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OPERATIONAL  
IMPLICATIONS  
*of*  
*Laser Weapons*

by  
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## EXECUTIVE SUMMARY

**Introduction:** *Weapons that rely on chemical reactions to propel projectiles have dominated warfare for centuries. The primacy of current weapons is under challenge by advances in high-energy lasers with military potential that use chemical reactions or electricity to release intense radiation instead of projectiles. Conventional weapons may co-exist or compete with directed energy systems for missions as these next-generation weapons increasingly assume existing roles in the battlespace, as well as new missions that may emerge, like active defense against projectiles. But despite progress in the technical development of laser weapons, the development of concepts for their operational employment is not keeping pace. Timely fielding of these capabilities requires that warfighters understand the implications of their introduction. The purpose of this paper, therefore, is to assess some of the operational implications of laser weapons and to urge warfighting professionals to make their study a priority, in time to guide laser weapons development and to craft concepts for their operational employment.*

## GROWING LASER WEAPONS CAPABILITY

Effective laser weapons are already being developed and tested. The Tactical High Energy Laser (THEL) has shot down short- and medium-range tactical missiles and artillery and mortar rounds. The laser for the Air Force's anti-missile Airborne Laser (ABL) aircraft achieved "first light" in a successful ground test, and three competitors in the DoD solid-state laser program are well on their way to achieving militarily significant power levels in their laboratory versions.

One of the challenges in understanding the operational implications of this progress lies in the varied characteristics of different laser weapons. The most technologically mature systems are chemical lasers that derive their very high power levels from chemical reactions that produce beams of intense infrared radiation. Electrically powered solid-state lasers (SSLs) are less powerful and pass electricity through a crystal or glass medium to produce laser beams. SSLs are also progressing rapidly and promise great tactical utility. A third class, Free Electron Lasers (FELs), use electricity to create laser light on different wavelengths to match changing environmental conditions.

## PROGRESS IN LASER WEAPONS SYSTEMS INTEGRATION

Significant progress has been made in integrating laser weapons into air, land and sea weapons systems. Much design work has already been done to modify the THEL into a deployable combat system. Systems concepts for integrating SSLs into existing or new platforms, such as the Joint Strike Fighter, have also been developed, although their technical maturity is 5-10 years behind that of chemical laser systems.

## DEVELOPING OPERATIONAL CONCEPTS FOR LASER WEAPONS

Technological development in laser weapons is outpacing generation of the operational requirements necessary to guide it. Throughout the services, many warfighters and decision makers are not aware of the progress being made in laser weapons, their capabilities, and their limitations.

For weapons developers to create the most appropriate and effective laser weapons, warfighters must be able to tell them what characteristics are most important to operational success.

## OPERATIONAL CHARACTERISTICS OF LASER WEAPONS AND THEIR POTENTIAL APPLICATION

Capabilities that make lasers attractive for operational use are:

- Highly agile speed-of-light delivery
- Multiple target engagements and rapid retargeting
- Deep magazines
- Low incremental cost per shot
- Exceptional accuracy and adjustability
- Lower logistical support requirements
- Flexible design

Factors that limit laser weapons operational utility include:

- Atmospheric attenuation and turbulence
- Line-of-sight dependence
- Minimal effects on hardened structures and armored vehicles
- Single wavelengths that limit the range of operational conditions in which they are effective
- Eye safety issues
- Chemical fuels and exhaust

## OPERATIONAL IMPLICATIONS

Balancing the strengths of laser weapons against their operational limitations makes them well suited to roles in two key mission areas:

- *Active Defense*: providing air, land, sea and space platforms the ability to defend themselves, other platforms and large areas against

missiles, aircraft, bombs, artillery shells or rockets.

- *Offensive Strike*: providing the capability to achieve lethal or non-lethal effects against a range of suitable targets.

**Defensive Operations:** Laser defenses could provide an on-board active defense capability for aircraft that could defeat or destroy incoming missiles or aircraft within their range. This greatly increases the survivability of many non-stealthy, subsonic, vulnerable platforms like Joint STARS, AWACS and B-52s. Because it reduces the requirement for suppression of enemy air defenses (SEAD), active defense allows strike operations against center of gravity targets to begin earlier in the air campaign.

Ground-based laser defenses can defeat most indirect fire threats (rockets, artillery and mortars), significantly increasing ground force survivability and freedom of maneuver.

For naval forces, lasers could provide an effective shield against adversary ballistic or cruise missile attacks.

Airborne and space-based lasers may also provide active defense over large areas and could engage targets, primarily ballistic missiles, much earlier in their trajectories than terrestrially based defenses.

Laser weapons can also help to provide a more affordable, and thus more widely-spread, terminal point defense against theater ballistic missiles.

The same characteristics that make laser weapons effective for these military active defense missions could also allow them to defend critical infrastructure or government facilities against aircraft and direct and indirect fire ground weapons.

**Offensive Operations:** Offensive applications of lasers will most likely be dedicated to those missions where laser weapons characteristics (e.g., precision, speed and numbers of engagements) are more important than pure destructive power.

The same laser weapons that provide an active defense capability for aircraft can also be used against ground targets, providing a significant

air-to-ground capability. The combination of their unique capabilities with current and new generations of air platforms and sensors may increase the ability to “fine tune” the application of force from the air, making air power more relevant in counterinsurgency and counterterrorism operations.

Laser weapons offensive applications in ground combat will most likely be dedicated to those missions where their precision, speed of light engagement time, adjustability and minimal collateral damage make them ideally suited. Counter-sniper missions might be a good example. Offensive use at sea may also meet niche requirements, especially in sea-borne special operations where precision and stealth are more important than destructive power.

U.S. experiments have already demonstrated that satellites hundreds of kilometers up are vulnerable to high energy lasers. The importance of this capability has not been lost on countries like China, which is pursuing a robust high energy laser capability.

## RECOMMENDATIONS

The U.S. needs a robust process for enhancing our understanding of the operational implications of laser weapons and pressing for the development of operational concepts for their use. Key steps include:

- Fielding a variant of THEL as rapidly as possible
- Completing the ABL program
- Aggressive wargaming and field experimentation with laser weapons

## CONCLUSION

In a historic sense, operational laser weapons are “right around the corner”; however, the operational community that will make many of the decisions related to their development and employment is relatively unaware of them. The ability of laser weapons to provide active defenses against a wide range of increasingly capable

offensive threats may reverse the trend of offensive weapons' increasing superiority over defensive capabilities.

If laser weapons live up to the potential they have shown thus far and if their development proceeds

as fast as projected, warfare could enter the age of laser weapons within the decade, much sooner than most expect. To leverage this emerging capability, we need operational concepts to guide our investment in the transformational technology of laser weapons.

# I. INTRODUCTION

*Weapons firing projectiles propelled by chemical reactions—bullets, artillery shells, missiles—have dominated the tactical level of warfare for centuries. Today, advances in the technology of high-energy lasers allow the application of other physical principles in a new class of weapons. Development of high-energy lasers<sup>1</sup> with military potential is leading to the production of light beam weapons that transfer destructive energy to targets via coherent light. Over time, the primacy of chemically propelled projectiles may give way to dynamic co-existence and competition with directed energy weapons as these next-generation weapons increasingly assume existing roles in the battlespace or new missions, such as active defense against projectiles.*

*The challenge to the U.S. military is that our understanding of laser weapons technologies is outpacing efforts to bring these capabilities into the force. Available funding for laser weapons development lags behind what would be necessary to bring technologies to maturity as quickly as possible. Equally threatening to the success of laser weapons in the field is the lack of attention to concept development for laser weapons operational employment. This situation is neither new nor unique to laser weapons. Historically, technical development of new warfighting capabilities – everything from ironclad warships, to heavier-than-air aircraft, to tanks, radar and radar-defeating “stealth” – has proceeded faster than military forces can adapt their warfighting approaches to incorporate the full advantage of the new capability.*

*Unfortunately, this imbalance frequently means that weapons developers move along at great speed in designing advanced systems with tremendous battlefield potential, but they do so in splendid intellectual isolation. Lacking the guiding hand of operational requirements, they are unable to properly prioritize resources or focus on the weapons capabilities that are most important to warfighters. They can waste precious time and resources pursuing weapons capabilities of lesser operational utility while foregoing development of those that might truly provide a decisive advantage. Just as sadly, military forces can field an expensive and promising new capability that remains underutilized because warfighters do not fully understand how to employ it to its greatest advantage. In today’s fast-changing threat environment, given tight Defense resources and the exciting possibilities offered by development of laser weapons, the U.S. cannot afford the wasted time or resources of such mistakes in developing one of the next breakthrough technologies. The purpose of this paper, therefore, is to assess some of the operational implications of laser weapons and to urge warfighting professionals to begin an urgent effort to understand these implications. This work must be made a priority if it is to take place in time to guide laser weapons development and to craft concepts for their operational employment.*

*In pursuit of that purpose, this paper first notes the progress being made in laser weapons capabilities and integration, then enumerates the potential application of these developing capabilities. Finally, the paper suggests their potential operational implications, using a warfighting scenario to illustrate their operational impact.*

<sup>1</sup> “Laser” is actually an acronym for Light Amplification by Stimulated Emission of Radiation: a device that converts incident electromagnetic radiation of mixed frequencies to one or more discrete frequencies of highly amplified and coherent radiation.—Webster’s II New College Dictionary, 2001. See <http://science.howstuffworks.com/laser.htm> for a simple discussion of the physics involved.

