Directed Energy Weapons and Reciprocity in Military Affairs: Reign of the Infantry

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Directed Energy Weapons and Reciprocity in Military Affairs:

REIGN OF THE INFANTRY

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EXECUTIVE SUMMARY

Title: Directed Energy Weapons and Reciprocity in Military Affairs: Reign of the Infantry

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Thesis: The introduction of Directed Energy Weapons (DEWs) demand the U.S. military change how it organizes to fight in order to promote the increased lethality of the individual and small unit armed with DEWs, while reducing our vulnerability to an adversary armed with DEWs.

Discussion: Although DEWs are considered a Revolution in Military Affairs (RMA) by many scholars and militarists, DEWs are simply a new means to attain the same ends. Although not an RMA, DEWs will usher in era of reciprocity between DEWs and DEWs countermeasures. More important than the physical weapons and countermeasures are the techniques and methods needed to maximize the effects and counter the threats from DEWs.

Because DEWs have the potential for destruction of “high-payoff targets,” the U.S. military must rethink how it amasses and projects military power. Large capital investments of military power projection, such as carrier battle groups, amphibious readiness groups, and forward deployed bases will need to be reconsidered to avoid vulnerability to destruction by DEWs employed from small platforms with little to no warning. As DEW technology advances to individual or team user employment, even our smaller “capital” investments, such as F-22 Raptor and main battle tank will also need to be reconsidered as to their usefulness on a battlefield where an enemy can destroy such an investment with a backpack DEW.

The most important reciprocal measure the U.S. can take is recognition that the small unit is the predominate “means” to attain the “ends”, regardless of the level of war. When armed with DEWs, the small unit represents a destructive capability previously unseen on the battlefield, yet remains a dispersed target for an enemy armed with DEWs. DEWs are like any other “future weapons” that have been incorporated in warfare and just as those weapons resulted in newer weapons and methods to counter or surpass the previous weapons and methods, so will DEWs. The important aspect of the introduction of DEWs is to recognize that U.S.’s current methods of warfare at all levels of war are inadequate to employ and counter DEWs.

Conclusion: Given reciprocal development in the evolution of weapons and the expected increase in lethality associated with DEWs, the U.S. needs to modify current military power projection to a more dispersed infantry force on the battlefield that can deliver increased lethality using DEWs, while reducing the force’s vulnerability to attack.
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January 1, 2021 - Reports are vague, but all indications from global surveillance assets indicate the U.S.S. John C. Stennis suffered catastrophic damage from an unknown source. “Advanced radar” assets within the carrier battle group detected a large energy disturbance within the atmosphere seconds before the Stennis was destroyed. CNN is reporting that a “death ray” from a Japanese communication satellite is the suspect...

PROPER PRIOR PLANNING PREVENTS PISS POOR PERFORMANCE

This scenario reads like a Hollywood script, but “when directed-energy weapons are mentioned, most people think of ‘death rays’... However, DEWs are a reality, and several have already been tested under battlefield conditions.”1 DEWs present a significant challenge to U.S. military strategy requiring changes for how we fight in order to successfully employ and counter DEWs. This challenge is made more difficult because such changes counter current paradigms for how we organize to fight and win wars. In a January 2009, Center for Strategic and Budgetary Assessments article, the authors noted:

Mention of the military Services raises a potentially even more daunting barrier to near-term fielding of battlefield (DEW); historically, the US military has often been slow to identify, adequately prioritize, and respond effectively to the emerging challenges likely to impose the greatest stresses on our forces in future contingencies.2

Our current methods of power projection, via capital investments, are extremely vulnerable to DEW attacks. The challenge to the U.S. military is to understand the implications that DEWs have upon how we organize and fight in support of our national defense at all levels of warfare. The introduction of DEWs demand the U.S. military change how it organizes to fight in order to promote the increased lethality of the individual and small unit armed with DEWs, while reducing our vulnerability to an adversary armed with DEWs.

