to scanners at supermarket checkout counters to the laser-surgery clinics in shopping malls. What is a fiber optic communication system but the focusing of light down a spun glass pathway or, in other words, energy directed along a confined path? Industrial lasers are employed for a myriad of functions in a wide variety of businesses both as measuring devices and as tools for cutting and shaping materials. Laser spectroscopy has allowed enormous advances in medical and materials research and such devices are essential equipment in any modern laboratory or research establishment.

Speed, precision, and tunability are all, to a greater or lesser extent, inherent characteristics of directed-energy systems that have made them desirable in both the commercial/civil and military environments. Speed and precision (focused power) are also characteristics of computer systems. It was the computer that allowed directed-energy technology to move from the laboratory shelf to ubiquity. Advances in computer controls and computer-aided design and manufacturing have enabled the explosive growth in directed-energy applications. The deployment of directed-energy weapons is a natural follow-on to the current RMA empowered by the information technology.

The weaponization of directed energy, which involves much more than simply increasing the system's power output, could prove as transformational a step for the U.S. military as was the initial introduction of directed-energy-based targeting and communications systems. The ability to focus several megajoules of energy (the equivalent of two sticks of dynamite) in a laser spot the diameter of a basketball on a target up to several hundred miles distant and moving at a thousand miles an hour, within a few seconds of acquiring it, is clearly a technological revolution, and potentially a military one as well. Directed-energy weapons hold forth the potential not merely of speedily killing a target, but of imposing variable effects through the management of the amount of energy employed.

Directed-energy weapons may be more than a force multiplier. They may be critical to military operations in an environment where there exist significant restrictions on the use of traditional explosive/kinetic weapons. One senior defense-industry official described the operational concept behind the push for directed-energy weapons thusly:

> Our strategy is simple. We want to replace high explosives with directed-energy weapons. Any munitions or platforms that carry high explosives, we want to replace with [directed-energy weapons]. We want to enable new missions where . . . high explosives [are called for but can't be used] because of problems of collateral damage or the need for a facility after the conflict.[3]

Directed-energy weapons may also be uniquely suited to support creation of so-called partly close space to standardize "system-of-systems" architectures such as those envisioned by people like retired Admiral William Owens.[4] Generally, in order to exploit the unique characteristics of directed-energy weapons, speed-of-light sensing capability is required. In essence, this would be a lower-power variant of the directed-energy weapon itself. The Airborne Laser (ABL) is itself a "system-of-systems," deploying both a laser for environmental sensing and another as a target designator in addition to a main weapons system.[5] These and other supporting sensor systems will enable the ABL to serve as a powerful battlefield intelligence collector, independent of its role as a weapons platform.[6]

Directed-energy weapons may have a unique role to play as defensive systems. The combination of rapid reaction times, long ranges and speed-of-light engagement is particularly attractive under conditions of short warning or times of flight for attacking systems. The Air Force Science Advisory Board recognized this possibility as far back as 1968.[7] It is not surprising that the initial focus of development for directed-energy weapons was both defensive and in the area of missile defenses. The targets are moving very fast, they are relatively fragile, operating under stress and the time from attack warning to impact may be only a few minutes.

The offensive role for directed-energy weapons is a product, in some instances, of their speed of response and range and, in other instances, of their precision and tunability. Directed-energy weapons may allow their users to operate outside the range of an adversary's weapons or to attack more swiftly.[8] Directed-energy weapons may also be able to more precisely engage potential targets in difficult or complex environments with a lower risk of collateral damage than might occur with an explosive or kinetic weapon. Certainly microwave weapons offer the prospect for nonlethal kills of a wide range of targets and systems with little risk of collateral damage. Another attribute of directed-energy weapons that make them useful in an offensive role is stealthiness. They usually provide no signatures that would allow an adversary to know he is under attack or from whence the attack originated.[9]

It is important also to consider the complementary role of directed-energy systems as sensors, as well as weapons. The ABL clearly has a major role to play in future air operations as a sensor platform. Directed-energy systems offer major improvement over existing capabilities for long-range, high quality target identification and tracking. One experimental device, the Sea Lite Beam Director, has demonstrated the capability to monitor complex missile engagements at long range. According to the Defense Science Board, "the ability to positively identify a contact at such ranges is quite possibly the most underrated attribute of a high-energy laser weapon system, and would likely become the most commonly used capability of such a system."[10]

Lasers and HPM weapons can generally be viewed as complementary ways of delivering energy on a target. There is one important difference between the two. The performance of lasers can be severely impacted by atmospheric phenomena. This is not the case with HPM weapons. Unlike lasers, microwave frequencies can penetrate clouds, water vapor, rain, and dust. Thus, they can be used under any weather conditions. They are able to transmit energy through clouds or fog.

The overall offensive utility of directed-energy weapons depends to a large degree on the vulnerability characteristics of the prospective targets. Directed-energy systems are most effective either against thin-skinned targets such as ballistic missiles and satellites, or against electronic sub-systems or components of hardened or armored targets. In the latter case the damage inflicted may not always prove lethal. Battle damage assessment may be more difficult in the event that the directed-energy attack is on electronic systems.

If the well-documented and understood technological and engineering hurdles can be overcome, directed-energy weapons could not only supplement and enhance traditional military capabilities but, in some important instances, supplant them. Directed-energy weapons not only offer advantages over conventional systems in speed of light engagement, rapid retargeting, long range, greater precision and lower cost per kill, but also the potential for a range of effects from simple interrogation of a target to non-destructive kill. In addition, directed-energy weapons offer a means for exploiting new domains, most notably outer space, for tactical purposes.

II. OPERATIONAL IMPACTS OF DIRECTED-ENERGY SYSTEMS

Innumerable studies, including recent ones by the Defense Science Board and the U.S. Air Force, have pointed to the possibility of directed-energy weapons revolutionizing warfare. The future of directed-energy weapons is likely to be decided in the next few years as existing programs, most notably the Airborne Laser (ABL) and Tactical High Energy Laser (THEL), are successfully developed and fielded. It may matter less how these two systems affect military operations (although they may have substantial impact) than that they demonstrate that the technological and engineering hurdles associated with weaponizing directed energy can be overcome. Dr. Richard Cooper, former director of the Defense Advanced Research Projects Agency (DARPA), described the importance of the current programs this way:

> Current development programs (ABL, SBL,THEL) are a cross between feasibility demonstrations and prototypes. When testing is complete, the test results will answer the 'prime time' question unequivocally.[11]

The DOD High Energy Laser Master Plan categorizes the operational applications of lasers as either defensive or offensive in nature.[12] This basic division is equally applicable to other directed-energy weapons. Applications in the first category include ballistic-missile defense, cruise-missile defense, counter-artillery and rockets, defense against surface-to-air missiles and counter-electronics, particularly sensors and targeting systems. Offensive applications could include airborne precision strike against a range of targets, counter-air, direct fires against ground and air targets, nonlethal anti-personnel attacks, and anti-satellite operations.

Directed-energy weapons will make their appearance on the battlefield over time, as the technologies associated with power generation and management, beam control and targeting continue to improve. In the case of laser weapons the limiting factors are power levels and the weight/size of the laser systems. Efforts are underway to improve the performance of existing chemical lasers and to field lower-power but much more compact solid-state lasers. The introduction of the latter will open up a new set of operational applications. With respect to high-power microwave (HPM) devices, the range of possible applications will depend on the ability to achieve adequate power levels in a sufficiently small and lightweight package and, for some potential uses, the ability to concentrate and direct the microwave energy.

It is useful to consider the operational applications of directed-energy weapons, as they are likely to unfold over time, based on improvements in the relevant technologies. In the near-term, directed-energy weapons are likely to be limited largely to the missile-defense mission. Some applications of HPM for precision strike are also possible. In the medium-term, that is, over the next decade, as technology matures, a wide range of new applications are likely to emerge. In the farther-term, there is the possibility of exploiting directed energy to create new military capabilities such as weapons in space.

Near-Term Missions

Just as the advent of ballistic missiles early in the Cold War revolutionized offensive operations, the advent of directed-energy weapons could revolutionize strategic and theater missile-defense operations. The basic characteristics of directed-energy weapons make them particularly well-suited to the missile-defense mission. The most significant operational impediment, as distinct from technological limitations, of directed-energy weapons is the requirement for line-of-sight to the target. Directed-energy weapons deployed at fixed locations do not necessitate the kind of trade-off between power/range and weight that conventional weapons do. For obvious reasons, however, their operational utility is likely to be fairly narrowly circumscribed. Whether directed energy will truly revolutionize missile defense will depend on the success of current programs to make directed-energy weapons mobile.

The Airborne Laser (ABL) and Mobile Tactical High Energy Laser (MTHEL) hold forth the possibility of revolutionizing defense against theater/tactical ballistic missiles and battlefield rockets. The ABL offers the advantages of a missile-defense system that is both mobile and operationally flexible. The ABL could provide the first and, in the absence of space-based weapons, possibly only means of conducting boost-phase intercepts of ballistic missiles. It will be highly responsive, more so than sea-based or mobile land-based missile-defense systems such as Navy Theater Wide or the Theater High Altitude Area Defense (THAAD). Under some circumstances a space-based directed-energy system could provide greater responsiveness. However, there are other issues associated with space-basing of directed energy, technical as well as operational and political, that could limit the potential of such a system. Space-based directed-energy weapons will be discussed later in this section.

The ABL is intended to operate against ballistic missiles in the early or boost phase of flight. This is the most desirable phase of the flight path in which to engage the missile since the booster itself is under extreme stress and it cannot release its warheads or employ countermeasures. Boost phase intercept can provide global protection. With its advanced sensor suite, the ABL can operate as a stand-alone missile defense system or as part of a layered system, along with other U.S. and allied forces. With a magazine that will hold 16-20 shots, the ABL alone should be able to counter the relatively small number of ballistic missiles that most prospective U.S. adversaries will be able to deploy in the next 10-15 years.

The concept of operations for the ABL is similar to that established for other large airborne electronic-warfare and intelligence platforms. Once on station, the ABL will establish a patrol pattern inside friendly airspace but within range of known or suspected missile launch areas. The plan is to deploy three ABLs as a squadron; with aerial refueling, this will allow maintenance of one aircraft aloft at all times. Operating in this mode, an ABL could provide defensive coverage of at least 60,000 square kilometers.

The ABL will not be able to hold all ballistic missiles at risk. It must be able to loiter in secure airspace. The ABL will also require bases within a reasonable distance of its operational positions. For this reason, the ABL will not pose a threat to the Russian or Chinese ICBM forces.

The ABL's primary mission is missile defense. Its suite of sensors will support a secondary mission as an intelligence, surveillance and reconnaissance (ISR) platform. In addition, the ABL has inherent capabilities to conduct suppression of enemy air defense (SEAD) missions either for self-defense purposes or as part of an overall air campaign.[13] Given the ABL's limited magazine, its employment for other defensive missions would have to be weighed against the importance of maintaining the capability to address the ballistic-missile threat.

The ABL is envisioned to be part of the Air Force's Global Strike Task Force (GSTF).[14] The GSTF will consist of the Air Force's most advanced, stealthy systems such as the B-2 and F-22, employed at the outset of hostilities to establish airspace dominance, neutralize enemy air defenses and strike strategic targets, including WMD and ballistic missiles. The role of the ABL would be, first, to prevent the launch of ballistic missiles until such time as an adversary's ballistic-missile force was destroyed and, second, support the operation of other GSTF elements by conducting ISR and/or SEAD missions. As the Air Force develops an ISR architecture capable of conducting persistent surveillance of the battle space, it may become relatively easy to eliminate any guesswork associated with deploying ABLs within range of an adversary's ballistic missiles.