## II. GROWING LASER WEAPONS CAPABILITY

Effective laser weapons have already been developed and tested. The joint U.S. Army-Israel Defense Forces Tactical High Energy Laser (THEL) has shot down short- and medium-range tactical missiles, artillery rounds and mortars, and has the ability to destroy other types of missiles in flight. Other laser weapons are making significant progress. The laser for the Air Force's anti-missile Airborne Laser (ABL) aircraft achieved "first light" in a successful ground-based test of its main laser, and three competitors in the DoD solid-state laser program are well on their way to achieving militarily significant power levels in their laboratory versions of solid-state lasers.

It is important in understanding the operational implications of this progress to be aware of the varied characteristics of different laser weapons programs. The U.S., for example, is pursuing three different types of laser weapons: chemical, solid-state and free electron lasers. All have different capabilities and limitations that make them better suited for certain operational applications. Their different stages of technical maturity will also play a part in determining their availability to U.S. forces.

### CHEMICAL LASERS

The THEL and the laser in the ABL aircraft are chemical lasers. Chemical lasers derive their very high power levels (measured from 100's of kilowatts, or kW, to megawatts) from chemical reactions that produce intense infrared radiation. The radiation is collected into beams and released. As the "heavy artillery" of the laser weapons family, chemical lasers are very powerful. They require relatively large amounts of chemical fuels and produce significant amounts of heat that must be convected away in the exhaust.

Chemical laser weapons have been under development for over thirty years and represent the most mature laser weapons technology. Current

versions tend to be large and somewhat bulky because of their high power, like the ABL, or because they have not yet been fully "productized" as field-ready weapons systems, like the THEL. Systems designed for field operations can be significantly smaller. For example, concepts have been developed for a transportable version of THEL that occupies 25% of the volume of the first generation system. Moreover, because THEL has been tested extensively and is technologically mature, an operational version could be fielded in about 18 months.<sup>2</sup> Chemical lasers can operate at a single wavelength (e.g. 1.315 microns ( $\mu\text{M}$ ) for ABL) or over a range of wavelengths (e.g. 3.5 to 3.9  $\mu\text{M}$  for THEL). These longer wavelengths also allow them to penetrate atmospheric turbulence better, giving them the ability to operate in a variety of atmospheric conditions. Longer wavelengths also mean that reflected laser energy will not damage human eyes.

### SOLID-STATE LASERS

Significant progress is also being made in developing the technology for electrically powered solid-state lasers (SSLs) that pass electricity through a crystal or glass medium to produce laser beams. Unlike the THEL chemical laser, SSLs only operate with one shorter wavelength. Light in this wavelength range has more difficulty penetrating atmospheric turbulence and is also damaging to human eyes.

Although they are less powerful (in the tens of kW today) than chemical lasers, recent improvements in SSL power levels promise to provide effective laser weapons in the near to mid future that are light enough to be mounted on smaller combat platforms (e.g. fighter aircraft and ground combat vehicles). SSLs can be powered by electrical sources on aircraft, ships or ground vehicles.

For the foreseeable future, however, these lasers will be lower power than their chemical laser brethren;

<sup>2</sup> Marc Selinger, "U.S. Army Studying Guns, Lasers, Interceptors to Destroy RAMS," *Aerospace Daily & Defense Report*, October 28, 2004. [http://www.aviationnow.com/avnow/news/channel\\_aerospacedaily\\_story.jsp?id=news/RAM10284.xml](http://www.aviationnow.com/avnow/news/channel_aerospacedaily_story.jsp?id=news/RAM10284.xml)

but they can support an extensive set of military missions requiring less power and smaller platforms. Parenthetically, if solid-state laser systems could be produced at the high megawatt power levels of chemical lasers, they most likely would be as large as chemical lasers of the same power.

The U.S. military operational community does not widely appreciate the progress that has been made in increasing SSL power levels. As noted earlier, the three corporations participating in DoD's Joint High-Powered Solid-State Laser Program either have achieved or will shortly achieve 25-kilowatt power levels with solid-state lasers in a laboratory environment.<sup>3</sup> While this is far from the 100 kW range that the DoD's High Energy Laser Joint Technology Office believes is necessary for a tactical laser to be effective, this work is viewed by many in the industry as promising. As technology progresses, weight might emerge as a problem as it is estimated that reaching an objective power-to-mass ratio would result in a laser system weighing about 11,000 pounds<sup>4</sup>, much heavier than would be feasible for some of the uses described above. However, some in industry argue that technological advances could reduce the weight of a SSL laser of optimal power to less than 4,000 pounds.<sup>5</sup>

Power levels, however, are not the only measure of laser weapons technological maturity. To create an effective weapon, the laser must be integrated into a complete system that can acquire, track and destroy targets and is fully mated with its carrying platform's power, control, and other systems. At current funding levels, it could be seven to nine years before an integrated solid-state laser weapon system can be delivered from the laboratory to the testing range.<sup>6</sup>

### FREE ELECTRON LASERS

The U.S. Navy is interested in the "tunable" Free Electron Laser (FEL) that uses electricity to create laser light on different wavelengths to match changing environmental conditions at sea. Navy weapons developers believe the FEL is better

suitable for multiple naval applications than single wavelength solid-state lasers.

Significant progress is also being made in increasing FEL power levels (now at about 10 kW),<sup>7</sup> and FELs might offer a more attractive path than SSLs to using electricity to achieve very high power levels. However, there are particular challenges to deploying FELs at sea. For example, their size dictates integration on only the largest ships and makes retrofitting existing ships extremely difficult.

### BEAM QUALITY

Research also has produced substantial improvements in beam quality at high power levels. Beam Quality (BQ) is essentially a measure of how tightly the laser beam can be focused to form a small and intense spot of light on a target at some distance from the laser. In many cases, the intensity of this focused spot is proportional to  $1/BQ^2$ , where a BQ measurement of 1 is perfect and higher numbers indicate "lower" quality. A fairly modest change in BQ (i.e. BQ "decreasing" from 1.5 to 2.0) results in a decrease of nearly a factor of two in the intensity of the beam deposited on the target. Thus, maintaining good laser BQ as power is scaled up is a very important requirement for the laser designer.

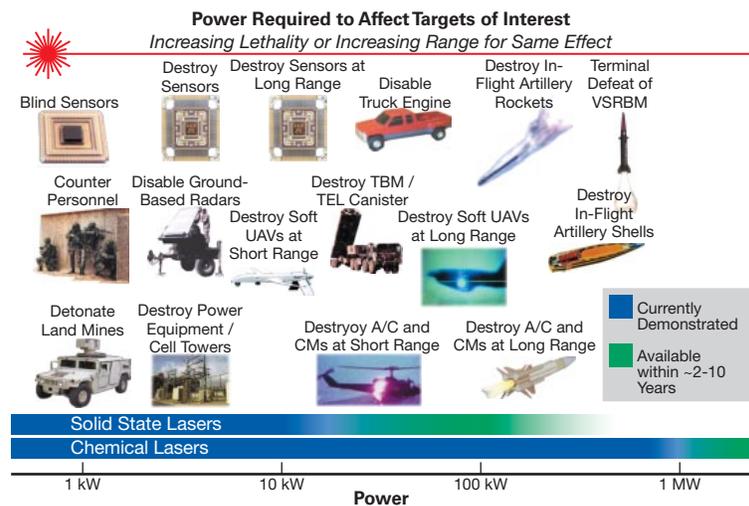


Figure 1. Power Levels Required for Different Missions

<sup>3</sup> Marc Selinger, "DOD Solid-state Laser Demos Delayed Three Months," Aerospace Daily & Defense Report, December 23, 2004.  
<sup>4</sup> Hampton Stephens, "Air Force, Army Effort is Advancing Tactical Laser Technology," Inside the Air Force, July 16, 2004.  
<sup>5</sup> Discussion with Dr. Gary Koop, Northrop Grumman Space Technology.  
<sup>6</sup> Statement by Art Stephenson, Vice President, Directed Energy Systems, Northrop Grumman Space Technology, National Press Club, Washington, D.C., May 4, 2005.  
<sup>7</sup> Dave Ahearn, "ONR Laser Power Jumps 10 Fold; Further 10-Fold Leaps Seen," Defense Today, August 4, 2004, p. 4.

### III. PROGRESS IN LASER WEAPONS SYSTEMS INTEGRATION

Developers are also progressing with design concepts for integrating laser weapons into existing and new air, land and sea weapons systems. The most advanced is the anti-missile Airborne Laser (ABL), whose ground-tested laser modules will soon be fitted into the extensively modified Boeing 747 aircraft for airborne tests.

Other chemical laser systems concepts are also well advanced. For example, much design work has already been done to modify the THEL into a deployable combat system known as High Energy Laser-Rockets, Artillery, and Mortars (HELRAM) that can be used to destroy multiple types of threats, including rockets and artillery and mortar rounds.