RECIPROCITY AND EVOLUTION, NOT REVOLUTION

History highlights that war, regardless of technological advances, has an immutable nature. The nature of warfare remains constant and changes to the “ways” (techniques and methodology for waging war) and the “means” (weapons) of warfare are not revolutionary, but evolutionary, resultant of adversaries’ reciprocal actions. DEWs will be as important to the evolution of warfare as gunpowder, tanks, aircraft, and nuclear weapons; all of which have been labeled “revolutions” in military affairs (RMAs). They were not RMAs in warfare, but simply an evolution of the means, which dramatically
impacted the ways for conducting warfare. Richard Simpkin wrote,

In almost every case, technologies are applied first in an attempt to improve the prevailing method of fighting. Then once the full capabilities of new technologies are fully grasped, new methods of fighting emerge. Often these new methods then produce organizations and training requirements as well as new demands on military leaders.³

The introduction of DEWs has the potential to introduce new means requiring adversaries to change their ways or risk irrelevance in armed conflict.

**DIRECTED ENERGY WEAPONS**

In layman terms a DEW is a non-projectile weapon which focuses and directs energy at an object in sufficient quantity to alter that object due to the introduction of the energy. "At the most fundamental level DEWs share the concept of delivering a large amount of stored energy from the weapon to the target, to produce structural and incendiary damage effects... a DEW delivers its effect at the speed of light, rather than supersonic or subsonic speeds typical of projectile weapons."⁴ This speed difference has the potential to change the dynamics of delivering energy at a target comparable to what gunpowder did to the delivery speed of the projectile.

The speed of light is 186,000 miles per second in a vacuum.⁵ The speed of a .223 Remington, 61 grain bullet is .59375 miles per second.⁶ A DEW employed under the same atmospheric conditions as the bullet delivers the energy at a speed of approximately 185,944 miles per second or 313 thousand times faster than the bullet.⁷ *MCDP 1-3 Tactics* highlights the importance of speed as a weapon,

How is speed a weapon? Think of sports again: The break away in hockey uses speed as a weapon. By rapidly passing the puck down the ice, one team denies the other the chance to set up a defense. Speed circumvents their opponent's ability to respond in an organized manner.⁸

If you increase the speed of the puck by 300,000 percent, it changes how we play the game. DEWs have this potential, so we must consider revising the way we play the game.

Given the common futurist representation of DEWs in science fiction, it is important to clarify what a DEW is not:

Most contemporary literature lumps together a broad mix of weapons technologies in the Directed Energy Weapon category, including High Energy LASER (HEL) weapons, High Power Microwave (HPM) weapons, particle beam weapons and LASER Induced Plasma
Channel (LIPC) weapons. The first two of these four classes of weapon are genuine Directed Energy Weapons. Particle beam weapons are best described as a form of projectile weapon, using atomic or subatomic particles as projectiles, accelerated to relativistic speeds. The LIIPC is a hybrid, which uses a LASER to ionise a path of molecules to the target, via which an electric charge can be delivered into the target to cause damage effects. 

While particle beam weapons, LIPCs, and other advanced technology weapons are in development, they are not DEWs because they still rely on a projectile to deliver the energy. In 2008, Australian defense analyst, Dr. Carlo Kipp, summarizes that, “of these four categories, HELs have the greatest potential in the near term to produce significant effect.” Because LASERs have the greatest potential for weaponization, they merit further consideration.

UNDERSTANDING LASERS

To consider the viability, capabilities, and limitations of LASERs for weaponization, it is necessary to understand how they function. Appendix 1 explains the scientific principles of the LASER in full detail. A summary of how LASERs provide energy is best described by the following passage from physicist Dr. Willaim Silfvast in his book, Understanding Lasers:

The simplicity of a LASER can be understood by considering the light from a candle. Normally, a burning candle radiates light in all directions, and therefore illuminates various objects equally if they are equidistant from the candle. A LASER takes light that would normally be emitted in all directions, such as from a candle, and concentrates that light into a single direction. Thus, if the light radiating in all directions from a candle were concentrated into a single beam of the diameter of the pupil of your eye (approximately 3 mm), and if you were standing a distance of 1 m from the candle, then the light intensity would be 1,000,000 times as bright as the light that you normally see radiating from the candle! That is essentially the underlying concept of the operation of a LASER.

FICTION A REALITY

There are many skeptics of the ability to weaponize LASERs because of the extreme precision required for the LASER process, but the process has been studied for more than 50 years. Experimentation and development began upon codiscovery of the MASER in 1953 and the LASER in 1958 by Dr. Charles Townes and Dr. Arthur Schawlow.