Although intended primarily as a missile-defense system, the ABL, if deployed in sufficient numbers or with a larger magazine, could fundamentally alter the character of future air war. The ABL provides extended reach against hostile air platforms.[15] Even were the ABL unable to cause physical damage to a hostile air platform, it could degrade sensors and other electronic systems. Although unable to detect and track targets below cloud cover, it could operate at lower altitudes if there was a sound military reason to so do. In addition, it is possible that operating in conjunction with other sensor platforms able to provide targeting information, a more powerful version of the current ABL could attack targets operating below cloud level while maintain a position above the clouds.

In describing its modernization program, the Air Force repeatedly points to the potential threat posed by so-called "double digit SAMs," meaning surface-to-air missiles comparable in performance to the Russian SA-10 or SA-12.[16] The ABL could contribute, along with stealthy aircraft armed with standoff weapons, to the defeat of the future SAM threat. With its speed-of-light engagement capability, the ABL could provide a terminal defense of U.S. air platforms attacked by SAMs.

Even in its current configuration, the ABL could also contribute to Air Force operations designed to establish and maintain space control. At one megawatt of energy on target, the ABL could be employed against satellites in low Earth orbit. While it is unlikely that the ABL could cause catastrophic failure of a satellite, it could interfere with optics and electronics.

The U.S. Army's THEL program, in contrast to the ABL, is designed solely for active defense, and then only against relatively short-range threats such as battlefield rockets, artillery shells and mortars. The THEL program is part of the High Energy Laser – Tactical Army (HELSTAR) program intended to develop a multi-platform, multi-mission directed-energy system for deployment as part of the Objective Force.[17] The THEL Advanced Concept and Technology Demonstration (ACTD) resulted in the development of a transportable, ground-based laser weapon system with the capability to intercept multiple rockets in flight. To date, the THEL ACTD has conducted more than 25 successful intercepts.[18] The THEL program's accomplishments led a senior DOD official to observe that, "Successful shoot-downs of tactical rockets indicates that laser weapon technologies may possess the maturity to begin integrating them into operational forces."[19]

A directed-energy system such as THEL appears to be the only means with which to meet the Army's requirement for an active defense against the extremely short time-of-flight threat posed by rockets, artillery and mortars (RAMs).[20] By their nature these targets are extremely hard and are accessible to a defensive system for a very short period of time. Current ways of addressing these threats include target movement and dispersal, target hardening (armor plate or other shielding materials) or counter-battery fire. When the target of an attack is a fixed installation or, as has been the case in Israel, urban areas, none of these methods has proven to be particularly effective.

The addition of a tactical directed-energy system to the Army's inventory of defenses against RAM threats could significantly impact ground force operations. Rocket, artillery and mortar threats have proven to be among the most difficult for U.S. and coalition forces to defeat. U.S. indirect fire systems, particularly artillery, are often out-ranged by those available to U.S. adversaries. It is often difficult to identify the launch locations for these threats in order to conduct counter-battery fires. Particularly in low-intensity conflict situations, an adversary could deploy his RAM systems in urban terrain complicating both ISR and counter-battery fires. The threat posed by hostile fire could increase substantially as adversaries acquire advanced precision munitions, particularly those with anti-armor capability. Faced with such a threat, active defenses become all the more important.

An advanced version of the THEL system could be employed against a range of air-breathing targets such as ground-attack aircraft, helicopters, UAVs (Unmanned Aerial Vehicles) and cruise missiles, depending on how the directed-energy weapon is deployed.[21] The United States is not the only country investing in UAVs for both ISR and strike purposes. The importance of efforts to deny adversaries ISR information will grow as the U.S. Army transforms itself into a lighter, more agile force with the introduction of the Stryker Interim Armored Vehicle and the follow-on Future Combat System (FCS). The survivability of the Army's future ground elements will depend to an unprecedented degree on a combination of mobility and information dominance. Counter-ISR will take on an increasingly prominent role in future Army operations. Directed-energy systems could play a critical role in meeting the requirements of the counter-ISR mission.[22]

The THEL program has demonstrated the high-speed target detection, acquisition, tracking, engagement and kill capabilities required for a useful tactical directed-energy system. The system's one significant drawback is its lack of mobility. The proposal to create a mobile THEL or MTHEL system is intended to address this shortcoming. The goal of the program would be to reduce the overall size and weight of the THEL components, specifically the radar and the laser itself, so that each could be mounted on a truck.[23] The system also must meet fairly stringent weight limitations if it is to satisfy the current goal of being transportable by a C-130 aircraft.[24]

The one significant offensive application of directed energy likely to be available in the near-term is the high-power microwave "bomb" (HPM). Such a weapon, in which detonation of an explosive charge creates a pulsed-power source to drive the HPM generator, could play a role in the disruption and even destruction of a wide range of electronic systems.[25] HPM weapons have very interesting operational characteristics. First, an HPM weapon is an area weapon, whose area of effect is determined by the frequency generated, the area of view of the antenna and the power of the pulse generator. Second, all targets within the area of effect will be attacked simultaneously (because HPMs can generate an electrical pulse over a wide area they can be used effectively against imprecisely located targets). Third, they can achieve a "system kill" by damage inflicted upon electronic circuits, components, and subsystems. Fourth, HPM's are effective against electronics even when those systems are turned off. Fifth, the only effective defense is to completely isolate the target from means of conducting energy -- a step that would in all likelihood produce a mission kill. Sixth, because they use an electromagnetic pulse that can affect electronic systems from a distance, HPM weapons offer the prospect of reduced collateral damage.[26] Finally, HPM weapons are inherently tunable, allowing the user to graduate the effects imposed on the target.[27]

Among the most likely near-term applications of high-power microwaves are as an adjunct to precision-strike weapons. An HPM weapon could address the problem posed by underground or deeply buried targets.[28] In addition, an HPM weapon could be employed against targets in urban environments or where collateral damage and casualty concerns constrain the use of explosive or kinetic weapons. [29]

HPM weapons could be used to support SEAD operations. Air defenses are extremely intensive users of electronics for ISR, command, control and communications and targeting. By their very nature, air defenses are potentially highly vulnerable to even minor electronic upset. System upsets or the degradation of components could prevent an air defense system from accurately detecting or tracking inbound aircraft and missiles, or from passing that information rapidly either up or down the chain of command. Centralized air defense networks could be especially vulnerable to disruption of the operation of command centers or ground controlled intercept sites. Depending on the power of an HPM weapon and the distance between elements of an air-defense site, a single HPM weapon could have the effect of several conventional weapons, such as the High Speed Anti-Radiation Missile, by simultaneously disabling or destroying the radar, missile launcher and associated command and control stations.[30] Even a limited attack by HPM weapons on an air-defense network could have a devastating impact on its effectiveness.

Microwave devices may also find utility as nonlethal anti-personnel weapons. There is an increased interest among militaries the world over in technologies that would permit the nonlethal application of force, particularly in complex and urban environments, with a high likelihood that noncombatants will be present.[31] The ultimate goal is to find the equivalent of the Star Trek “phaser” that could be set on stun.

The Joint Nonlethal Program Office is developing an Active Denial System that is based on the use of a focused millimeter-wave beam to cause painful heating of the skin out to ranges of as much as 750 meters.[32] A microwave-based weapon has distinct advantages over existing nonlethal anti-personnel weapons such as rubber bullets or electric stun guns. The first advantage is significantly greater range. The second, according to reports, is the relative safety of such a device. Unlike other potential candidates that can cause disabling or even, on some occasions, lethal injuries, the device being tested in the Active Denial System only penetrates the first skin layer and cannot cause permanent injury.

Integrating directed-energy weapons systems into existing force structures and operational concepts, without a doubt, will pose a number of challenges. Not the least of these is the coordination of directed-energy operations with those of other forces on what may be relatively crowded battlefields. The problems of weapons deconfliction and battle-space management are not new. But the problem may be more acute for the U.S. military, given its intensive use of information technologies, than for others. While laser systems are extremely precise, reducing the risk of friendly fire casualties, the effects of near-term HPM “bombs” are indiscriminate within their area of influence. Thus, it will be important to develop procedures for the employment of HPM weapons that ensures the safety of U.S. and coalition forces.

Emerging Roles and Missions

Several years ago, the U.S. Air Force published a report that looked to that service’s future. The study, titled *New World Vista*, focused much of its attention on the development of directed-energy weapons. The study asserted that both laser and HPM weapons would become commonplace in the future. Missile defense would remain a core mission for directed-energy weapons. In addition, the study envisioned that directed-energy weapons, due to their speed-of-light engagement, would be employed to defeat anti-aircraft missiles by blinding the missile’s seeker or damaging vital electronic components. The study envisioned two classes of directed-energy weapons: "compact weapons constituting only a small fraction of the aircraft payload, for short-range self defense, and medium-range weapons, constituting a primary payload, employed for escort defense." Ultimately, the study concluded, directed-energy weapons would be deployed on a variety of airborne systems, both manned and unmanned, to support air-to-ground operations.[33]

One key to the exploitation of directed energy for the range of missions proposed by the Air Force and Army is the development of compact devices that can be carried on aircraft, deployed on ground vehicles or even carried by individual soldiers. With respect to lasers, this means developing solid-state devices in the 100 kilowatt range – as compared to the ABL's one megawatt system. For HPM weapons, these roles would require systems that could operate from power supplies that could be carried aboard an aircraft or ground vehicle. The onboard engines could power a directed-energy weapon in the case of large aircraft and, even more so, ships.

Another key is the development of the Unmanned Combat Air Vehicle (UCAV). The limits of current engineering are likely to restrict the effective power, and hence the range, of aircraft-deployable directed-energy systems in the medium term. However, even at relatively low power levels, directed-energy weapons can be effective at disrupting electronic systems if the weapon and the target are very close. An effective tactical laser weapon would require power levels of approximately 100KW. A 100 KW solid state laser or its HPM equivalent would have an effective range of perhaps 15 kilometers, depending on the effect being sought. This may not matter for defensive purposes, but could pose a problem for the offensive use of directed energy. Increasingly, the Air Force is looking to provide standoff engagement distances of 50 kilometers or more for both air-to-air and air-to-ground missions.

A UCAV would provide the means for introducing short-range directed-energy weapons into an intense air-defense environment. There is also great potential for a stealthy UCAV armed with a directed-energy weapon to be very effective as a preemptive weapon or in suppression of air defenses. Air Force Chief of Staff General John Jumper described the combination of the UCAV and directed-energy weapons, in this instance an HPM weapon, as follows:

> If you combine directed energy with the UCAVs of the type we have today, you have a combination that uses stealth to go into [heavily defended territory and HPM to] tell the SA-10 that it's a Maytag washer on the rinse cycle rather than a missile about to shoot somebody down. You can fly this thing in and debilitate in various ways the sophisticated communications and electronics that are going to cause you the greatest worry [and make the attack] with deniability. I don't think it will compete with F-15Es and the Joint Strike Fighter, but it would be valuable to commanders in an [air defense] suppression or information operations role.[34]

A UCAV with a directed-energy weapon could attack a large number of targets in a single sortie. A microwave-armed UCAV could be the ultimate SEAD weapon, able to fly over known sites or along penetration corridors as a precursor to the ingress of manned aircraft or cruise missiles. Even if the air-defense system were turned off, a tactic used by Serbian air defenders during the Kosovo campaign, the microwave would still be able to attack radar and missile sites. So long as the UCAV had fuel to fly and energy for the HPM weapon, it could continue to operate against hostile air defense and command and control sites.