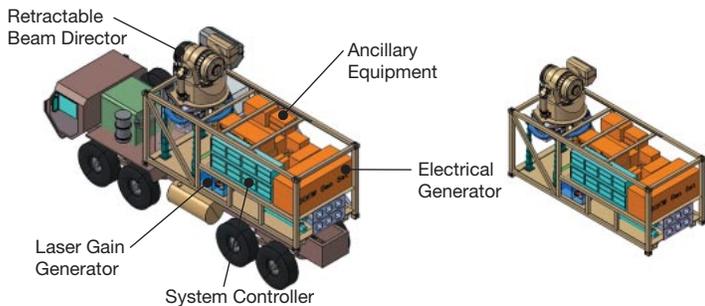


Figure 2. HELRAM Fire Unit

Systems concepts for SSLs have also been developed, although their technical maturity is four to five years behind that of chemical laser systems.<sup>8</sup> Because SSLs draw very large amounts of electric power, weapons developers have focused on power supply. For example a laser weapon could be carried on a hybrid electric ground fighting vehicle (Figure 3) and powered by the electrical system.

Similarly, the concept for integrating a SSL into the F-35 Joint Strike Fighter would place the laser system in the fan cavity of the short-take-off-and-vertical-landing version of the aircraft and use the fan shaft to power a megawatt-sized generator (Figure 4).



Figure 3. Hybrid Electric Vehicle with Solid State Laser

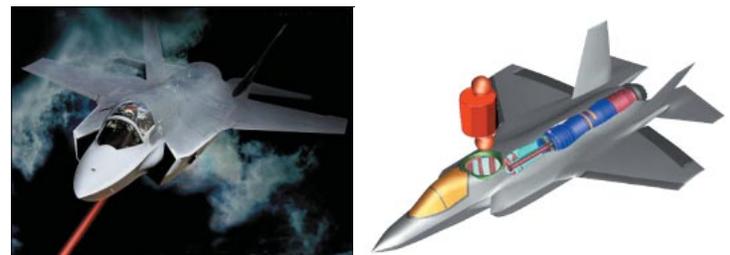


Figure 4. 100kW Solid State Laser Weapon System for F-35 (Joint Strike Fighter)

Other concepts have been developed for a whole range of military platforms including unmanned aerial vehicles (UAV's), bombers, C-130s and surface vessels (Figure 5).

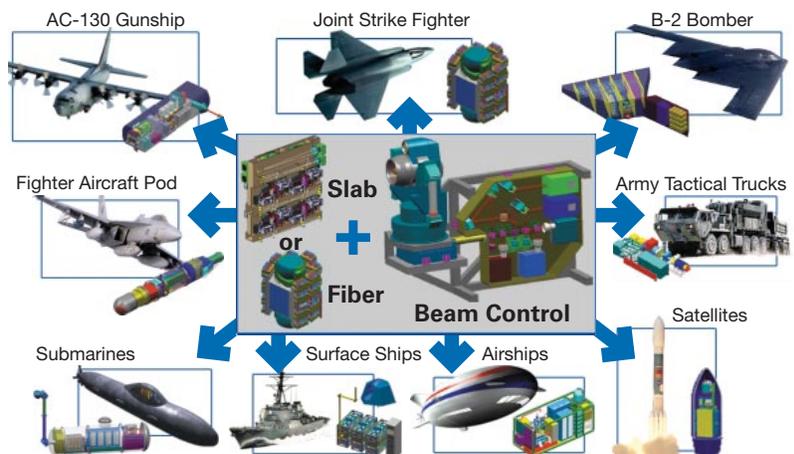


Figure 5. SSL Weapons Integration Concepts

<sup>8</sup> Stephenson.

## IV. DEVELOPING OPERATIONAL CONCEPTS FOR LASER WEAPONS

Despite these technical advances in laser weapons, much of the military operational community remains unaware of their potential. Numerous discussions with serving officers at seminars, conferences and wargames over the past several years indicate that understanding of the current state of progress in laser weapons is mostly limited to the scientific and technical communities. Beyond that, even the leading thinkers and writers of the military operational community have paid scarce attention to laser weapons and their operational implications. A search of Air University Library's very comprehensive *Index to Military Periodicals* reveals a scant total of 15 articles with the term "laser weapon" in their titles—in a 102,810 page database.<sup>9</sup> Despite several nascent efforts to understand the military worth of these systems, appreciation of their potential throughout the military operational community remains low.

A serious consequence of this lack of laser weapons awareness among warfighters is that technology development is outpacing generation of the operational requirements necessary to guide it. This may cause developers to pursue technology advances in sub-optimal directions, wasting precious time and resources. To develop the most appropriate and effective laser weapons U.S. forces will need, warfighters must be able to tell the weapons developers what characteristics are most important to operational success. To begin developing appropriate operational concepts, platforms and organizations, tactics, techniques

and procedures to exploit the advantages of laser weapons, warfighters also need to determine how laser weapons relate to and interact with kinetic and chemical energy weapons.

We also need to figure out how to defend against laser weapons.<sup>10</sup> This will be an important part of our own laser weapon development process because we must avoid fielding weapons that can be easily countered by an enemy. However, it will also be very important to protect our own forces against laser weapons.

Since World War II, an underlying assumption of U.S. defense planning has been that U.S. forces will enjoy a technological edge over potential adversaries. That might not be true of laser weapons. Because they offer an opportunity to overcome the huge U.S. advantage in advanced missiles and other high-technology capabilities, other countries and non-state actors may pursue directed energy weapons based on their own security, economic and political objectives.<sup>11</sup> These objectives will shape the kinds of capabilities these actors develop and ultimately the range of responses and operational concepts the U.S. pursues. While the U.S. is believed to hold a significant lead in laser weapons development, there is no guarantee that we will not face an enemy with at least some laser weapons capability in the not-too-distant future. Thus, it behooves us to consider possible counters for laser weapons as we develop operational concepts that might exploit their capabilities to our own advantage.

<sup>9</sup> Air University Library Index to Military Periodicals (AULIMP), <http://www.dtic.mil/dtic/aulimp/index.html>

<sup>10</sup> Several feasible approaches to defending missiles and other targets from laser weapons include spinning the missile or aircraft, highly reflective surfaces, or ablative materials. The effectiveness of these approaches is yet to be determined.

<sup>11</sup> Bob Preston, et. al., *Space Weapons Earth Wars*, MR-1209-AF (Santa Monica: RAND, 2002), p. 86.

## V. OPERATIONAL CHARACTERISTICS OF LASER WEAPONS AND THEIR POTENTIAL APPLICATION

In order to appreciate how different laser weapons and their varied characteristics might impact future warfare, it is important to understand the unique capabilities and limitations of these weapons. In general, laser weapons offer warfighters opportunities for quick and precise target engagement, flexibility and a light logistics burden. They are limited by atmospheric conditions, dependence on line of sight, relatively low power levels and several safety concerns.

### CAPABILITIES:

The following capabilities make lasers attractive for operational uses.

- Highly agile speed-of-light delivery:* Laser weapons engage targets at the speed of light—there essentially is no time of flight as for projectile weapons. This makes them well suited for engaging close-in maneuvering targets (e.g. surface-to-air missiles or SAMs, air-to-air missiles or AAMs, UAVs and cruise missiles) and extremely fast ballistic targets (e.g. rockets, artillery and mortar rounds). There is no requirement to calculate and fly an intercepting trajectory with a target as for guided missiles. However, laser weapons do require some time to acquire and track targets and have to “dwell” on the target long enough (several seconds) to deposit sufficient energy to destroy or neutralize it.
- Multiple target engagements and rapid retargeting:* Because laser weapons have few moving mechanical parts and are constantly powered or reloaded by recharging their chemical or electrical energy stores, they can engage multiple targets very quickly, limited for the most part only by their ability to be supplied with fuel or electrical power or to dissipate waste heat. Shifting from one target to another involves only repointing and refocusing mirrors. Thus, they are well suited for the types of multiple-target engagements that might be required to deal with salvo firings of artillery or rockets.
- Deep magazines:* Because lasers only consume chemical fuel or electricity, the total number of shots they can fire is limited only by the amount of chemical fuel available or, in the case of solid-state lasers, the fuel available to drive the electrical power source.

Chemical lasers can operate continuously for the full duration of their magazines (e.g. for 10-20 targets for HELRAM). “Refueling” the laser requires exchanging the depleted magazine by hooking up a depot-filled tank mounted on a palletized trailer, a relatively easy procedure that takes just minutes. Space permitting, the laser could be connected to two magazines; one could be switched out while the other provides fuel for firing.