In the sixties a number of physicists suggested it may be possible to pump a molecular gas to LASER action by rapid heating or cooling. Further research showed that such cooling could be achieved through the expansion of a heated gas through a supersonic nozzle. In 1966, a team of physicists and engineers working for Avco Everett constructed and operated the world's first
Gas Dynamic LASER (GDL), operating on a mixture of C02, N2 and H20. By 1970, continuous power outputs of 60 kiloWatts were being generated and a 1973 pulsed GDL delivered 400 kiloWatts for 4 milliseconds. It was then clear that High Energy LASER weapons were feasible.\textsuperscript{13}

“Missile Defense Agency (MDA) officials demonstrated the potential use of directed energy to defend against ballistic missiles when the Airborne Laser Testbed successfully destroyed a boosting ballistic missile Feb. 11 over the Pacific Ocean.”\textsuperscript{14} This news headline and associated story (Appendix 2) proves that HELs are viable for weaponization.

The ABL is one of multiple programs under development by the U.S. “Congress has already moved to stimulate LASER development . . . included additional funds in 2009 defense bill for LASER programs and directed the Pentagon to accelerate efforts to make DEWs operational in near future.”\textsuperscript{15} Successful testing in programs such as ABL further substantiates LASERs as weapons. While there have been multiple challenges to generating and directing sufficient LASER energy to enable weaponization, physicists have developed processes to overcome these challenges. Appendix 3 outlines current LASER programs that demonstrate the ability to generate LASER energy of much greater amplification than the ABL energy production process, making them more efficient for weaponization than the proven ABL.\textsuperscript{16} Appendix 4 outlines the technology of adaptive optics to precisely focus and direct energy of the LASER beam to penetrate the atmosphere, thereby enabling weaponization of LASER.\textsuperscript{17} In order to consider DEW capabilities and implications to modern warfare, we must evaluate DEW advantages and limitations.

**DEW ADVANTAGES**

Energy delivered at the speed of light is the fundamental advantage that a DEW has over conventional projectile weapons and enables other advantages, such as:

**Gravitational immunity.** Simply put, energy beams are immune to effects of gravity because they lack the mass of the projectile. They are not prone to aerodynamical constraints and therefore can be directly focused and aimed, at a target without complicated trajectory calculations.

**Precise and adjustable targeting.** Because the amount of energy in the beam can be adjusted by the input amount, the effects desired can be tailored to from non-lethal to complete destruction
by increasing the temperature to the point of distorting the molecular structure of the target.

Repetitive engagements. DEWs have the potential to have deeper magazines since they derive their energy from a production source that is able to be recharged.

Versatile. The same energy beam that can be pumped up to levels to have lethal or non-lethal effects, can also be scaled down to simply acquire and track targets.

Affordable. Initial cost of the devices that emit the energy are high, but the cost of recharging is not comparable to purchasing multiple weapons, such as in the case of projectiles and the products required to deliver the projectiles. These advantages stress the importance of DEWs as future weapons, but their limitations must be considered to understand how to maximize their potential, while reducing our vulnerability to them.

DEW LIMITATIONS

DEWs have limitations associated with precision components, straight-line attack, atmospheric distortion, susceptibility to refractive countermeasures, target suitability, and safety considerations including human rights concerns. Current production capable DEWs require precise components and exacting conditions to produce an efficient energy beam. These conditions have been overcome in such platforms as the ABL and other programs of research, but they remain a challenge for mass production. DEW proponents disregard this argument based on the success of the atomic weapon program after its introduction and the technological development analogy between atomic weapons and DEWs - "Trinity (first atomic weapon) owed her success to 3M because masking tape was holding all the components together."

Currently, LASERs are direct-fire weapons; they do not bend or fire indirectly. Although this does not preclude their usefulness based on current advantages over projectile weapons, it remains an employment consideration. Additionally, adaptive mirrors promise to enable bending the LASER beam via mirror relays, mitigating this limitation.