Lightweight, hence short-range, directed-energy weapons are also desirable to meet future Army missions. Such weapons would be based either on solid-state laser devices or HPMs. While the MTHEL will be mobile, it will still be a relatively large system. The Army's ultimate desire is for a directed-energy weapon that can be deployed on a single vehicle.[35] One of the attractive features of lightweight directed-energy weapons employing a vehicle's own engine or portable power source is the potential for very deep magazines. In essence, as long as power is available, meaning diesel fuel or gasoline, the weapons should be able to operate.

The impact of directed energy could be equally profound on the air-to-ground battle. In addition to the HPM "bomb" discussed above, directed-energy weapons could be employed on tactical fighters, UCAVS and gun ships for use against ground targets. Such weapons would be particularly useful against thin-skinned targets or where electronic systems are present. Even relatively hard targets such as main battle tanks could be vulnerable to the effects of HPM, on critical electrical and electronic sub-systems.[36] A ground-attack laser could be particularly valuable for close-air support and offensive counter-air missions involving attacks on fuel supplies, ammunition storage areas and aircraft on the ground. A future AC-130 gunship could be equipped with both cannons and directed-energy weapons, allowing it to engage a broader range of targets and to defend itself against short-range SAMs.

A possible variant of the directed-energy-armed UCAV or AC-130 gun ship is the Advanced Tactical Laser (ATL). The ATL would be a platform-independent system that could be deployed on a ground vehicle, ship, tactical aircraft or rotorcraft. The ATL would perform a number of missions including precision target engagement and high-resolution imagery for target identification.[37] In theory, such a system could be deployed aboard a transport aircraft or a V-22 as a defensive escort with early-entry forces, and then be removed from the aircraft and mounted on a ground vehicle to provide direct-fire support or air/missile/artillery defense to ground units. An ATL could also provide an aerial defense against cruise missiles and a means of both defense and counter-battery fire against artillery, mortars and rockets. It has also been suggested that because of its high precision and lack of signatures when fired, the ATL would be an excellent long-range precision strike system for Special Operations Forces or for ground forces operating in an urban environment.

HPMs weapons could provide new means for conducting both interdiction operations and strategic strikes. The weapons could permit attacks on strategic assets without risk of collateral damage. HPM systems could be employed to strike a wide range of military and defense industrial assets including air-traffic control systems, rail yards, military and civil communications, industrial facilities, equipment stockpiles, ammunition and fuel and even vehicles carrying military equipment or troops. Because of the inherent tunability of HPMs, they could be employed strategically in a compellance campaign designed to inflict gradually increasing pain on an adversary through a process of escalating effects on strategic targets. In addition, such weapons could be employed in counter-proliferation operations against WMD production, storage sites and against delivery systems.

Directed-energy weapons could dramatically affect land warfare too. For example, directed-energy-equipped aircraft might provide close air support for ground forces. In this role laser-equipped aircraft would target command and control capabilities, communications, electronic-tracking systems, artillery radars, and even ground platforms. The Defense Science Board has encouraged the U.S. Air Force to examine ways of employing the ABL against critical, time-urgent ground targets.[38] An HPM-armed aerial system could conduct undetected attacks on hostile forces merely by passing within the appropriate range.[39] HPM warheads could also be delivered against ground targets by long-range Army artillery, the Multiple Launch Rocket System or the ATACMs battlefield missile.

Directed-energy weapons could become a critical element of the Army's future Objective Force. Central to the creation of the Objective Force is the Future Combat System (FCS). The Objective Force is intended to enable a revolution in ground warfare, exploiting a wide range of advanced technologies to create a lightweight, strategically deployable and operationally mobile ground capability. The FCS is envisioned as a "system-of-systems" employing both manned and unmanned ground and aerial vehicles equipped with a wide range of weapons, including directed energy.[40] The inclusion of directed-energy weapons in the FCS "system-of-systems" is particularly interesting to those designing the Objective Force in no small part because directed-energy weapons could significantly reduce the logistics burden on the Objective Force. As discussed by the DSB Task Force, the FCS could employ directed-energy weapons to perform a number of missions including counter-surveillance, air defense and mine clearance.[41] Directed-energy systems could be deployed across the full range of manned and unmanned FCS platforms. One particularly important role for a vehicle-mounted directed-energy weapon is active defense against short-range artillery, mortars and rockets. Another possible application is the use of HPM as a means of defeating mines and addressing the danger posed by unexploded ordinance at a distance.[42] Currently, no effective remote means of de-mining exists.

The U.S. Navy has long been interested in directed-energy weapons for ship self-defense. The potential value of directed-energy-based defenses has increased as the Navy is required to operate more in littoral waters where it faces a growing threat from high-speed, sea-skimming anti-ship missiles.[43] In addition to ship-based directed-energy weapons, the Navy could also deploy airborne directed-energy weapons systems on tactical fighters, helicopters or rotorcraft. Such systems would be expected to complement current Navy investments in the Radar Modernization Program for the E-2C Hawkeye and in network-centric warfare to provide enhanced over-the-horizon defense against cruise missiles. Directed-energy systems could serve both as high-resolution sensors, adding to the capabilities provided by other Navy intelligence and surveillance systems, or as weapons, exploiting the advantages provided by a networked force.[44]

In addition to the threat of high-speed, sea-skimming cruise missiles, the Navy is confronted by the littoral challenges posed by small boats and sea mines. To counter this challenge, the Navy is considering developing a new class of ship, the Littoral Combat Ship (LCS).[45] The Navy's intention is to design the LCS to address a wide range of missions in littoral waters. The Navy hopes to rely heavily in the LCS program on unmanned vehicles, both air and sea-based, and on advanced weapons technology. Directed-energy sensors and weapons deployed on the LCS or its unmanned auxiliaries could be particularly valuable in countering the threats posed by small boats and planes, sea mines and short-range anti-ship cruise missiles.

The Navy is exploring the potential of the free-electron laser (FEL) for shipboard missions. An FEL can be powered by a ship's electrical power sources, rather than requiring a separate, chemically-based power source. The FEL appears to be more suitable to the range of environmental conditions that would confront a directed-energy system at sea level (e.g., fog, rain, wave induced mists, etc.).

The Navy is currently looking at solid-state lasers to enable earlier entry of the weapon system into the Fleet. The goal is to deploy such a weapon onto a ship sometime this decade to allow the Navy to better understand its capabilities and operational concepts in a real maritime environment. The next generation of lasers for the Navy then may very well be FELs on the DDX destroyer. However, looking at the Navy's re-capitalization plan it will be decades before all the legacy ships are gone. Therefore, the Navy is looking at solid-state lasers as a prudent means of getting a laser weapon on all these non-DDX ships.

The final emerging mission for directed-energy weapons is that of space control. Space control includes both the defense of U.S. satellites from attack and actions taken to deny the use of space by adversaries. Such actions are not limited to the destruction of hostile satellites but include as well the temporary degradation of operation. Indeed, because the United State must confront the growing use by adversaries of commercial communications and surveillance satellites, it needs to develop less-lethal means of preventing the exploitation of space by hostile forces. One potential advantage of employing directed-energy weapons against satellites is deniability. Virtually no satellites, military or commercial, today possess attack warning and characterization sensors that would enable them to report they were under attack by a directed-energy weapon.

The extent to which the U.S. could successfully engage in the mission of controlling space depends on the type of directed-energy architecture that is developed. A system that could be deployed in the next decade or two would have to be based on the ABL or a ground-based directed-energy system. The current-generation ABL is judged as having capability to degrade or damage low-orbiting satellites but a high-confidence system would require a laser at least twice as powerful as that developed for the ABL.[46] A ground-based system has the advantage of nearly unlimited power and can employ very large optics for increased range. However, a system can only operate against satellites within its line-of-sight. To deploy a global space-control capability, the United States would have to invest in a constellation of space-relay mirrors which could convey energy from the ABL or ground site(s) to a battle mirror that would deposit it on the target.

There are reports that the U.S. Air Force is investing in a transportable laser system designed to temporarily "blind" electro-optical satellites.[47] A laser beam can "dazzle" an optical satellite's sensors, much like shining a powerful flashlight into a person's eyes. At low power such a "dazzling" effect would be temporary, but at higher power levels it would permanently damage or destroy optical receivers. Similarly, an HPM device could interfere with the operation of satellite downlinks or operate directly against space-based electronic systems.

As adversaries acquire advanced ISR capabilities, including access to very high quality space-based imagery and long-range strike systems, the struggle for information dominance in future conflicts will require the ability to interfere with information collection and targeting and to prevent the transmission and processing of data. This means, in part, that the United States must be able to deny adversaries access to information from space-based surveillance systems.

Farther-Term Missions

Beyond 2015, increases in output power combined with reductions in the size and weight of directed-energy weapons could permit them to be deployed widely on tactical aircraft. In 1998-99 the Air Force Research Laboratory sponsored the Directed Energy Applications for Tactical Airborne Combat study. That study concluded that it was both possible and desirable to arm future airborne platforms, including tactical aircraft, with directed-energy weapons.[48] A very important conclusion of the study was that weather, particularly clouds and other obscurants, would not significantly degrade the performance of a tactical high-energy laser.

The 2001 Defense Science Board Task Force on High Energy Lasers also concluded that once the ABL has demonstrated its war-fighting utility, the next step is the development of an airborne tactical-laser capability. Such a system, the task force noted, would provide many useful mission capabilities, including: unlimited magazines, long standoff ranges, precision engagement, speed-of-sight engagement, aircraft self-defense, multifunctional operations, and of particular interest in an era of "double digit" SAMs, the ability to recapture the battlefield to 15,000 feet.[49]

The combination of a second-generation ABL and a directed-energy tactical aircraft system would transform air-to-air and air-to-ground operations. A second-generation ABL would be lighter and smaller than the current system, have a more powerful laser with an increased lethal range and/or a larger magazine. Such a system would be able to "sanitize" a larger area and engage more targets than can the current ABL. At shorter ranges, a second-generation ABL could also strike ground targets, contributing to the precision-strike and SEAD missions.

The Defense Department is considering the deployment of directed-energy weapons on a range of platforms including UCAVs, an advanced version of the AC-130 gunship, and even the F-35 Joint Strike Fighter.[50] The development of relatively compact and lightweight laser or HPM devices would revolutionize tactical air operations. Directed-energy systems could be employed both as a weapon, engaging air-breathing and ground targets, and as an advanced sensor capability for tracking and targeting airborne and mobile ground targets. A directed-energy weapon could be built integrally to the F-35 or UCAV, drawing power from a drive shaft, or could be carried internally or externally as single-shot munitions.[51]

Directed-energy weapons will change the character of air warfare, both defensively and offensively. One of the first emerging missions for laser weapons will be aircraft self-defense. Heat-seeking SAMs are demonstrating increased capability to overcome passive countermeasures such as chaff and flares. The Air Force has an active program to develop a directed-energy-based Large Aircraft Infrared Countermeasures system designed to actively engage IR missiles, particularly man-portable SAMs.[52] A similar system could be employed on tactical aircraft, providing space and energy where available. Because the target of such a defensive system would be approaching the directed-energy-armed aircraft, the power requirement and size of a defensive system should be relatively modest. Deployed in rotating pods, such a system could provide 360-degree defensive coverage. Triggered by the aircraft's own missile-warning system, the infrared countermeasure system could rapidly engage multiple SAMs.[53]

Directed-energy systems could replace cannons and, eventually, even missiles, as the primary offensive air-to-air armament for both tactical fighters and UCAVs. A rapid-firing directed-energy system offers the opportunity to exploit the ability of modern phased-array radars to track and target a large number of objects simultaneously. At present, the limiting factor in air-to-air engagements is the number of missiles an aircraft can carry. Directed-energy weapons could overcome this limitation, permitting a few aircraft so equipped to engage many targets. Directed-energy weapons also allow for very rapid target engagement, facilitating improved engagement opportunities against both maneuvering aircraft and low-flying, high-speed or terrain-following cruise missiles.