For SSLs, the number of shots that can be fired at any one time is limited by the laser’s ability to reject heat or the capacity of its batteries. These limitations translate into a “duty cycle limit”: the laser can only be fired for so long before it has to shut down to recharge batteries or eliminate heat. For some platforms, such as airplanes or ground vehicles, typical duty cycles are such that after engaging roughly 10 to 20 targets the laser must cool or be electrically recharged over a time span of 10-20 minutes before being able to fire again. For other platforms, like naval ships where large amounts of electricity and cooling are available, properly designed SSLs could run almost indefinitely. Outside of the cooling periods and over long periods of time, only the fuel onboard the platform limits SSL firings. On aircraft, ships and ground combat vehicles that can be refueled during missions, fuel availability is not a limiting factor.
- Low incremental cost per shot:* For a projectile weapon system, the incremental cost per each shot is essentially the cost of the ammunition expended. Guided missile systems in particular expend a lot of expensive hardware (i.e. rocket motors, guidance systems, avionics,

seekers, airframes, etc.) in the form of missiles every time they fire. Laser weapons, on the other hand, only expend energy. The cost per incremental shot is essentially the cost of the chemical fuel or the fuel required to generate the electricity needed to power a solid-state laser or FEL, and these tend to be low. The cost of employing laser weapons systems, therefore, lies in developing, building, fielding and maintaining the systems, not in the “ammunition” they consume. Whether a system fires one shot or a thousand shots, the cost is relatively fixed. For laser weapons, the low incremental cost per shot helps to reduce limited inventory problems that can handicap weapons like highly advanced but expensive missile systems.<sup>12</sup>

- *Exceptional accuracy and adjustability:* Once cued by radar or other sensors, laser weapons use a low-powered beam to acquire and track their targets. This beam can be focused anywhere on the target with great precision before the co-aligned high-power laser is engaged, delivering the desired level of damage at that exact point on the target. If designed to do so, laser weapon’s power levels could be adjustable. Additionally, the “dwell time” on the target can be changed to adjust the amount of damage inflicted. Accuracy and adjustability combine to allow exceptional precision strike capability, eliminating or limiting collateral damage and allowing lethal or non-lethal applications.
- *Lower logistical support requirements:* Unlike guns that must be resupplied with ammunition or missiles that must be replaced once expended, laser weapons only require additional chemical fuel or fuel to generate the electricity needed for power. For electrically powered solid-state lasers or FELs, this eliminates the requirement to transport, store and load munitions, resulting in an extremely short logistics tail. Chemical laser fuels can be resupplied by factory-loaded fuel “magazines” that can be transported in standard cargo vehicles.
- *Flexibility:* Laser weapons are modular and scaleable. Several identical laser modules can

be “stacked” to create a higher-powered laser. They can also be configured to correspond to the carrying capacity of different platforms. Unlike guns and missiles that often have to be designed for specific missions, a single laser design can fill multiple mission requirements.

#### LIMITATIONS:

Laser weapons do have unique limitations that could impact on their operational utility.

- *Atmospheric attenuation and turbulence:* Because laser beams must be propagated through the atmosphere, they can be affected by airborne particles (dust, smoke), water vapor or atmospheric turbulence that absorb, bend or scatter laser energy. To adjust for some of these factors, laser weapons use “adaptive optics” that compensate for atmospheric distortion of the laser beam. Space-based lasers will only be affected if they are used against targets in the atmosphere.
- *Line-of-sight dependence:* Laser weapons require direct line-of-sight to engage a target. Screening or shielding materials that cannot be readily burned through reduce their effectiveness. Projectile weapons, on the other hand, can have significant penetrating capability and can follow arcing ballistic trajectories to hit targets in defilade behind buildings, mountains, etc.
- *Target Suitability:* Because of their relatively low power levels, laser weapons will probably lack the “punch” of larger non-laser chemical or kinetic weapons for some time. They are best suited for targets that must be engaged very quickly and precisely, such as rockets, missiles or artillery rounds in flight, or that can be killed or disabled by focusing damage on small areas, such as thin-skinned vehicles. Their effects are minimal on hardened structures like bunkers or even buildings. Against armored vehicles they are effective only in disabling vulnerable components such as antennas, sensors and external fuel stores.

<sup>12</sup> For comparison, procurement costs of the JDAM are \$21,000 (tail kit only); for the JSOW, \$660,000; for the JASSM, \$300,000; and for the AMRAAM \$386,000. Even the basic Maverick can cost \$152,000. By contrast, the fuel required per shot of the large laser in the ABL costs approximately \$10,000. David H. Freedman, “Lasers: the Light Brigade,” Strategic Affairs, No. 26/Issue: August 16, 2001, p. 3. For a 100 kW solid state laser, the cost of the fuel required to generate electricity for each shot is less than a dollar.

- *Single wavelength.* Different wavelengths transmit energy better under different atmospheric conditions. Chemical and solid-state lasers typically generate light energy either on a single wavelength or over a small range of wavelengths. The FEL can be “tuned” to a wide range of wavelengths to meet specific requirements, but this “tuning” involves a lengthy process to make the appropriate changes to the optical system or requires that a very complex mechanism be included in the design of the laser.<sup>13</sup>
- *Eye Safety Issues.* Eye safety is a major concern in the use of laser weapons. While some chemical lasers operate at eye-safe wavelengths, all high power SSLs currently do not.<sup>14</sup> Because any laser energy that is not absorbed by the target is either scattered or reflected, this non-absorbed energy poses an eye safety risk to friendly personnel without laser eye protection or civilians in the target’s vicinity. For this reason, efforts are currently underway to develop concepts for high power SSLs that operate in the eye-safe portion of the electromagnetic spectrum.
- *Chemical Fuels and Exhaust.* Chemical lasers require chemical fuels and generate exhaust when they fire. Some fuels, like the highly corrosive fuel of the ABL’s Chemical Oxygen Iodine Laser (COIL), require multiple safety systems and risk mitigation plans. Others, like the deuterium fluoride reactants used by the THEL, are relatively safe. The exhaust from the ABL is released high in the atmosphere, where it poses no hazard. The exhaust from ground-based lasers like THEL contains small amounts of toxins that are readily absorbed by commercially available scrubbing systems.

<sup>13</sup> Tuning” involves major re-configuration of the laser (e.g. switching optics.) Thus a laser system is tunable in the sense that it can be designed to operate at 1.5  $\mu\text{M}$  or 2.0  $\mu\text{M}$ , or 2.5  $\mu\text{M}$ , but it cannot change from 1.5  $\mu\text{M}$  to 2  $\mu\text{M}$  to respond to changing mission conditions unless considerable complexity is built in to allow this to be done remotely.

<sup>14</sup> Deuterium fluoride lasers like THEL and the ABL’s Chemical Oxygen Iodine Laser (COIL) are eye safe. Most current versions of SSLs are not.

## VI. OPERATIONAL IMPLICATIONS

If the U.S.—or another power—successfully fields laser weapons on different warfighting platforms, how might they affect the conduct of military operations? This question is fundamental in prioritizing operational requirements to guide the technical development of laser weapons.

Analyzing the capabilities and limitations of laser weapons in an operational context implies they are well suited to roles in two key mission areas:

- *Active Defense:* Lasers can provide air, land, sea and space platforms the ability to defend themselves, other platforms and geographic areas. They can defend against missiles, aircraft, bombs, artillery shells or rockets by destroying or neutralizing these threats before they reach their intended targets. For missile defense, lasers can provide point defense of a specific target or area defense against theater ballistic and cruise missiles as a complement to defensive missiles.
- *Offensive Strike:* Lasers can provide the capability to achieve lethal or non-lethal effects against a range of suitable targets, mostly as a complementary capability for chemical and kinetic weapons.

The following sections address the operational implications of laser weapon capabilities for these mission areas. The fictional vignette illustrates these implications in an operational context. It is not in any way predictive of future events.

### Vignette:

#### Operational Impact of Laser Weapons on Combat Operations

##### The Second Korean War: 2024

Laser weapons made their major combat debut in the Straits of Hormuz Crisis of 2014. During initial operations against Iranian forces blocking the

Straits, U.S. strike aircraft suffered unacceptable losses to advanced model long-range Russian SAMs imported by Iran. To minimize escalation, U.S. national leaders wanted to restrict the conflict to the area in the immediate vicinity of the Straits and were reluctant to authorize strikes against SAM sites hundreds of kilometers inland. Urgently seeking a non-escalatory counter to these threats, USCENTCOM requested the four available prototype F-35 Joint Strike Fighters equipped with lasers, then in the demonstration and validation phase of development, to provide active defense for strike packages.

Flying with only one aircraft escorting each strike package, the F-35 Laser Fighters were highly successful in defeating the late-model SAMs, even when they were fired in volleys. The Laser Fighters' reputation was further enhanced when one also shot down several low-flying supersonic antiship cruise missiles.

Following this highly successful combat performance, the Services placed a top priority on developing and fielding laser weapons, mostly for active defense purposes but also to complement interceptor missile point defense capabilities. When hostilities threatened with a resurgent North Korea in 2024, most U.S. rapid deployment forces were equipped with these capabilities.

#### DEFENSIVE OPERATIONS

The ability of laser weapons to defend airborne platforms has been known for several decades. The U.S. Air Force's Air Force Weapons Laboratory (AFWL) first demonstrated the technical feasibility of employing laser weapons to defeat airborne threats in 1973 by using a ground-based gas dynamic CO<sub>2</sub> laser to shoot down a drone aircraft flying at 200 miles per hour.<sup>15</sup> By 1983 AFWL's Airborne Laser Laboratory program was able to integrate an airborne high energy chemical laser with the required target acquisition, tracking and laser beam training technologies to shoot down five AIM-9B Sidewinder air-to-air missiles (traveling around 2000 miles per hour) and a simulated antiship missile.<sup>16</sup> The technologies to defeat a range of fast moving, highly maneuverable threats have been available for some time.