It is likely that for the foreseeable future, the wisest course will be to equip aircraft with a mix of missiles and directed-energy weapons. Nevertheless, the impact of directed-energy-armed aircraft on the battlespace could be as profound in principle as was the introduction of jet aircraft.

The application of directed-energy weapons technology with the greatest potential to change the conduct of warfare over the long term is in space. Two concepts have been studied. The first involves the deployment of weapons on satellites in space. The second would place the weapon and associated power generation systems on the ground or, alternatively, on an aircraft such as the ABL, but achieve the desired leverage of the high ground of space through the use of a series of space-based mirrors.[54] Space-based directed-energy weapons could perform a range of missions from strategic and theater missile defense to counter-air, strikes against surface targets, offensive and defensive counter-space and ISR support to other forces.[55] By deploying the weapons in space, a nation would be able to maximize the inherent advantages of directed-energy weapons, notably rapid access to targets, speed-of-light engagement, long range and continuous coverage of the battlespace.[56]

Space-based directed-energy weapons could be employed independently or as part of a joint force. Independent operations are particularly important in those instances where only space-based directed-energy weapons can access the target. Independent missions would include both offensive and defensive counter-space, boost-phase missile defense (particularly against a limited number of missiles) and, perhaps, ground strike against critical strategic targets. Space-based directed-energy weapons would operate as part of a joint force in the conduct of layered missile-defense operations, air defense, suppression of enemy air defenses, ISR and targeting support to other forces, and operational ground strikes.

III. LIMITATIONS AND COUNTERMEASURES TO DIRECTED-ENERGY WEAPONS

With the deployment of any new weapons system, there is a need to understand its technical and operational limitations. Directed-energy weapons clearly offer some novel and potentially very important military capabilities that could serve as the basis for entirely new missions and operational concepts. At the same time, there are serious concerns regarding the ability of directed-energy weapons to operate under real-world conditions and to be effective against relatively simple countermeasures.

One of the major criticisms offered against the utility of directed-energy weapons, particularly high-energy lasers, is that they are unable to operate through inclement weather or in the presence of obscurants, whether naturally occurring or man-made. Modern laser systems such as the ABL employ adaptive optics to compensate for the problem of beam attenuation caused by atmospheric turbulence. The ABL addresses the problem of weather and obscurants by engaging targets above cloud level.

Clouds and obscurants are a challenge to the current generation of chemical-laser weapons. This matters least for ABL or an SBL engaging ballistic and airborne targets above cloud level. Clouds are also not a problem for the THEL/MTHEL or similar systems operating near the Earth. However, fog, smoke and other obscurants will be a problem for near-Earth laser weapons.

Directed-energy weapons also must confront efforts by adversaries to counter their effects. A variety of countermeasures are possible depending on the kind of directed-energy weapon and the type of target. Shielding or ablative material can attenuate the effectiveness of continuous-wave laser weapons but will be relatively ineffective against pulsed lasers that use impulse power as their damage mechanism rather than target heating. A highly reflective surface or rapid rotation of the target could also reduce damage from continuous-wave laser attack.

Another potential limit to the military application of directed-energy weapons is damage assessment. Not all electronic systems will respond the same way to the deposition of an equal amount of energy. [57] In light of this, directed-energy weapons will have to be "oversized" in order to have a high likelihood of creating the desired effect even in a resistant target. In addition, the effects on targets of directed-energy weapons, particularly HPMs, may be difficult to assess externally. The absence of electronic emissions from a bunker, for example, may be a sign that the facility was neutralized by HPM weapons or, conversely, that the target is "playing possum."[58]

HPM weapons appear much harder to defend against. Shielding can work, but it is difficult to fully shield either platforms or facilities. There are few systems, particularly conventional weapons, which employ hardened electronics. U.S. nuclear-capable platforms have been hardened against electromagnetic pulse. So too have U.S. Navy ships. Most platforms are not so hardened. It is very expensive to provide such protection. It is likely that only a small number of platforms will have even modest hardening.

A fixed facility such as a command bunker could be built inside a metal grid, a sort of "Faraday cage," in order to be secure against electromagnetic energy. But this is costly. By shutting itself off from the external world, a command center effectively places itself out of action. Or the command center could stock spare electronic devices such as radios and computers in the event of an HPM attack. But it is unlikely that even the best-equipped facility could withstand more than one such event.

Deployment of fiber optic communications networks also can reduce the effects of HPM weapons. But unless the facilities at either end of a fiber optic cable are also hardened, it may make little difference in terms of the overall vulnerability of the network to attack.

The deployment of obscurants or the use of hardening techniques as a countermeasure against laser weapons is neither easy nor cost-free to the defender. It would be extremely difficult to effectively shield aircraft, helicopters or tactical missiles against laser weapons. The same problem exists for light-skinned ground vehicles. It might be possible to incorporate polarizing materials in the canopies of helicopters and aircraft that could reduce the risk of damage to avionics. Providing hardened electronics for vehicle computers, radios and sensor systems would be possible but also would be very expensive.

Directed-energy weapons are not the proverbial "silver bullet." They have a number of potentially very useful, even revolutionary, applications. Like all other weapons systems, they also have limitations and can be affected by countermeasures. However, on balance, their potential impact on the battlefield far outweighs the possibility that they may confront countermeasures.

IV. THE NATIONAL SECURITY IMPLICATIONS OF DIRECTED ENERGY

An assessment of the current state of U.S. directed-energy technology and its potential to change the nature of modern warfare must conclude that directed-energy weapons are the essence of transformation. Directed-energy weapons offer the potential for the most dramatic transformation of modern militaries since the advent of electronics and possibly even gunpowder. The deployment of weapon systems with extremely long ranges, speed-of-light engagement, deep magazines and, in some instances, no obvious countermeasure would naturally revolutionize the way military forces are equipped, organized, supplied and operated.

One of the most interesting and potentially transformative features of some directed-energy weapons is their ability to be employed as both sensor and weapons systems. U.S. military leaders have spoken at length of the importance of shortening the sensor-to-shooter time line. The first and easiest way of doing this is by allowing the sensor to communicate directly with the shooter. The next step in shortening the time line is to place both the sensor and the weapon on the same platform. An example of this is the ABL. The final step in this process is to make the sensor also the weapon system. Such as approach offers sensor-to-shooter-to-target timelines that could be measured in seconds. In addition, it will allow directed-energy systems to contribute to the campaign for information dominance.

Even in the near-term, directed-energy weapons could change the face of air combat. Airborne laser weapons will enable those who possess them to dominate absolutely the airspace within the range of their beams. Directed-energy weapons can engage ballistic missiles, SAMs, and virtually any airborne platform. The current airborne directed-energy technology is limited with respect to power and number of shots available per aircraft sortie. However, current systems could be improved by a factor of ten over the next decade.[59] This would provide a next-generation ABL with a magazine of more than 100 shots. A 100KW solid-state laser could be deployed on small, stealthy UCAVs providing a nearly undetectable capability to achieve air dominance. Laser or HPM weapons would also provide an active defense of aircraft against heat-seeking SAMs. A similar ground-based capability could be used in either mobile or fixed deployments to defend airfields against the threat of short-range, man-portable SAMs.

In addition to employing directed-energy weapons against airborne SAMs, directed-energy weapons hold forth the promise in the near-term for major improvements in SEAD capabilities. Directed-energy weapons will be able to rapidly respond to attacks, locating and attacking even highly mobile SAM systems. HPM weapons could greatly improve anti-radiation attack capabilities and, most significantly, defeat efforts by an air-defense system to survive by turning off electronic systems. Depending on the size of the country and the robustness of its air-defense system, a directed-energy armed force could achieve air dominance within days or at worst a few weeks.

Directed-energy weapons systems could contribute significantly to efforts by the United States to dissuade potential adversaries or proliferators from seeking to acquire a range of advanced military hardware. For example, directed-energy missile defenses, whether airborne or in space, raise the bar to any would-be missile proliferator. Directed-energy systems can provide a highly effective boost-phase defense. In addition, while the initial expense associated with deploying directed-energy-based missile defenses are likely to be high, the marginal costs for increasing the capability of such a system are low. Thus, a directed-energy missile-defense capability can achieve a cost-effectiveness advantage over missile proliferation or even countermeasure deployments. The mere capability to deploy directed energy in space could serve as a powerful disincentive to would-be proliferators or to any desire on the part of Russia or China to engage in a strategic arms race with the United States.

U.S. counter-proliferation strategy has focused, of late, on the potential requirement to preempt the efforts by proliferators to acquire or deploy weapons of mass destruction and their means of delivery. Directed-energy weapons could contribute significantly to preemption operations. HPM weapons, in particular, would be useful in attacking WMD facilities that are buried, hardened or co-located with civilian populations or infrastructure.

Directed-energy weapons, primarily HPM but in some instances lasers too, could greatly enhance the ability of U.S. forces to conduct precise, effects-based operations. Directed-energy weapons can address one of the most problematic asymmetric strategies potential adversaries might pursue: the use of civilian populations as shields. Already, laser guidance systems permit the precise delivery of explosive ordinance against targets in urban environments. Directed-energy weapons would allow strikes against a wide range of targets co-located with civilian infrastructure or even shielded by the presence of noncombatants. Virtually any electronic system can be attacked with HPM weapons without doing direct harm to nearby civilians.

A directed-energy-equipped force could conduct new forms of strategic warfare. In recent conflicts, the United States employed nonlethal weapons to disrupt power generation and distribution. Such systems are relatively crude, relying in essence on a form of physical disruption of power systems. This capability is not tunable nor is it applicable to other target sets. Directed-energy weapons provide the means to engage selectively in strategic strikes against any adversary target that relies on electrical or electronic sub-systems. Modern civil societies, industrial systems and military infrastructures are highly dependent on electric power and electronic systems. Directed-energy weapons will permit those systems to be struck separately or collectively and with a range of effects from short-term disruption of service to sub-system destruction.

In the near-term, directed-energy weapons provide the means whereby the U.S. military can achieve at least limited space control. Employed defensively, directed-energy weapons can provide protection under certain circumstances of U.S. and coalition space assets. Employed offensively, directed-energy weapons can temporarily deny the use of space assets by opponents or, as necessary, cause significant damage or even the destruction of hostile satellites.

In the longer term, the national-security impact of directed-energy weapons will be tied closely to the deployment of weapons in space. Space is a logical location in which to deploy directed-energy weapons so as to make maximum use of opportunities for long-range, line-of-sight target engagement. High-power directed-energy weapons in space could provide the means for militarily dominating not only space, but also the surface of the Earth and the air above it. Space-based, directed-energy systems could provide continuous high-quality, real-time surveillance of the Earth and near-Earth environments as well as instantaneous target engagement.

The problem that space-basing of directed-energy weapons poses for U.S. national security is whether such deployments will require that the United States limit access to space by other countries in order to secure the military advantage that space basing of weapons provides. The principal problem is the inherent first-strike threat created by the co-occupancy of space by two or more directed-energy-armed powers. It is somewhat ironic that the same characteristics that make directed-energy weapons so attractive for operations in the near-Earth environment -- speed-of-light engagement, long-range, deep magazines -- create a potential first-strike instability in space.

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The introduction of new military technologies, particularly if they serve as the catalyst for a Revolution in Military Affairs (RMA), can send shockwaves through the international system. An RMA is a transformation in the way military forces are equipped, organized and employed. It is usually based on the introduction of new technologies. Among the historical examples of technology-driven revolutions in military affairs cited by experts are the stirrup, gunpowder, the internal combustion engine, and nuclear weapons.[1]

It is not surprising that political and legal issues arise when a new class of weapons with radically different characteristics is introduced. Weapons imply power, and changes in power relationships or potentials are central issues in the management of the international system. Among the problems that new weapons can bring forth are changes to the balance of power, strategic instability, arms races, and tensions within preexisting collective-security arrangements.

The legal issues that confront new weapons technologies have to do, in the main, with established laws of warfare and existing international norms. There is a body of international law that does address some limited aspects of directed-energy weapons use. As directed-energy weapons become more ubiquitous and support new types of operations or military activities in new domains, the range of legal issues their use suggests will grow.

The political and legal consequences of directed-energy weapons will be experienced over time as the applications of these technologies expand and their presence in the force structure grows. In the period between 1916 and 1939, the technologies of air power and armored warfare were in their infancy, and they had only limited impact on warfare and the international system. From 1939 on, they became central. Similarly, it took nearly twenty years for precision weapons to become a central element of military force-structures.

I. THE IMPLICATIONS OF DIRECTED-ENERGY WEAPONS FOR U.S. INTERNATIONAL RELATIONS

The early applications of directed-energy weapons are unlikely to have major impacts on the international environment. Initially, at least, the role of directed-energy weapons systems will be extensions of existing capabilities and also will be largely defensive in character. The systems closest to deployment, the Airborne Laser (ABL) and the Mobile Tactical High-Energy Laser (MTHEL), are defensive in character. Even here, their role is tactical in nature. If anything, these directed-energy capabilities may exert some stabilizing influencing on international affairs by offering non-offensive means of responding to threats posed by theater ballistic missiles, short-range rockets and even long-range artillery fire.

However, both systems will have some impact on the international environment as elements of a general movement by a number of nations to expand their abilities to defend against ballistic missiles. The 1972 ABM Treaty never prohibited theater ballistic-missile defense systems. ABL will provide a significant new defensive capability by engaging theater ballistic missiles in the earliest, or boost, phase of their trajectory. The limited number of ABL that will be procured initially and operational constraints on their use suggest that this system will not pose a threat to strategic stability.

Some critics of missile defenses were concerned that directed-energy weapons violated the Treaty's prohibition on developing defenses based on "new physical principles." Since the U.S. withdrew from the treaty in December 2001, even that restriction is no longer applicable. The creation of a nationwide or global missile-defense capability is an event that will have important international consequences -- specifically by undermining the utility of long-range ballistic missiles in the hands of so-called rogue regimes. The role of directed-energy weapons is only ancillary to the development of such a defense.

The situation with respect to the offensive use of directed-energy weapons is similar to that of defensive applications. High-power microwave (HPM) weapons will provide only a limited additional capability beyond that which can be attained with modern precision high-explosive weapons. What is significant is the potential that HPM weapons provide for non-destructive strikes against critical military targets that are co-located with civilian personnel or assets, or those that are dual-use in character. In addition to their military utility against imprecisely located, defended or hardened targets, HPM weapons could provide additional means whereby military objectives can be pursued with a reduced risk of collateral damage.

As directed-energy weapons become more common and the range of missions they can perform expands, their impact on military affairs and international relations will grow. As discussed in the preceding chapter, directed-energy weapons could prove transformational in a number of arenas of conflict. Long-range airborne lasers, the successors to the current ABL system, could fundamentally change the nature of air combat. The ability to “sanitize” large volumes of airspace with a relatively small number of airborne directed-energy platforms might have the same dramatic military and political impact of the construction of the *HMS Dreadnought*.[2] Such a capability could negate billions of dollars of investment in both tactical fighters and surface-to-air missile systems. Nations that wish to deploy credible, effective air power will have to consider how they can acquire directed-energy capabilities.

The initial deployments of directed-energy capabilities also will underscore and even extend the dominance of the U.S. military in so-called transformational capabilities. The research and development portion of the U.S. defense budget by itself is larger than the overall defense budgets of most other nations. At present, no other nation has a program remotely similar to the ABL. Although the MTHEL is a cooperative U.S.-Israeli program, the majority of the funding and technology comes from the United States. Directed-energy weapons rely on advances in C4ISR and systems integration that are the forte of the U.S. defense industry and one of the features that distinguishes the U.S. military from any other. As a result, it is likely that the gap in military capabilities that currently exists between the United States and even its closest security allies will grow larger with time.

Directed-energy weapons could more directly impact the international environment and U.S. foreign policy to the extent they enable new types of missions, particularly involving new physical regimes. The first mission area that could have significant international repercussions is space control. Space control involves the ability of the United States to maintain free access to and use of outer space and, simultaneously, to deny the use of space to adversaries.[3] Directed-energy weapons such as the ABL or a ground-based laser could be employed both defensively and offensively to exert space control. Defensively, directed-energy weapons could attack hostile anti-satellite weapons targeted on U.S. spacecraft. Used offensively, directed-energy weapons could interfere with the operation of hostile satellites, blinding their sensors, damaging electronics and power systems and, if power levels were sufficiently high, destroying them.

The ability to exert space control could dramatically impact military balances and the course of future conflicts. The use of outer space for military purposes is increasingly important not only to the U.S. but also to all modern military powers.[4] Even nations that do not have dedicated military space systems can make use of commercial communications and earth-sensing systems to support military operations. The United States has made it almost a routine practice to acquire all commercial earth surveillance of those regions where U.S. forces are engaged in conflict to prevent that information from being available to U.S. adversaries. Military and commercial navigation is increasingly reliant on space-based navigation (GPS and Galileo). The recent Commission to Assess United States National Security Space Management and Organization (the Space Commission) warned that space would become an arena of conflict. It also concluded that the ability of the United States to maintain control over access to and use of space is of increasing importance in future conflicts.[5]

The United States is the most extensive user of space for national security purposes. This has led many observers to warn that the U.S. military is highly vulnerable to attacks against its space-based systems.[6] The attractiveness to adversaries of attacking U.S. space systems is likely to increase as the U.S. military seeks to exploit information in order to transform itself into a 21st century fighting force. The ability to defend critical U.S. space assets may be the *sine qua non* of success in future conflicts.

The possibility of war in space has been a source of controversy and disagreement not only internationally but also within the U.S. military. Opposition to the "militarization" of space is based largely on the idea that space is a pristine environment, the common heritage of mankind, and thus, should not be a place in which warfare occurs. Opponents of space combat point to the Outer Space Treaty as evidence of an international consensus against militarizing outer space.

Even military experts are divided on the advisability of attempting to pursue space control and, in particular, on deploying weapons that could attack objects in space. Some experts argue that space will inevitably become an arena of conflict, particularly if U.S. adversaries perceive space as the United States' 'Achilles heel.'[7] Others take the same basic facts and argue the opposite solution. According to this perspective, it is precisely the unique dependence of the United States that makes it advisable that Washington seeks to protect outer space from any militarization.[8] The best defense, in the estimation of those holding this view, is no defense at all. In the words of one expert, "There is nothing to be gained, and much to be lost, by rushing such a momentous change in space policy."[9]

Deployment of directed-energy weapons in orbit would have an immediate and dramatic impact on the international environment. Although this is not currently in U.S. long-range defense plans, DoD has supported an R&D program to eventually deploy a space-based laser. Advocates of a strong missile-defense shield have suggested that a constellation of directed-energy-armed satellites, or ground-based lasers with space mirrors, would be the most effective means of defeating a large ballistic-missile attack.

The first nation to deploy weapons in space, particularly long-rang directed-energy systems, might be able to establish unassailable space control.[10] In addition, space-based weapons could provide an extremely effective missile defense and markedly influence particular aspects of terrestrial and near-Earth combat.[11]

It is hard to imagine a time when the decision by one nation, even the United States, to deploy any kind of weapon in space would not provoke strong reactions by other nations. It is likely that other nations would seek to develop and deploy their own weapons in space, if they had the capability, or ground-based anti-satellite weapons. Because space-based directed-energy weapons could serve, in theory, multiple functions (space control, missile defense and offensive strike), it is likely that nations with significant arsenals of ballistic missiles will also seek to proliferate and upgrade those systems in order to maintain an adequate strategic deterrent. Thus, an arms race both in space and on the Earth would be likely.

A situation in which more than one nation deployed directed-energy weapons into space could result in an unstable and even dangerous environment. As one well-known strategic analyst noted some twenty-five years ago:

> If effective laser antisatellite weapons were deployed in large numbers on aircraft by both superpowers, the temptation to strike first might grow. Both sides might perceive that important advantages could be gained by preempting the opposition during a developing crisis.[12]

What Smernoff described was the classic first-strike instability problem that was a favorite topic of strategic writings during the Cold War. Both sides are postured to be vulnerable to a first strike by the other side. Both gain tremendous advantages from going first and risk much by waiting and attempting to strike second. The problem of first-strike instability is rendered more problematic to the extent that either side could readily detect a directed-energy attack on their space-based systems. An antisatellite weapons platform in an equatorial orbit crosses the path of all other orbiting satellites. The speed with which such a system could sweep outer space of hostile satellites would depend only on the rate at which the antisatellite weapon could fire, its total magazine and how rapidly it came within range of its targets. A long-range, space-based directed-energy weapons system would appear to be the optimum first-strike weapon against other satellites.

The deployment of any weapons in space would clearly mark a departure from current practice and custom. It is not particularly relevant what type of weapon is deployed. Space basing is often associated with directed-energy weapons because space offers an optimal position from which to exploit the inherent advantages of speed and long reach inherent in such weapons. However, the first weapons deployed in space are likely to be kinetic/explosive kill or electronic-warfare systems, not directed energy. This technology is more mature and can be deployed on very small platforms that could escape detection. Once such weapons are deployed, however, the "taboo" on weapons in space will be broken and the deployment of directed-energy weapons for satellite defense may be necessary.

Two other applications of directed-energy weapons could impact U.S. international relations. The first is the widespread use of HPM weapons for counter-value targeting. A central virtue of HPM weapons is they do not cause physical destruction while still permitting strikes against a range of high-value targets such as communications systems, power grids, and even critical industries. One of the advantages of HPM weapons in such a campaign is their ability to strike buried and camouflaged targets. Another is that they may be used near sensitive sites such as chemical plants or WMD production facilities with less risk of inadvertent release of harmful chemicals or biological agents.

HPM weapons offer interesting and unique options with which to address the problem of urban warfare. The use of urban terrain has been identified in a number of U.S. studies as a possible asymmetric strategy that adversaries could employ to counter U.S. advantages in conventional combat. Although the use of HPM weapons could inflict pain and suffering on civilian populations to the extent that dual-use targets such as water and power systems are attacked, the extent of the damage caused must assuredly be less than if explosive weapons were employed. Moreover, the costs and time associated with recovery would be substantially less.

Effective HPM weapons could allow the U.S. to conduct non-destructive coercive campaigns. It is possible to envision a nonlethal strategic campaign intended either to punish an aggressor or coerce appropriate behavior from a rogue state.[13] The presence of HPM weapons would provide an additional set of rungs on an escalation ladder. They expand the range of options available to decision-makers.