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<sup>15</sup> Robert W. Duffner, *Airborne Laser: Bullets of Light*. (New York, NY: Plenum, 1997), pp. 23-41.

<sup>16</sup> Duffner, pp. 279-315.

*Air Operations: Enhanced Survivability and Campaign Flexibility* — Laser defenses could provide an on-board active defense capability for aircraft to defeat or destroy incoming missiles or aircraft within their range. This has several major implications for air operations.

First, it greatly increases the survivability of many aircraft. With active laser defenses on board, non-stealthy, subsonic, vulnerable platforms (e.g., Joint STARS, AWACS, ABLs<sup>17</sup>, B-52s) become much more survivable against SAMs and AAMs. Conversely, laser-equipped aircraft (like the ABL with its very long range laser) could also escort aircraft that lack their own laser defenses. Second, because modern SAMs have ranges of hundreds of kilometers and fighters have operational radii of several thousand kilometers, suppression of enemy air defenses (SEAD) and air supremacy campaigns today may have to actively suppress air defenses over tens of thousands of square kilometers, a major operational task. By defending individual aircraft or flights of aircraft against SAMs and AAMs rather than attempting to neutralize these threats throughout the battlespace, active defense laser systems could significantly reduce SEAD requirements.

Active defense lasers could also improve the sequencing of SEAD and air supremacy campaigns. Today, these must be completed to a significant degree before strike operations begin, to limit the attrition of strike aircraft. However, because aircraft defensive lasers can shoot down SAMs or AAMs as they are fired at the defended aircraft, commanders could have the option to begin strike operations before either a SEAD or air supremacy campaign is complete. This means that “center of gravity” targets that affect the outcome of the operation directly, such as command and control facilities or invading enemy ground forces, can be prosecuted from the very beginning of air operations, significantly reducing the time required to execute a successful air campaign. Because active defense laser weapons provide significant aircraft self-defense against SAMs and AAMs, other defensive requirements, such as electronic warfare support for strike packages, might be reduced.

#### *Korea 2024 Continued...*

Attacking with little warning in January 2024, North Korean forces intended to capture Seoul, then the rest of South Korea, before U.S. forces could intervene. They began their attack by suppressing South Korean air bases with a constant barrage of SCUD missiles carrying a mix of persistent chemical and submunition warheads. They also used non-persistent chemical weapons to open corridors through ROK defenses for their mechanized forces.

The North Koreans recognized that the US-ROK Combined Forces Command (CFC) would use both naval air and long-range strike aircraft operating out of Japan and Okinawa to strike bridges, assembly areas and other key targets to slow and attrit their ground forces. In response, they deployed long-range advanced Russian SAMs to provide effective air defense coverage of their forces without displacing their air defenses to the south. Deployed in hardened shelters and employing updated Russian and Chinese-provided systems to defeat U.S. electronic counter measures, the North Korean integrated air defense system (IADS) proved relatively effective against all non-stealthy U.S. airborne platforms, except those equipped with active defense lasers.

Protected by laser defenses, U.S. manned and unmanned ISR assets operated over friendly forces well within the SAM envelope and rapidly developed high-resolution, near-real time targeting data against the invading North Korean mechanized forces. The North Koreans had anticipated U.S. air forces would have to dedicate their initial efforts to suppressing the North Korean IADS, but active laser defenses on many U.S. strike aircraft reduced the SAM threat to a manageable level and allowed U.S. forces to immediately support the hard-pressed ROK defenders. Long-range bombers employed precision munitions that were supplied targeting data by near-real time ISR, providing highly accurate and persistent close air support for coalition ground forces.

*Ground Operations: Deployability and Mobility without Sacrificing Survivability* — Ground forces, like air forces, can profit from the enhanced survivability provided by active defense lasers. Because high power laser defensive systems will probably weigh several thousand pounds for the foreseeable future, they are not man-portable. These systems will be mounted on dedicated vehicles that provide active defense for other

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<sup>17</sup> Although ABLs lasers are intended to defeat ballistic missiles in boost phase, they provide an inherent capability against AAMs and SAMs as well.

combat systems and units within their coverage range. But the improvements in survivability offered by laser systems may enable the design of lighter combat vehicles, supporting efforts to build more strategically deployable, tactically mobile ground forces.

Today, most losses on the conventional ground battlefield are caused by indirect fire weapons, - including artillery, rockets and mortars that follow ballistic trajectories - and air-delivered bombs. Guided direct fire weapons, such as anti-tank guided missiles (ATGMs) and man-portable air defense systems are also very lethal. Hypervelocity large caliber tank rounds are another significant direct fire threat. An example is the armor-piercing discarding sabot (APDS) rounds fired by the Army's M-1 tank, which essentially are yard-long depleted uranium rods traveling at thousands of feet per second.

Protecting against these weapons at present requires heavy armor, leading to massive vehicles such as the 70-ton M-1 tank that require considerable resources to deploy and consume large amounts of fuel on the battlefield. Active laser defenses could improve the survivability of lighter vehicles by defeating some of these threats before they reach their targets. The THEL has already destroyed rockets, artillery and mortar rounds in flight, demonstrating that lasers can deal with these indirect fire threats.<sup>18</sup> Given THEL's demonstrated capabilities, it appears that similar laser systems would also be capable against manned aircraft.

In addition to protecting combat forces, active laser defenses can also protect key facilities and infrastructure, such as logistic bases, airfields and ports from indirect fire. In counterinsurgency environments, such as Iraq and Afghanistan, this would probably be their key role.

However, lasers are not well suited for defeating direct fire threats, like ATGMs, tank rounds and rocket-propelled grenades (RPGs). The flat trajectories, very short times of flight, and mass of these munitions make them difficult targets for a laser system, which must dwell on a target long enough to cause it to explode or veer off course. Consequently, laser active defense systems will work best when complemented by other active

defense systems. Current development efforts have focused on detecting and tracking incoming direct fire threats with millimeter-wave radars or infrared sensors, then engaging them at close range with proximity-fused grenades or at longer ranges with rockets. These rocket and grenade active defense systems will most likely remain the preferred solution to direct fire threats for the foreseeable future.

Development of effective active defense lasers would assist ground force designers in balancing the conflicting requirements for strategic deployability and tactical mobility and survivability. Survivability requires armor that adds weight and reduces deployability and mobility. In combination with rocket or grenade active defenses against direct fire threats, active defense lasers can enhance survivability and reduce the requirement for heavy armor, reducing the weight of combat vehicles and thus increasing their strategic deployability and tactical mobility.

#### *Korea 2024 Continued...*

**Pinned in their defensive positions by heavy volume of North Korean artillery firing from hardened positions north of the DMZ, ROK ground forces were unable to maneuver into the flanks of the North Korean penetrations. However, the sole remaining U.S. Army heavy brigade in Korea had recently been equipped with organic active defense laser vehicles. These destroyed a high percentage of the thousands of artillery rounds and rockets fired at the brigade as it successfully counterattacked to isolate, then destroy, the lead North Korean corps.**

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*Naval Operations: Electric Ships Could Power Lasers* — Many of the characteristics that make active defense lasers attractive to ground and air forces would benefit naval forces as well. An operational solution deploying lasers at sea could provide the U.S. Navy significant capabilities and enhanced operational flexibility. For example, lasers could provide an effective shield against adversary ballistic or cruise missile attacks, enabling safer operation in the littoral environment and establishment of sea bases well within enemy missile range.

<sup>18</sup> Space Daily, August 27, 2004, <http://www.spacedaily.com/news/laser-04r.html>.

Developments in naval shipboard power also favor electrically-powered laser weapons. The Navy is moving toward greater electrification, notably with ships like CVN-21 and DD(X). These ships will have significant excess electrical generation capacity and a backbone of power cables to move large amounts of power throughout the ship efficiently,<sup>19</sup> making it relatively easy for them to host solid-state laser weapons.

Lasers would work well in supporting the Navy's "Sea Shield" concept for sea-based defensive operations.<sup>20</sup> They offer significant opportunities for improving the protection of the "Sea Base" (the Navy's concept for sustaining forces ashore without shore bases) or protection of ships and shipping at sea. For example, naval forces are increasingly being required to operate in littoral regions, where they are threatened by small, fast and potentially suicidal craft such as jet skis, fast racing craft known as cigarette boats, and Boghammers<sup>21</sup> that can easily hide among the commercial fishing, cargo and passenger craft fleets. With their adjustable power levels, ship-mounted laser weapons could provide a graduated yet robust response to these threats while avoiding serious damage to innocent civilian craft that might inadvertently approach naval vessels.

Another major threat to naval forces is the next generation of advanced supersonic sea-skimming antiship cruise missiles (ASCMs) that may not be detected until they are seconds from hitting their targets.<sup>22</sup> Active defense lasers offer a high speed of engagement to complement close-in defensive guns and missiles. Defensive laser systems

mounted on escorting ships also have an advantage here not only because they can engage targets for a longer period but also because they can engage the more vulnerable soft side rather than the harder nose of cruise missiles.<sup>23</sup> Aircraft-mounted laser systems might provide the best fleet area defense against hypersonic cruise missiles.