The second application of directed-energy technology with significant potential to influence the international environment is nonlethal weapons. As U.S. and coalition forces are confronted with growing requirements to conduct peacekeeping activities and with the political sensitivities of the war on terrorism, equipping forces with nonlethal capabilities is increasingly desirable. The conditions which promote the search for nonlethal weapons are articulated quite well in the Joint Concept for Nonlethal Weapons developed by the Marine Corps Joint Nonlethal Program Office:

> Increased interaction between friendly troops and friendly, neutral, or hostile civilian populations has become a feature of the contemporary operational landscape. This is likely to remain the case for the foreseeable future. Two factors account for this development. First, worldwide patterns of population growth and migration have resulted in increased urbanization, not only within the established industrialized states, but also in many undeveloped and developing societies.
>
> Second, U.S. forces increasingly operate in the challenging environment known as military operations other than war. This category of operations includes such missions as humanitarian assistance, military support to civil authorities, peace operations, and noncombatant evacuations. These operations commonly involve close and continual interaction between friendly forces and noncombatant civilians. Some military operations other than war scenarios include the presence of paramilitary forces or armed factions which present a real but ill-defined threat. In these situations, the mission of military forces commonly has aspects that are preventive in nature.[14]

To date, efforts to develop an effective long-range and area nonlethal capability have confronted a number of problems. As demonstrated by the recent Moscow theater tragedy, gases and chemicals are difficult to employ accurately and safely. Moreover, they may violate international treaties. The U.S. is experimenting with a microwave-based technology, the Active Denial System. This may be the first useful long-range, area-denial nonlethal system.

The ability to equip military units with effective nonlethal weapons could have considerable beneficial effects on the conduct of peacekeeping and other similar missions. This, in turn, could help shape national attitudes towards the undertaking of peacekeeping missions. Such a system also could be used by paramilitary and even police forces in riot control situations, minimizing the need to rely on lethal force for crowd control.

II. DIRECTED-ENERGY WEAPONS AND INTERNATIONAL LAW

Throughout history, new forms of warfare have been the subject of international efforts to control their proliferation and use.[15] The effort in the Middle Ages to ban the use of the crossbow may have been the first such attempt. Modern arms control efforts have generally taken two forms. The first are arrangements that seek to place constraints on deployments of subject systems, either by location or numbers. Examples of these include the London and Washington Naval Treaties and the SALT/START Treaties. The other kind of arrangement is a prohibition on the possession/use of such weapons. These include the Chemical Warfare Convention, the Biological Warfare

Convention and the ban on blinding lasers. Rarely has international law or a treaty regime been developed before a new type of military technology is deployed. The law tends to follow technology and practice.

As mentioned briefly above, the deployment of any type of weapon in space is subject to existing international law. The Outer Space Treaty bans the deployment of weapons of mass destruction, generally held to mean nuclear weapons, in outer space or on the Moon. The Treaty furthermore prohibits interference with the transit of objects through space. The Treaty does not prohibit the transit of weapons through space (e.g., ICBMs). Nor does it ban the use of space for military support functions such as intelligence collection, navigation or communications. This has led many observers to conclude that the deployment of non-nuclear weapons, including those employing directed energy, in space would not be a violation of current international law.

Reflecting this view of international law, during the Cold War both superpowers pursued anti-satellite weapons. The Soviet Union developed and repeatedly tested a co-orbital anti-satellite weapon. The United States developed a direct-ascent anti-satellite system. The Soviet system was based on an explosive kill mechanism while the U.S. system used kinetic impact.

The reluctance to break the taboo on deploying weapons in space, over time, does present itself to the international community with the force of customary law.[16] Some observers had challenged the development of missile-defense systems, including those employing directed energy, based on an inherent capability to attack satellites. They argued that the overall capability of a space-based missile-defense architecture to destroy all hostile satellites constituted a "-weapon of mass destruction.[17] The issue of inherent capability was central to many of the compliance decisions taken regarding missile-defense systems. However, particularly with the demise of that Treaty, it is likely that the Bush Administration would assert a demonstrated-capability standard. Under such a standard, a system is only judged by what capabilities it has demonstrated in tests or following deployment. Thus, the ABL would not be judged as having antisatellite capability until it was actually tested against an object in space.

During the Cold War, the Soviet Union often sought to limit the ability of the United States to deploy advanced weapons systems that Moscow was unable to match. The Soviet Union attempted to have precision conventional weapons labeled as weapons of mass destruction based on their potential to cause widespread damage if successfully employed against certain classes of targets such as nuclear power plants. While these efforts ultimately proved unsuccessful, they may have set precedent. The United States should consider the possibility that other nations may seek to have directed-energy weapons banned or otherwise constrained precisely in order to prevent their full exploitation by the U.S. military.

One of the few specific areas in which there is international law regarding directed-energy weapons is that of blinding lasers. With the widespread introduction of targeting lasers, reports of eye injuries began to arise. At the same time, there were reports that a number of countries, including the United States, were developing so-called "dazzling lasers," designed to interfere with enhanced vision systems and targeting lasers.[18] A campaign led by Human Rights Watch resulted in the formulation of the Blinding Laser Protocol of the Convention on Conventional Weapons. The United States signed the Protocol in 1995, and as a consequence a number of U.S. dazzling-laser programs were cancelled.[19]

The precedent set by the ban on blinding lasers is influencing the way the U.S. military is approaching the possible use of nonlethal directed-energy weapons. According to DoD, nonlethal weapons are "weapon systems that are explicitly designed and primarily employed so as to incapacitate personnel or materiel, while minimizing fatalities, permanent injury to personnel, and undesired damage to property and the environment."[20] According to international law and U.S. policy, nonlethal weapons must be shown to be effective while minimizing death or permanent injury. Extensive testing is currently underway to demonstrate the degree of safety attainable with the Advanced Denial System, the microwave-based nonlethal weapon currently in development.

As tactical-laser weapons proliferate, care must be given to understand the possible unintended consequences of their use. It would be wise for DoD and the relevant program offices to assess the possible human effects of anti-material directed-energy weapons such as the MTHEL or the Advanced Tactical Laser. Although such systems are not designed for use against human beings, it is important to be aware of the effects of a missed shot that does strike people.

It would also be worthwhile to anticipate possible concerns that could arise regarding the long-term biomedical consequences of the extensive use of directed-energy weapons, particularly HPMs. Questions have been raised regarding the bio-medical consequences of the use of depleted-uranium rounds. There have been lawsuits filed in the United States regarding the alleged biomedical effects of emanations from power lines. It is conceivable that the U.S. could be accused of war crimes for using HPMs in the vicinity of civilians or if long-term harmful effects could be demonstrated. DoD needs to anticipate possible international concerns and develop appropriate responses.

III. CONCLUSIONS

The international and legal impacts of directed-energy weapons are likely to be directly proportional to their utility and to the extent to which they proliferate throughout conventional force postures. The most powerful impacts of directed-energy weapons on international relations will be a function of their ability to change existing means or methods of warfare or support the creation of entirely new missions.

The combination of airborne and ground-based tactical lasers could radically alter the character of air warfare. The change could be as dramatic as that which ensued with the invention of the dreadnought, the first big-gun battleship. Other nations will scramble to develop both similar and countervailing capabilities. However, the ability of an advanced airborne laser system to attack aircraft and missiles, whether offensively or defensively, suggests that it may be the centerpiece for a new kind of air power. If such a system can also conduct strikes on ground targets, then a true Revolution in Military Affairs will be in the offing.

Directed-energy weapons systems could serve as the basis for a redefinition of the balance between strategic offense and defense. Current U.S. military strategy supports a more balanced posture between offensive and defensive means. The inherent capabilities of directed-energy weapons could support such a strategy or even tip the balance in favor of defense over the strategic offense. In order to realize such a change, it may be necessary to deploy directed-energy weapons in space. Such a move would have enormous international political and legal repercussions. It is doubtful that any nation, but certainly not the United States, would undertake such a step unless the threat to the homeland from hostile strategic forces was much greater than it is at present and space-based directed-energy weapons could be demonstrated to be highly effective.

How directed-energy weapons will be viewed by international law is, as yet, largely unknown. There is only a limited body of international law that applies directly to such weapons. Directed-energy weapons might enhance efforts in the international system to restrain the consequences of the use of force. They could contribute to this goal to the extent that their accuracy and tailored effects support the objective of reduced collateral damage.

At the same time, directed-energy weapons raise some concerns. Most important of these is the potential effect of such weapons on human beings. The campaign for the Blinding Laser Protocol to the Geneva Convention could serve as a template for efforts to impose limitations on other directed-energy weapons, even those designed and intended only for anti-material applications. DoD needs to expect that issues of human effects from directed-energy weapons will be raised and it must carefully assess the implications of the use of such weapons, even inadvertently, on human beings.

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I. MILITARY TRANSFORMATION AND DIRECTED ENERGY

In order to grasp the potential significance of directed-energy weapons, their introduction on the battlefield must be understood in the context of the broad set of changes the U.S. military is undergoing. Over the past several years, defense experts have begun to make references to something called the new "American way of war." This phrase generally means the exploitation of advances in technology to support a unique style of military operations, one based on new functional capabilities, organizations and military doctrines. The capabilities include information superiority, stealthiness, strategic and tactical mobility and precision employment of weapons. The resulting style of military operations involves rapid seizure of control of the air and the conduct of high-tempo joint operations throughout a theater against the entire range of enemy targets from the onset of hostilities. A book written by a group of noted defense experts described the overall effect of this new way of waging war as "shock and awe."[1]

Achieving the capacity to conduct a new way of war is the overriding goal of the Department of Defense's plan to transform the U.S. military into a 21st Century fighting force. The United States in the new century is confronted by a novel set of security challenges, many of which are not addressable by traditional military means or at least in the same manner as were the threats of the last century. New adversaries threaten U.S. interests, allies, friends and forces, often in different ways. In addition, the U.S. homeland is now vulnerable to many of these same threats. Potential adversaries are seeking new methods and means of warfare intended to counter or neutralize the massive U.S. advantage in conventional military power. Some states are developing new types of weapons systems, most notably ballistic missiles and weapons of mass destruction (WMD), against which the United States currently has no defense.

The Defense Department's transformation plan is intended not only to extend and enhance the current capabilities of U.S. forces, but to counter the threat posed by asymmetric means and methods of attack that adversaries in the future may employ. It is intended also to create conditions that both deter attack and dissuade prospective adversaries from pursuing strategies that could pose a future threat to U.S. forces or the homeland. Secretary of Defense Rumsfeld described the key elements of the transformation strategy in 2002:

> Our experiences on September 11th, and indeed in the Afghan campaign, have served to reinforce the importance of moving the U.S. defense posture in these directions. Our challenge in the 21st Century is to defend our cities and our infrastructure from new forms of attack while projecting force over long distances to fight new and perhaps distant adversaries.
>
> To do this, we need rapidly deployable, fully integrated joint forces capable of reaching distant theaters quickly and working with our air and sea forces to strike adversaries swiftly, successfully, and with devastating effect. We need improved intelligence, long-range precision strikes, [and] sea-based platforms to help counter the access denial capabilities of adversaries.[2]

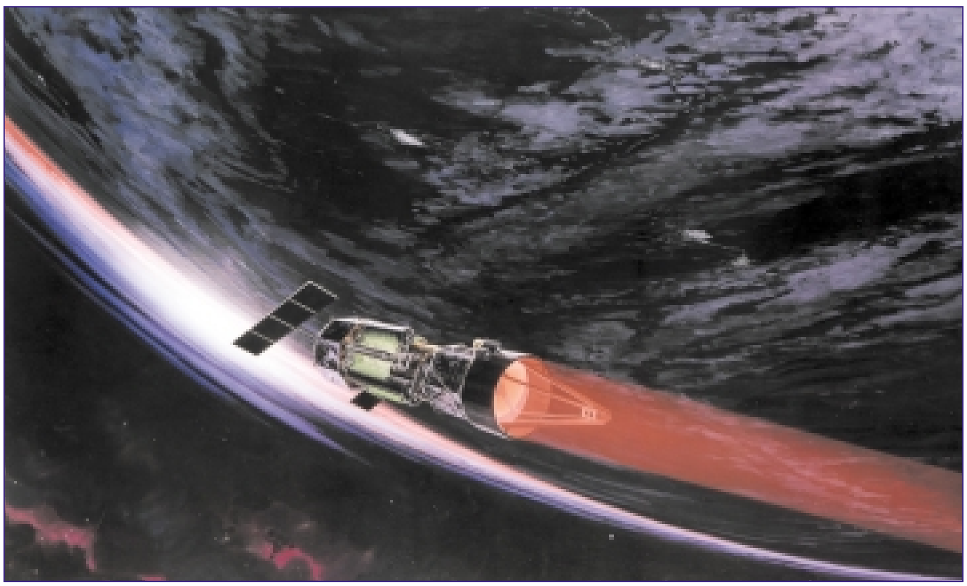
Although successful transformation requires the development of new organizations and doctrinal concepts to facilitate the application of force in different and improved ways, Secretary Rumsfeld's statement suggests that without advances in military technology, there could be no new way of war. For nearly thirty years, DoD has been investing in a wide

The Air Force is reportedly developing a high-power microwave weapon that can be carried internally on the F-35 Joint Strike Fighter.

Several companies are developing laser weapons that could be deployed on the ubiquitous C-130 transport.

A palletized laser could be deployed on the V-22 Osprey tiltrotor aircraft for employment in a wide array of operations.

A ground-mobile tactical laser could intercept artillery rounds, rockets and other fast-moving munitions.



Space-based lasers would be well-suited to interception of intercontinental ballistic missiles in their vulnerable “boost” phase.

Pentagon plans envision deploying directed-energy weapons on many different military platforms.

range of technologies that now provide the basis for the desired transformation of the U.S. military. These technologies include reliable and secure communications, high-speed computing, advanced remote sensing, precision navigation and geo-location, new composites and coatings and novel kill mechanisms. Their impacts on military forces can be widely seen in such systems as the Predator Unmanned Aerial Vehicle (UAV), the GPS-guided Joint Direct Attack Munition (JDAM), the Tomahawk cruise missile and the E-8 Joint STARS airborne ground-surveillance aircraft.

Directed-energy-based systems are already contributing to the new capabilities that undergird the emerging American way of war. Laser range-finders and targeting systems are deployed on tanks, helicopters and tactical fighters. These laser systems provide both swifter engagements and greatly enhanced precision. The role of directed-energy systems in support of military operations will continue to grow. DoD is looking closely at the introduction of laser-based communications.

Directed-energy weapons are a natural next step in the transformation of the U.S. military. Insofar as the last decade was marked by the shortening of the sensor-to-shooter cycle, this decade is likely to demonstrate a marked reduction in the shooter-to-target cycle. Directed-energy weapons provide a means for instantaneous target engagement, with extremely high accuracy and, in many instances, at very long ranges. Thus, they will enable U.S. military forces to capitalize better on the rapid flow of information that is a feature of modern warfare. In addition, these weapons support the more effective use of information by providing the warfighter with a broader set of effects that can be applied against a target. The collection and exploitation of large amounts of information, the conduct of high-speed operations, an emphasis on long-range engagements, and the pursuit of extreme precision are all aspects of the new American way of war.

In addition, directed-energy weapons could provide new means of countering so-called asymmetric threats. The introduction of directed-energy weapons could be an asymmetric counter to efforts by potential adversaries to develop means of neutralizing the U.S. advantage in conventional military power. Initial deployments of directed-energy-weapons are intended to counter the asymmetric threat posed by ballistic missiles and rockets. The first mission of the Airborne Laser (ABL) will be defense against theater ballistic missiles. The primary mission of the Mobile Theater High Energy Laser (MTHEL) will be to defeat rocket attacks. High-power microwave (HPM) weapons can be employed against mobile targets deliberately moved into close proximity with non-combatants or against fixed targets placed near to or beneath civilian sites. Directed-energy weapons could be a key aspect of the transformation of the U.S. military intended to ensure this nation's asymmetric advantage over potential adversaries.

Directed-energy is a military capability that is rapidly coming of age. It is doing so in the context of a broad transformation of U.S. military forces and changes in the ways weapons are employed and wars are fought. Directed-energy weapons are likely to have implications for the future of warfare as great as the introduction of the ballistic missile or jet aircraft has been in the recent past. A recent Defense Science Board report on high-energy lasers stated the case for the revolutionary implications of the deployment of directed-energy weapons:

> Appropriately developed and applied, high-energy laser systems can become key contributors to the 21st Century arsenal. In the relatively near-term, the new capabilities afforded by the use of high-power lasers could improve numerous aspects of warfare from initial detection and identification of targets to battle damage assessment after their attack. Directed-energy

weapons systems . . .could be a significant force multiplier, providing 'speed-of-light' engagement, unique damage mechanisms, greatly enhanced multi-target engagement and deep magazines limited only by the fuel available. The use of these weapons offers the opportunity for the strategist to select from a range of lethal through nonlethal effects to the target system.[3]

II. PROGRESS TO DATE

The effort to turn directed-energy weapons from the stuff of science-fiction novels into a military reality began in the early years of the Reagan Administration. At that time it was hoped that directed-energy weapons, particularly if deployed in space, could provide a powerful counter to the threat posed by Soviet intercontinental ballistic missiles (ICBMs). It soon became evident that the state of the art in directed-energy was not ready to support early weaponization. Nevertheless, the efforts initiated during the Reagan years and carried on by succeeding administrations have now reached the point that the first generation of directed-energy weapons are about to appear on the battlefield.

What has been accomplished to date in preparing the movement of directed-energy weapons out of the laboratory and off the testing range and into the hands of the U.S. military?

• The Airborne Laser (ABL) is on track to demonstrate a missile "shoot down" sometime in 2005. The program has been restructured to reflect a more realistic timeline. A Boeing 747 aircraft has been modified as the basic weapons platform. Ground-based testing of the laser modules will begin shortly.

• The Tactical High Energy Laser (THEL) has demonstrated the inherent advantages of directed-energy weapons, particularly speed of response and rapid retargeting. The THEL demonstrator has successfully intercepted Katyusha rockets more than twenty times. On several occasions it intercepted multiple rockets launched in a single salvo. Recently, the THEL successfully intercepted and destroyed an artillery shell, demonstrating yet another role for a tactical ground-based laser system.

A program is now underway to develop a mobile THEL or "MTHEL." Such a system would consist of one or two relatively large vehicles that would have road mobility and could be readily transported in large aircraft.

• The Air Force and Army have serious initiatives to develop active infrared-countermeasure (IRCM) devices that would use directed-energy to defeat heat-seeking missiles. The Air Force's Large Aircraft IRCM is designed to protect transport aircraft primarily from shoulder-fired missiles. The Army technology roadmap is looking at the development of a family of IRCMs that would defeat air and ground-launched anti-tank missiles.

• There has also been significant progress in the development of a first generation of high-power microwave (HPM) weapons. It is likely that these weapons will not be directional but will consist of an explosively-driven HPM generator functioning much like an electromagnetic pulse bomb.

- There has been significant progress also towards the development of compact solid-state lasers. The goal is a minimum of 100kw for such a laser device. The present state of the art is approximately 10kw. It is not clear how soon it will be possible to achieve an order-of-magnitude improvement in solid state laser performance.

As discussed elsewhere in this report, there are many potential applications for directed-energy weapons. The first finding of the DoD High Energy Laser Master Plan is that "HEL systems are ready for some of today's most challenging weapons applications, both offensive and defensive."[4] In order to realize the military potential inherent in directed-energy weapons, there are a number of steps that must be taken in the areas of technology, operational and doctrinal development. In addition, the military must anticipate and be prepared to address concerns regarding the human effects of such weapons. In some instances, notably in the area of nonlethal directed-energy weapons, this type of testing and evaluation is underway currently.

III. CONCLUSIONS

A review of recent studies and assessments suggests that the promise of directed-energy weapons is real. Within the next few years, the first weapons systems built with directed-energy as their kill mechanism will be deployed. This study has identified two sets of conclusions regarding the significance of directed-energy weapons. The first set of conclusions focuses on the implications of the introduction of directed-energy weapons for strategy, operations, force structure and tactics as discussed in Chapter 2. These implications need to be appreciated in the context of the broader effort by the Department of Defense to transform the U.S. military. The second set of conclusions derives from the discussion in Chapter 3 of the implications of directed-energy weapons for U.S. foreign policy and the impact of current international law on the ability to deploy such weapons.

The following conclusions reflect a consensus in the technical community that directed-energy weapons can be made operational and that they cannot be readily countered. It must be recognized that there are limitations on the uses of directed-energy weapons. Environmental phenomena and obscurants can limit the utility of some directed-energy weapons, particularly chemical lasers. Protective shielding and coatings can also reduce the effectiveness of some lasers, albeit potentially at a price in terms of the performance of the shielded platform. Nevertheless, it is believed that a combination of improvements to the performance of the directed-energy weapons (i.e., increased power, improved accuracy) and tactical counter-countermeasures should enable such systems to perform well under operational conditions. The truth of this observation will have to be verified through rigorous operational testing.

The Military Implications of Directed-Energy Weapons

The study arrived at seven major conclusions regarding the implications of directed-energy weapons for military operations and force structure:

1. The military impact of directed-energy weapons will be revolutionary. This revolution will be experienced at three levels: tactical, operational and, finally, strategic. Tactically, directed-energy weapons will provide new mechanisms for killing targets. Directed energy is an extremely fast means of delivering lethal force against a target. Moreover, the use of directed-energy weapons may be all but undetectable. In some applications, the range of directed-energy weapons also will be greater than that attainable by other means (e.g., air-to-air missiles). As a result, tactical units equipped with directed-energy weapons are likely to be more capable than adversaries deploying only traditional weapons systems.

The revolutionary impact of directed-energy weapons at the operational level of war will come about both as the result of their proliferation throughout the U.S. force posture and also as a consequence of their ability to change the way current missions are accomplished. For example, directed-energy weapons, particularly ground and airborne lasers, could radically change the meaning of the term "air superiority" and alter how air-to-air and air-to-ground operations are conducted. The ABL could establish air dominance over a very large volume of airspace, certainly above cloud level, in the face of both air-to-air and air-to-ground threats. Nearer to the earth, the operational utility of laser weapons will depend largely on their ability to overcome environmental effects. If these effects can be adequately mitigated, laser weapons could dominate both air-to-air and air-to-ground combat. Directed-energy weapons could radically reduce the effectiveness of ground-based air defenses, enabling U.S. forces to more swiftly and completely gain and hold dominance over enemy airspace.

At the strategic level, the impact of directed-energy weapons will be a function of their ability to support entirely new missions. One of the most significant of these new missions could be space control and space strike. Directed-energy weapons are particularly well suited to exploiting the advantages of position and extended line-of-sight inherent with deployments in space. Another mission area with revolutionary strategic potential is non-destructive strategic strike. Broad-area HPM weapons conceivably could be employed to cause the sudden and total failure of major national communications and power systems, both civilian and military. Entire sectors of a nation's economy could be held at risk with no direct danger to civilian populations.

2. Directed-energy weapons are both enabled by and enablers of other military systems. It is important to recognize that directed-energy weapons are moving to the battlefield at a time when a number of other significant new technologies are also making their appearances. Directed-energy weapons will be enabled by advances in sensors and computing capability that have become the backbone of a revolution in information warfare. For the potential of directed-energy weapons to be realized, they must rely on highly precise, nearly-instantaneous target detection, identification, tracking and lock-on.

Among the most significant advances in military hardware that support the weaponization of directed-energy is the advent of the unmanned aerial vehicle (UAV). There appears to be a natural synergy between UAVs and directed-energy weapons. Armed UAVs have already made their appearance on the battlefield. One of the advantages that UAVs provide as a platform for directed-energy weapons is their ability to enter high-risk environments with no danger to personnel. A UAV could deliver a low-power laser weapon within range of its target without risk to pilots. An HPM-armed, long-loiter UAV programmed to fly a particular course could sweep battlefields or even entire cities.