Sea Shield is also focused on the projection of defense ashore and here, too, lasers could offer important capabilities. As lasers transition into the sea Services, great opportunities will arise for projecting defense throughout the littoral – both over the water and inland. Navy ships could protect U.S. and allied forces ashore from many forms of indirect fire weapons. For example, a large deck amphibious ship operating close to shore with a large, long-range laser defense system could theoretically provide a "sea shield" against air, missile or artillery attack over elements ashore, significantly improving their survivability and ability to maneuver.

The Navy operates at long ranges and in changing maritime atmospheric conditions like sea haze, both of which challenge the capabilities of laser weapons. Therefore, the Navy is most interested in laser weapons with the high power levels normally associated with chemical lasers. However, as noted earlier, the Navy is focusing on all-electric ships and, for this reason, some argue that a high-powered FEL is best suited for naval very high power applications. Determining whether SSLs or FELs or some mix thereof will best meet Navy requirements will probably require significant development and operational testing.

<sup>19</sup> Scott C. Truver, "Team Effort," *Jane's Defense Weekly*, April 9, 2003, p. 26. The DD(X) in particular has an Integrated Power System capable of "near instantaneously switching power from propulsion to weapons and back."

<sup>20</sup> Sea Shield is the U.S. Navy's concept for protecting our national interests with layered global defensive power based on control of the seas, forward presence, and networked intelligence. It includes theater air and missile defense. Admiral Vern Clark, "Sea Power 21: Projecting Joint Capabilities," *Proceedings*, U.S. Naval Institute, Vol. 128/10/1, 196, October 2002, p. 35.

<sup>21</sup> The term "Boghammer" specifically refers to speedboats manufactured by Boghammer Marin in Sweden. Capable of 50-knot speeds, 40 were sold to Iran in 1983 and used by the Iranian Revolutionary Guards for attacks against oil tankers and other vessels in the Straits of Hormuz in the mid-late 1980's. Boghammer has since become a common term referring to this class of small, fast attack craft. *The Aida Parker Newsletter*, Issue 200, October, 1996. <http://www.cycad.com/cgi-bin/Aida/aida-200.html>.

<sup>22</sup> Antiship cruise missiles are difficult targets for existing cruise missile defense systems such as the gatling-gun Close-in Weapon Systems (CIWS) long deployed by the US and other navies. Trends in cruise missile development include increases in speed (now supersonic: mach 2) and reductions in both flight altitude and radar cross section. These make detection difficult until the missile is close to the target. U.S. General Accounting Office, Report to Congressional Requesters, *Defense Acquisitions: Comprehensive Strategy Needed to Improve Ship Cruise Missile Defense*. GAO/NSIAD-00-149, July 2000.

<sup>23</sup> Power requirements for the laser drop by a factor of 5 to 10 because of the better aspect angle to the target and ability to put the beam on a softer part of the target.

*Korea 2024 Continued...*

Seeking to defeat the North Korean forces decisively before they could withdraw into strong defensive positions, CFC opted to conduct a fixing attack with ROK forces in the south while U.S. forces conducted an amphibious envelopment into North Korea. Success of the amphibious operation depended on the ability to build combat power ashore very rapidly.

Consequently, CFC decided to accept risk and place its Navy Sea Base well within range of North Korea's numerous supersonic antiship cruise missiles (ASCMs). Keeping these missiles in their hardened and camouflaged shelters until the Sea Base was in range, the North Koreans launched waves of ASCMs that exhausted the magazines of available missile defense missiles. Anticipating this possibility, the admiral commanding had kept his Sea Base flotilla in tight formation and boxed by the four available DD(X)s equipped with active defense laser systems. The defending destroyers and Navy UCAVs armed with laser weapons guided by the naval forces' net centric command and control were able to defeat most of the ASCMs that penetrated the initial defenses.

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### *Space Operations: Satellite-Based*

*Laser Weapons*<sup>24</sup> — Space-based lasers may also provide active defense over large areas, depending on the wavelength of the energy propagated and existing atmospheric conditions, including weather.<sup>25</sup> A space-based laser satellite constellation would have the inherent advantages and disadvantages conferred by orbital mechanics. Operating in space allows the placement of satellites far above the earth in vantage points that provide line-of-sight access to large portions of the earth's surface, including potentially denied areas within a hostile state. These vantage points have obvious advantages for directed energy weapons based in space just as they do for sensors. However, this access is complicated by the motion of satellites within their orbit versus the motion of the earth. Only satellites in very high (23,000 mile) geosynchronous (GEO) orbits

maintain their position relative to the earth's surface. But GEO orbits are not suitable for space-based lasers for a number of reasons, the most obvious being that they put the laser at too great a distance from potential targets. The best solution for laser systems would be a constellation of satellites to achieve the desired coverage at lower orbits. The satellites would not linger over specific portions of the globe but would orbit the earth on predictable paths with "access" to different surface locations. About a dozen satellites at an altitude of around 1,200 – 1,500 km can provide continuous coverage of most of the earth (excluding polar regions).

Space-based lasers could engage targets, primarily ballistic missiles, much earlier in their trajectories than terrestrially based defenses. Ballistic missile threats could be engaged shortly after they ascend above the clouds during their vulnerable boost phase, before they deploy decoys.

Active defense lasers could also potentially protect high-value satellites from attack by nano- or micro-satellites operating in a kinetic collision or parasitic mode. In the vacuum of space, potentially short engagement ranges would likely keep such a satellite self-defense system relatively lightweight.

*Ballistic Missile Defense (BMD): For Affordable Layered Defense* — Ballistic missiles armed either with weapons of mass destruction or advanced capability conventional warheads pose one of the greatest threats to forward deployed or deploying U.S. forces. Although missiles such as the Patriot Advanced Capability-Phase 3 (PAC-3) have proved relatively effective against theater ballistic missiles (TBMs), they are expensive. SCUDs and other TBMs based on 1940's technology are relatively inexpensive (around \$1 million)<sup>26</sup> while a single PAC-3 costs approximately twice as much.<sup>27</sup>

For budgetary reasons, then, defensive missiles tend to be low-density/high-demand items for even the most wealthy and advanced military

<sup>24</sup> U.S. policy does not advocate the weaponization of space, and Northrop Grumman Corporation supports that policy. However, any policy discussion should be informed by analysis of the potential operational implications of space-based lasers. Therefore, such analysis is included in this effort. See Scott McClellan, White House Press Secretary, Press Briefing, The White House, May 18, 2005, for statement of U.S. policy.

<sup>25</sup> Preston, et. al., p. xvi.

<sup>26</sup> Statement of Christopher Bolkcom, Analyst in National Defense, Congressional Research Service, before the Senate Governmental Affairs Committee, Subcommittee on International Security, Proliferation, and Federal Services, Hearing on Cruise Missile Proliferation, June 11, 2002, p.2.

<sup>27</sup> Bradley Graham, "Missile defense program changes course," The Washington Post, August 6, 2002.

powers. Defending a point target<sup>28</sup> such as an air base against theater ballistic missiles with a high level of confidence can require two defensive missiles for each attacking missile. Defending more than a few critical targets against large numbers of missiles quickly becomes cost prohibitive. Because offensive missiles can be retargeted against any target within their range arcs, even relatively robust missile defenses can be overwhelmed if the enemy is willing to expend the required number of offensive missiles.

An attacking ballistic missile goes through three phases of flight enroute to the target: boost phase, when the rocket motors are firing; mid-course, when the missile is coasting along its ballistic trajectory; and terminal, when it is descending toward its target. One of the basic principles of missile defense is to create as many different “layers” of defense in as many of these phases of flight as possible because each defensive layer increases the probability that the enemy missile will be destroyed before it hits its target. Longer-range defensive systems can provide area defense of large areas, shorter range systems provide point defense of specific targets.

The projected role of the Airborne Laser in boost phase missile defense is well known, but ground-based lasers are also well suited to terminal point defense of critical targets. These lasers can fire tens of shots against offensive missiles very quickly, making them difficult to overwhelm. The chemicals consumed per shot cost less than \$10,000, much less than the millions of dollars for defensive missiles. Thus, even taking into account the initial cost of the laser weapons, laser-based point BMD may prove to be a highly effective—and more affordable—means of adding an additional layer of defense against TBM attack.

Because they are more affordable, laser defenses can be more widely spread. They can complement missile defense missiles of longer ranges. Megawatt-class chemical lasers could defeat theater ballistic missiles. Multi-megawatt class lasers (much larger than any system under development today) would be required to defeat the faster and

much harder targets presented by ICBM reentry vehicles (RVs). In both cases, effectiveness of a laser defense would depend on developing systems concepts that overcome the potential effects of clouds, fog or dust storms. For example, aircraft basing would allow the laser weapon to operate above these weather effects.

Because solid-state lasers are modular and stackable, it may eventually be possible to create megawatt solid-state lasers that could fulfill the BMD role, assuming they can be linked to sufficiently powerful electrical sources. Alternatively, FELs may prove scaleable into the megawatt range. This would be particularly important for fleet-based missile defense because chemical lasers require chemical fuels, making them less well suited for shipboard use.<sup>29</sup> With their advanced electrical power systems, next generation naval vessels could be ideal platforms for large solid-state lasers or FELs. However, even with lasers in the megawatt range, the amount of energy that would have to be used against a TBM RV in a very short time will limit ship-based BMD coverage areas.