3. The first and possibly most significant impact of directed-energy weapons will be defensive in character. In the case of short-range rockets, artillery shells and mortars, laser weapons for the first time will provide a means of active defense. This alone could constitute a revolutionary advance in defensive means. Mobile laser defenses could provide protection for valuable fixed targets such as air bases.

The ABL holds forth the promise for an effective boost-phase defense against ballistic missiles. Even deployed in small numbers, the ABL will provide a stand-off capability against the relatively small arsenals likely to be available to so-called rogue states over the next several decades.

Laser countermeasure devices promise to provide significantly enhanced protection of aircraft, vehicles and even fixed facilities against precision weapons with optical or infrared seekers. The speed with which laser systems can respond to threats and their ability to neutralize targets without having to destroy them in flight make such weapons the ideal countermeasure.

4. Directed-energy weapons will provide new means for attacking time-sensitive and imprecisely-located or buried targets. U.S. forces face a growing problem of locating and attacking in a timely manner mobile, time-sensitive targets such as ballistic- and cruise-missile launchers, aircraft on runways and vehicle-mounted command and control nodes. In some instances, the location of these targets will not be known with sufficient precision to allow them to be attacked with conventional weapons. Directed-energy weapons, both lasers and HPMs, can address these problems, albeit in different ways. Lasers can shorten the shooter-to-target time line, thereby enabling attacks on mobile targets before they can move beyond sensor range. HPMs can be employed against mobile targets when locational uncertainty exists.

HPMs could be particularly useful against buried targets or those that are located in populated areas. Adversaries intent on pursuing asymmetric strategies are increasingly seeking to protect critical assets by burying them or co-locating them in urban centers. HPMs can be employed to strike many such targets with no collateral damage. HPMs could be employed in a less-lethal "strategic bombing" campaign designed to attack critical national electrical and electronic assets.

5. In the event it is necessary to engage in conflict in or from space, laser weapons could play a critical role in establishing and maintaining space control. Directed-energy weapons in space, or ground/airborne lasers with battle mirrors could provide highly effective control of space and protection for other critical space-based assets. Deployed in a constellation of satellites, space-based lasers would provide highly capable defense against ballistic missiles and even high-flying aircraft.

6. High-power microwaves offer the prospect for the first effective means of conducting nonlethal engagements at medium ranges. The Advanced Denial System (ADS), undergoing development, employs microwaves to create nonlethal effects on human beings. If successfully demonstrated and shown to have no irreversible effects, the ADS would support policing and peacekeeping activities and could be employed in urban environments against hostile combatants.

7. Directed-energy systems could also provide important new means of defending the homeland. One of the goals of the National Homeland Security Strategy is to protect transportation. Another is to reduce the vulnerability of critical infrastructure. Recent events underscore the threat to civilian airliners from man-portable surface-to-air missiles deployed near airports. Fixed-site laser defenses employing sensors to detect fast-moving objects on trajectories characteristic of man-portable SAMs could be deployed at major airports, providing protection against such threats. Civilian aircraft could also be equipped with laser countermeasures. Laser defenses aboard aircraft could contribute to the defense of the U.S. homeland against cruise-missile or short-range ballistic-missile attacks.

The Political and Legal Implications of Directed-Energy Weapons

The introduction of qualitatively new weapons systems often has had important implications for a nation's foreign relations and for the larger international environment. Care needs to be taken in the manner in which directed-energy weapons are made a part of the U.S. arsenal. There is concern among some allies regarding U.S. efforts to transform its military. Although directed-energy weapons are but one of a series of new capabilities which the United States is developing, their potentially revolutionary impacts could generate widespread concern.

The study formulated five major conclusions regarding the impact of directed-energy weapons on U.S. foreign policy and international relations, and concerning the potential constraints imposed by international law on the use of directed-energy weapons.

1. The introduction of directed-energy weapons is but one aspect of a broader U.S. military transformation that is impacting on security relations between the Untied States and many other nations. This transformation will enable the United States to better protect its allies, friends and overseas interests. At the same time, transformation will contribute to the growing disparity in military capabilities between the United States and its major allies. The introduction of directed-energy weapons by the United States is likely to further increase that gap.

2. Even though the impact of directed-energy weapons over time will be revolutionary, their introduction should not be destabilizing. Currently, the United States possesses a demonstrable capacity to establish and maintain air superiority under almost any conceivable circumstances. This is one reason potential adversaries are pursuing so-called access-denial strategies designed to counter that superiority. Many near-term applications of directed-energy weapons will be for the purpose of enhancing existing areas of U.S. military advantage, such as in precision strike or air superiority, or to counter asymmetric threats such as ballistic missiles.

The United States is engaged with its closest allies in efforts to improve interoperability and mutual support among their respective military forces. The advent of directed-energy weapons is not likely to seriously hamper these efforts. Rather, it reflects a continuing need for dialogue and close military-to-military cooperation.

The revolution in military affairs (RMA), created in part by the introduction of directed-energy weapons, will not happen overnight. Some new mission areas enabled by directed-energy weapons, such as space control, will not be attainable for at least the next fifteen or twenty years. Moreover, the effort to develop such a capability is likely to come about only in response to the rise of a major new threat to U.S. survival. Closer to the Earth, the capability to conduct non-destructive strategic strikes will also take many years to develop.

3. The United States will need to consider very carefully any decision to deploy directed energy into space. Although the deployment of directed-energy weapons would not violate the Outer Space Treaty, such a move probably would confront significant international opposition. This opposition reflects a commonly held view both in the United States and abroad that space should be a weapons-free zone. Hence, the decision to deploy any weapons into space should be taken only if it is necessary to address a very serious, even dire, threat to U.S. national security.

4. There are few current limitations in international law on directed-energy weapons and the United States should resist efforts to constrain their use. Following the U.S. abrogation of the ABM Treaty, the most significant constraint on directed energy is in the blinding laser protocol to the Geneva Convention. This addresses only one specific application of directed energy. Many of the military applications of directed energy currently under development or being considered would actually improve prospects for limiting collateral damage. In the future, directed-energy weapons

may also enable the United States to end conflicts more swiftly and with reduced casualties. For these reasons, the United States should oppose any initiatives to place new limits on directed-energy weapons.

5. It will be important to conduct extensive effects testing of any directed-energy weapons that are likely to be employed in close proximity to human beings. Systems such as the ADS, which is intended for use against human beings, must undergo rigorous human-effects testing. Other systems such as the ABL and MTHEL, designed for use against unmanned systems, may not require such testing. Those designed to be employed against manned platforms or against targets where human beings are present should undergo extensive effects testing to ensure that they do not pose a significant health risk. Opponents of directed-energy weapons are likely to assert a danger to human health or to the environment. The Defense Department should anticipate such a possibility and conduct the necessary testing before the systems are deployed.

IV. RECOMMENDATIONS

A number of well-thought out plans exist for the development of directed-energy weapons. The 2000 DoD High Energy Laser Master Plan, the Air Force Laser Master Plan and the U.S. Army's Technology Roadmap each address the subject of a path to the weaponization of directed energy. In general, these plans provide an appropriate set of roadmaps for development of a range of directed-energy weapons. This study finds little to criticize in the Pentagon's plans.

What is required is diligence in pursuing goals already established in a variety of plans. In addition, more attention needs to be provided to military-operational and political issues that will arise with the proliferation of directed-energy weapons throughout the U.S. force structure.

The study does make a number of recommendations. These recommendations reflect the basic reality that directed-energy weapons are on the verge of becoming a major force in modern warfare. Yet, history is filled with examples of opportunities to gain decisive military advantage that were lost through simple inattention, lack of commitment or a scarcity of resources. The Defense Department has recognized that the process of transformation requires not only investments in technology, but also in new organizations and operational concepts.

1. *DoD must support current plans to develop and deploy first-generation directed-energy weapons systems.* The most important test of the transformational potential of directed-energy technology will be demonstration of the ability to employ functioning directed-energy weapons in real-world engagements. The focus of DoD and Service efforts must be on proving that directed-energy weapons can be built and are effective in operational tests. Priority must be given to ensuring that the ABL program is seen through to completion. There also needs to be adequate attention and resources provided to the Army in the development of the MTHEL.

2. *DoD must ensure adequate investment in both near-term and advanced directed-energy weapons systems.* At present DoD and the services do not provide sufficient funding to support the additional research and development required in order to develop the next generation of directed-energy weapons The average annual expenditure on science and technology is about $2 billion across all defense elements. The DoD Master Plan makes the specific point that more dollars need to be spent to complete current acquisition programs and assure progress in advanced technology development. The amount of resources devoted to directed-energy science and technology should be doubled. One aspect

of this investment strategy must be to preserve the viability of critical parts of the directed-energy supplier base. A strategy of selective, carefully targeted investments would go a long way toward maintaining that base.

3. *Experimentation in additional missions for directed-energy weapons will be important to the full exploitation of their potential.* The focus of near-term directed-energy weapons development is on defensive missions, particularly those associated with defeating ballistic missiles and rockets. This effort must continue. However, where possible, DoD and the Services need to begin to experiment with expanding the range of missions. The Army recently began testing the THEL against artillery projectiles. Once the ABL has proven itself able to intercept ballistic missiles, experiments should begin to test the system against aircraft and surface-to-air missiles. The THEL and its successor, the MTHEL, should be tested against the full range of air-breathing targets that will confront the Army in the future. An effort should also be made to include directed-energy weapons and even notional directed-energy-equipped units in future service and joint exercises. The Air Force is currently considering how to incorporate the ABL in its Global Strike Task Force. Similar efforts need to be undertaken by both the Air Force and Army involving other types of directed-energy weapons.

4. *DoD should consider designating a single focal point for R&D into advanced directed-energy weapons.* In order to make the best use of relatively scarce funds and avoid duplication of effort, DoD needs to create a single focal point to manage its disparate directed-energy programs. A Joint Program Office would allow for the effective management of all the directed-energy programs. Consideration should be given to creating two offices, one for high-energy laser programs and another for HPM programs.

5. *DoD should expand its research into countermeasures against directed-energy weapons.* Greater effort needs to be devoted to work on countermeasures to directed-energy weapons. This effort should have two foci. First, it should improve understanding of possible adversary countermeasures to U.S. directed-energy weapons programs. The Russian SS-27 ICBM is reported to have incorporated a number of countermeasures to directed-energy weapons, including reflective coating and booster rotation. Second, there needs to be an effort to develop countermeasures to adversary use of directed-energy weapons.

Former Air Force Chief of Staff Gen. Ronald Fogleman observed at a recent seminar that directed-energy weapons will be a key feature of the future U.S. force structure and combat capability. His assessment was based in part on the progress made to date in moving directed-energy technology out of the laboratory and into the field. It was also based on an awareness of the potential strategic and tactical roles that directed-energy weapons could fulfill in the future. Twenty years from today, the validity of Gen. Fogelman's assessment will probably be readily apparent to all observers. Directed-energy weapons are a true revolution in warfighting -- a technological advance that stands out even in an era of unparalleled innovation.

1 Harlan K. Ullman and James P. Wade, *Shock and Awe: Achieving Rapid Dominance*, Washington, D.C.: National Defense University, 1996.
2 Secretary of Defense Donald Rumsfeld, *21st Century Transformation*, Washington, D.C.: National Defense University, 2002.
3 Defense Science Board, *High Energy Laser Weapon Systems Applications*, Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, Washington, D.C., June 2001, p. v.
4 *Report of the High Energy Laser Executive Review Panel*, Department of Defense Laser Master Plan, Washington, D.C., March 24, 2000, p. 5.

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