For maritime forces, BMD may become even more important in the future if TBMs are equipped with maneuvering warheads capable of striking ships under way. Even limited laser defensive coverage areas could be very important to future fleet BMD because missile defense of the fleet and the littoral areas it protects requires greater numbers of assets than resources and practical limitations make feasible. Current and future vessels have a finite number of vertical launch system (VLS) tubes that can be dedicated to defensive missiles. These tubes cannot be reloaded at sea; consequently, once all of a vessel's defensive missiles are expended, it must return to port to reload. A vessel defending a fleet off the coast of Taiwan, for example, might have to transit all the way to Guam and return. This limits the numbers of TBMs that naval forces can engage. However, if next-generation large naval vessels were to power megawatt-sized solid-state laser or FEL missile defenses, they could essentially reconstitute their laser missile defense capability with each refueling at sea.

<sup>28</sup> “Point targets” are specific geographic locations, such as an airbase, as opposed to “area targets” that refer to a larger geographic area.

<sup>29</sup> See “Chemical Fuels and Exhaust” discussion on page 12.

Korea 2024 Continued...

Recognizing that U.S. air bases in Japan and Okinawa were a critical coalition center of gravity that had to be neutralized before their forces could renew their attack, the North Koreans began salvo firing No Dong intermediate range ballistic missiles with persistent chemical agent warheads at them. Although these missiles were a major threat, CFC opted to reserve its limited Airborne Laser (ABL) and ship-based Kinetic Energy Intercept (KEI) missiles assets to prevent successful launch of North Korean nuclear missiles. The hundreds of No Dong reentry vehicles reaching Japan began to overwhelm the limited numbers of Theater High Altitude Air Defense (THAAD) missiles available to the Japanese Self Defense Forces before additional U.S. missile defense forces could arrive in theater. However, the Japanese had deployed laser point defenses at the most critical bases and these destroyed many of the remaining No Dong warheads aimed at those targets.

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### Homeland Defense Operations —

The same characteristics that make laser weapons effective for these military active defense missions could also allow them to defend critical infrastructure such as bridges, nuclear power plants and chemical plants, or government facilities like the White House, Capitol and the Pentagon, against aircraft and direct and indirect fire ground weapons. Against an attack by a hijacked aircraft, for example, laser defenses could provide a graduated response that might first illuminate the cockpit, then disable control surfaces to impede maneuverability and force the aircraft to fly away from the target. The same weapons could defeat terrorist mortar or missile attacks, providing a highly flexible point defense against multiple threats. Located at airports, they could also defend aircraft landing and taking off against MANPADS.

Cruise missiles launched from ships at sea are another homeland security challenge that could be met by airborne laser systems. THEL-like chemical lasers scaled up to megawatt-class power levels on wide-bodied aircraft (about the size of a C-130) could defend relatively large areas with small numbers of aircraft, providing an effective, persistent defense at affordable cost.

## OFFENSIVE OPERATIONS

Because lasers put considerably less destructive energy into a target than the larger chemical or kinetic munitions, offensive applications of lasers will most likely be dedicated to those missions where their other characteristics (e.g., precision, speed and numbers of engagements) are more important than pure destructive power.

### *Air Operations: New Relevance in Counterinsurgency, Counterterrorism Operations* —

Laser weapons could add significant air-to-air capabilities to air platforms. Because laser “bullets” travel at the speed of light, engagements have no “fly out” time and can be completed very quickly. Solid-state laser weapons also have “deep magazines,” meaning they do not run out of ammunition as long as they can be recharged and cooled.<sup>30</sup> This would make laser-armed aircraft ideal for missions that might require multiple air-to-air engagements over a protracted period. For example, Unmanned Combat Air Vehicles (UCAVs) armed with lasers (and equipped with sufficient electrical power generation capability) could conduct denial-of-flight operations over large areas of enemy territory for an extended period. A mission such as NORTHERN or SOUTHERN WATCH over Iraq could become a far more economic operation.

The same laser weapons that provide an active defense capability against SAMs, AAMs or aircraft can also be used against targets on the ground, providing a significant air-to-ground capability. In combination with current and new generations of air platforms and sensors, laser weapons may significantly increase the ability to “fine tune” the application of force from the air. This could make air power more relevant in counterinsurgency and counterterrorism operations.

Laser weapons’ accuracy, range and adjustability allow for major increases in the precision with which destructive effects can be delivered from the air. They can reduce the minimum area of damage from multiple square meters for small diameter bombs to several square centimeters. This makes it possible to engage point targets

<sup>30</sup> See “Deep Magazines” discussion on page 10. For some electricity-limited tactical platforms (e.g. airplanes) SSLs can only fire about 15-20 “bullets” before they have to recharge batteries or cool down. However, for platforms where power and cooling are readily available (e.g. ships) some SSL configurations can operate for unlimited run times and 100% duty cycle.

with little or no collateral damage, allowing close air support of ground forces intermingled with enemy forces or engaged in urban or close terrain.<sup>31</sup> Such precision also allows engagement of specific sub-elements (e.g. antennas, external transformers) of critical targets like radio stations and electrical power plants without totally destroying them. However, as previously noted, eye safety issues, particularly in urban environments, would need to be addressed, or the lasers used must operate at eye-safe wavelengths.<sup>32</sup>

One of the limiting factors for strike aircraft today is the amount of ordnance they can carry. This is particularly true of fighter-bombers that provide the majority of today's strike capability. Even advanced models, such as the F/A-22 and the F-35 JSF can at best carry eight next-generation small diameter bombs or air-to-air missiles. Once these are expended, the aircraft must return to base to rearm, even if it has fuel remaining. Thus the amount of on-board ordnance sometimes hinders the ability of air power to maintain a persistent presence in the battlespace with a fixed number of aircraft.

Solid-state laser weapons, however, require only electricity provided by on-board generators (usually driven by the engines) to fire. This means that even small strike aircraft can potentially fire hundreds of laser shots (allowing time to recharge and cool between series of shots). Refueling the aircraft essentially rearms the laser. Thus, if an aircraft can be refueled in the air, it can provide a persistent presence in the battlespace limited only by crew endurance and the reliability of electro-mechanical systems. This would point to an ideal marriage between solid-state laser weapons and long-endurance airborne platforms, such as UCAVs.

Effective application of such persistent precision attack capability will enable a major expansion in the way we think of air power's relevance across the full spectrum of conflict. For example, laser weapons with their deep magazines mounted on high-altitude, stealthy UCAVs also equipped with high resolution sensors could persistently deny enemy personnel the ability to operate in the

open over large, remote areas. Employing these capabilities to their full advantage requires the development of new tactics, techniques and procedures for everything from targeting to engagement to battle damage assessment.

#### *Korea 2024 Continued...*

The ROK defenders stabilized their positions and began to build combat power for a decisive counterattack while the North Koreans desperately attempted to resupply and reinforce their stalled forces. However, these efforts were greatly hampered by U.S. area denial operations. Operating in near-space, surface moving target indicator radar (SMTI) platforms equipped with active laser defenses cued other manned and unmanned SMTI platforms that effectively tracked and identified all North Korean ground traffic from Pyongyang to below the DMZ. These sensors guided long-range, persistent, stealthy UCAVs flying from bases in Japan and off carriers. Equipped with laser weapons, these UCAVs destroyed a significant portion of the soft-skinned North Korean resupply vehicles attempting to move south.

North Korea was left with no strategic options after the successful amphibious envelopment supported by precision air support defeated the attacking North Korean forces. Its available No Dong missiles were exhausted and its limited nuclear missiles would be destroyed by orbiting ABLs if they were launched. The UCAV area denial cap cued by persistent ISR essentially blocked their ability to move most forces throughout the country. Recognizing the futility of their situation, the North Korean government requested a complete and unconditional ceasefire.

*Ground Operations: Ideal Sniper Weapons* — Because of their size, weight and lack of heavy armor piercing / deep penetration capability, offensive applications of laser weapons in ground combat will most likely be dedicated to those missions where the precision, speed-of-light engagement time, adjustability and minimal collateral damage of laser weapons are desired. For counter-sniper missions, for example, a laser weapon paired with acoustic and optical sensors that track a sniper's bullet back to the firing point almost instantly could automatically be aimed to

<sup>31</sup> The U.S. Special Operations Command (USSOCOM)/DARPA Advanced Tactical Laser Advanced Technology Demonstration is intended to develop this air-to-ground capability. It will develop a modular laser, initially installed on a C-130, that reportedly will be able to slice metal at a nine-mile range. "Advanced Tactical Laser (ATL)," GlobalSecurity.org. <http://www.globalsecurity.org/military/systems/aircraft/systems/atl.htm>.

<sup>32</sup> The use of lasers for close air support is not totally without risk to supported troops. Scattered laser energy possibly reflecting from targets is likely to blind personnel in the immediate area who are looking at the target unless they have appropriate laser eye protection.

engage the sniper before he is able to take cover. The advantages of laser weapons over conventional machine guns are that lasers have no “time of flight” and produce little collateral damage.

The “stealth” characteristics of lasers also make them ideal sniper weapons. Unlike their portrayal by Hollywood, real laser weapons have no visible beam and have no sonic “report”, muzzle flash or recoil. Under most atmospheric conditions, the only way an enemy would know he was being engaged by a laser would be to see the effect on the target. The systems use low-power lasers to establish the aim point for co-aligned high-power lethal lasers. Once the aim point has been established, the operator only has to energize the high power laser to kill the target—the epitome of the sniper’s “one shot, one kill” motto.

The precision and adjustability of laser weapons could make them highly effective in counterinsurgency or stability and support operations (SASO) where force must be applied carefully to achieve a desired effect. For example, laser weapons could be used to kill or neutralize armed insurgents hiding within a crowd where other weapons would injure innocent civilians. At lower power levels, lasers might achieve only non-lethal effects. For these purposes, laser weapons would probably be most effective when mounted on UAVs or helicopters and used at extended ranges. Operational planning must take into account existing treaty constraints that prohibit the intentional blinding of combatants and non-combatants by lasers.

*Naval Operations: Finding a Niche* — The same factors that limit the offensive role of laser weapons in ground operations also limit their offensive utility at sea. However, lasers may meet niche requirements, especially in sea-borne special operations where precision and stealth are more important than destructive power.

Another opportunity for lasers might be in submarine operations. Integrating a laser head with a periscope would give submarines the capability to engage surface targets from periscope depth.

This would allow them to strike targets such as small boats without revealing their presence or expending a torpedo or missile. They could also attack low altitude aircraft and soft targets ashore.

*Space Operations: Could Give New Meaning to “Space Superiority”*<sup>33</sup> — Laser weapons speed-of-light delivery, exceptional accuracy and adjustability make them well suited for engaging targets in space from the ground or for engaging targets on the surface or in the lower atmosphere from space. The lack of atmosphere to attenuate power and the fact that they only need to be recharged to be rearmed (for SSLs) also makes them ideal space-to-space weapons. As noted earlier, laser weapons can play a defensive role on space platforms, but they clearly have offensive utility as well.

Concerns over the offensive use of lasers against space targets have risen steadily since a Soviet ground-based laser (GBL) tracked the Challenger space shuttle at low power in 1984, causing equipment malfunctions and crew distress.<sup>34</sup> U.S. experiments have also demonstrated that satellites hundreds of kilometers up are vulnerable to high energy GBLs.<sup>35</sup> The importance of this capability has not been lost on countries like China, which is pursuing a robust high energy laser capability.<sup>36</sup> For technologically sophisticated nations with militaries that are dependent on information and data (e.g., positioning/navigation/timing, intelligence, surveillance and reconnaissance, and communications) derived from space-based systems, the potential threat from GBLs is real. Information about the target satellites’ operational characteristics, like orbital parameters, is readily available in open sources. The physical destruction of satellites may not be as important to the attacker as the ability to jam, spoof or otherwise inhibit a spacecraft’s functional effectiveness for a limited period of time. The beam’s intensity and point of impact will determine the GBL’s lethality and effectiveness against a space-based target. Due to the megawatt levels of power required, chemical lasers rather than solid-state lasers will most likely be the lasers of choice for GBLs for the foreseeable future.

<sup>33</sup> See footnote 24.

<sup>34</sup> Steven J. Zaluga, “Red Star Wars,” *Jane’s Intelligence Review*, May 1997, p. 207.

<sup>35</sup> CNN, “Pentagon beams over latest military laser test. U.S. wants to determine vulnerability of satellites.” <http://www.cnn.com/US/9710/20/pentagon.laser/>, October 20, 1997.

<sup>36</sup> U.S. Department of Defense, FY04 Annual Report to Congress on PRC Military Power, <http://www.defenselink.mil/pubs/d20040528PRC.pdf> p. 42.

Laser weapons could also be placed into orbit. The vacuum of space is an ideal environment for lasers, but orbital mechanics will dictate space-based lasers' operational utility. However, for offensive counter-space operations, timelines are not usually critical. Over a period measured in hours, a few space-based lasers get a good shot at

all low earth orbit (LEO) satellites. With sufficient power levels, they could attack targets from the earth's surface well into orbit. If such weapons are eventually developed and fielded, they might be so overwhelming that they would make successful operations in other mediums impossible without first achieving true "space superiority."

## VII. RECOMMENDATIONS

As important as the consequences of fielding the laser weapons described in previous sections may be, experience shows that technological innovation may generate even more important consequences that are impossible to predict. This makes it imperative that the U.S. defense community pursue a robust process toward enhancing our understanding of the operational implications of laser weapons and development of operational concepts for their use.

The first requirement is to develop a true appreciation of laser weapons capabilities by hands on, practical experience with them. This means we need to press on with existing laser weapons programs as rapidly as practical. Serious consideration should be given to fielding a productized prototype of the THEL as quickly as possible. With its proven effectiveness against rockets, artillery and mortars, relatively modest improvements in the existing test system would allow prototypes to defend key facilities and bases in Iraq and Afghanistan. This is an important objective in itself, but it would also demonstrate the combat effectiveness of active defense lasers, serving to spur interest and progress in laser weapons development. Experts have said that either laser weapons will prove themselves in current combat operations or it will be another ten years before they are fielded.<sup>37</sup>

We also need to bring the Airborne Laser program, long the flagship of laser weapons development, to fruition within the planned timeframe. Like THEL, having a real, flying laser weapon for experimentation and demonstration purposes will do much to catalyze interest in the potential capabilities of all categories of laser weapons.

Other efforts to speed our appreciation for laser weapons should include an aggressive wargaming and experimentation program. This program should take the following standard steps for operational concept development:

- Tabletop wargames to identify critical areas of focus.
- Detailed modeling and simulation that will in turn guide the development of prototype weapons and employment concepts.
- Prototype modular laser weapons packages that can be mounted on operational aircraft, vehicles and vessels for hands-on field experimentation.
- Field experimentation in operational units to develop tactics, techniques and procedures for laser weapon employment.

<sup>37</sup> Army Brigadier General Philip Coker, the director of capabilities development at U.S. Army Training and Doctrine Command, has stated that he sees two alternatives to the development of effective laser weapons. Either a viable system is fielded within a year or it will be 10 more years before laser weapons are fielded. Defense Daily Network, January 24, 2005, <http://defensedaily.com/VIP/dd/current.htm>.

## VIII. CONCLUSIONS

From the technology development standpoint, operational laser weapons are right around the proverbial corner. Given adequate resourcing, a “productized” chemical laser weapon could be shooting rocket and mortar rounds from battlefield skies within 18 months.<sup>38</sup> If the Airborne Laser program continues to make progress as predicted, the ABL may be tested against ballistic missiles in a few years.<sup>39</sup> Solid-state and free-electron laser weapons, adding to the range of laser weapons capabilities, may be less than a decade away.<sup>40</sup> Meanwhile, the personnel who will make key decisions on the development, acquisition and employment of these systems are already half-way or more through their military careers but most have developed little awareness of the potential implications of laser weapons.

Even a relatively cursory examination of the potential capabilities of laser weapons indicates that their introduction to operations can cause significant shifts in warfighting dynamics, especially in the competition between offensive and defensive capabilities. Lasers can provide effective active defenses against a range of increasingly capable threats that are now difficult or impossible to defeat, such as SAMs, AAMs, rockets, artillery and mortars—and potentially, theater ballistic missiles. Major improvements in accuracy, range and lethality have made these attacking weapons more and more dangerous, but laser weapons may reverse this trend by making it much easier for forces to defend themselves. Offensive use of laser weapons may make possible the much more precise application of force from a variety of combat platforms.

The consequence of these shifts in all warfighting dimensions is illustrated in the scenario.

- Active laser defenses on airborne platforms will reduce the need to suppress air defenses,

significantly speeding up the prosecution of air campaigns. However, as these defenses reduce the effectiveness of SAMs and AAMs, ground-based air defenses may also turn to laser systems, forcing airborne platforms to either operate at very low levels or become very stealthy to avoid detection. Offensive use of airborne lasers against ground targets could allow the much more precise application of force from the air.

- For ground forces, active laser defenses against mortars, artillery, rockets and even aerial bombs will significantly reduce the impact of these threats on the battlefield, minimizing the requirement for counterfire and allowing ground combat units to maneuver much more freely even while underneath the enemy’s threat umbrella.
- Similarly, active laser defenses will increase the survivability of naval surface forces against cruise and ballistic missile threats, allowing them to operate more safely inside an enemy’s missile threat envelope.
- By adding another affordable layer of point defense against theater ballistic missiles, laser defenses will significantly enhance the ability to defend ports, airfields and other high value U.S. and allied targets, making it more difficult for adversaries to pursue anti-access strategies or to threaten regional allies.

If laser weapons live up to the potential they have shown thus far and if their development proceeds as fast as projected, warfare may enter the age of laser weapons much sooner than most expect. To leverage this emerging capability, we need operational concepts to guide our investment in the transformational technology of laser weapons. The implications for our national security are so significant that developing these operational concepts merits top priority for our military intellectual energy.

<sup>38</sup> Selinger, “U.S. Army Studying Guns, Lasers, Interceptors to Destroy RAMS.”

<sup>39</sup> Tariq Malik, “The Power of Light: An Airborne Laser for Missile Defense,” Space.Com, November 17, 2004.

<sup>40</sup> Stephenson, Ahearn.



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