Currently, scientists are exploiting two existing technologies to counter atmospheric distortion of the LASERs. One technology is the adaptive mirror. The second is the Lidar, or LASER radar. The Lidar measures the distortion along the beam path to the target and feeds this data to the adaptive
mirrors making corrections to the beam path so it hits its target.21

A beam of light can be refracted and possibly deflected, therefore suggesting DEWs can be easily negated by countermeasures. Scientist have slowed down the speed of light through the use of an exotic medium at super-low temperatures and super-high vacuum.22 (Appendix 5) This experimentation provides evidence that the energy beam could be diffused, thus prompting reciprocal actions of measures and countermeasures.

Another limitation of DEWs is target suitability as described by author's in a 2006 Landpower Essay, Implications of Laser Weapons for Ground Combat Operations:

Currently, DEWs do not have the required energy to destroy hardened targets such as bunkers and armor, therefore, target selection will be vital to achieve results that neutralize the target, rather than destroy. This neutralization attack can be against the electronics or sensors associated with such targets.23

DEWs present multiple safety hazards which must be considered when employing them. Current chemical LASERs require highly corrosive fuels that require risk mitigation plans to reduce the risk to personnel and systems that employ such chemicals.24 Eye safety is a concern regarding LASER energy because any energy not absorbed has potential to harm unintended personnel.25 Safety concerns of DEW employment against targets, animate or inanimate, presents human rights issues that nation states have to address when considering employment of DEWs. “Weapons designed to cause undue suffering are banned under the Geneva Convention . . . for example, the Chinese ZM-87 LASER interference device can permanently blind a soldier, will that constitute undue suffering?”26 The question of using DEWs is likely to be as controversial as the use of atomic weapons, because of what that usage may prompt in reaction from an adversary. Regardless of the limitations of DEWs, the mere existence of DEWs as possible weapons justifies better understanding of how they can be employed in the defense and offense.

**DEWS IN THE DEFENSE**

DEWs are professed to be defensive in nature as an anti-projectile weapons. “The motivation for developing DEWs to counter guided rockets, artillery, mortars, and missiles (G-RAMM) stems
from...” recent experience of needing the ability to counter projectile threats ranging from strategic intercontinental ballistic missiles to incoming mortar rounds at the tactical level. The ABL has demonstrated success as an anti-G-RAMM weapon. The Mobile Tactical High-Energy LASER (M-THEL), a land-based anti-G-RAMM weapon, successfully destroyed multiple mortar rounds in flight. Current projectile-based anti-G-RAMM systems such as the Patriot Missile Air Defense System (PAC-3) can defend at a range of 44 miles in three and half minutes, while a DEW can reach the same distance in .0000672 of second.

In addition to the anti-projectile capability, DEWs have proven successful against improvised explosive devices.

The Zeus-HLONS (HMMWV LASER Ordnance Neutralization System), uses an industrial solid state LASER, normally used to cut metal, but can also ignite explosives up to 300 meters away. Normally, engineers have to approach such munitions (shells, cluster bombs aircraft bombs) or roadside bombs, place explosives next to it, then move away, trailing a detonator wire behind them, and then set off the explosive to destroy the bomb or unexploded munitions. Using the Zeus LASER is a lot cheaper (a few cents per LASER shot) and safer than the traditional method. Zeus is particularly useful when you have an area with a lot of unexploded munitions just lying about. The munitions are often unstable, meaning that just picking them up could set them off. The Zeus system can be fired up to 2,000 times a day. Last year, a Zeus-HLONS was sent to Afghanistan for six months last year, where it destroyed 200 items, including 51 in one 100 minute period.

Another DEW, the Active Denial System (ADS) is currently designed to defend the force. “ADS projects... energy beam to induce an intolerable burning sensation on an adversary’s skin and causes that individual to be repelled without injury.” These capabilities, while oriented to the defense, certainly lend themselves to offensive employment.

DEWS IN THE ATTACK

The advantages DEWs offer in the defense are multiplied in the offense because of the synergy created in tempo of the attack. DEWs can attack, re-attack, and alternate to new targets at a much faster rate than currently possible with projectile-based weapons. The LASER beam can be designed to emit neither noise nor visible light when fired, therefore a DEW attack offers no apparent warning signs or point of origin for counterattack.
While no nation state currently promotes DEWs as offensive weapons, recent successful Advanced Tactical Laser (ATL) tests of destroying a ground target gives reason enough to believe DEWs offensive capabilities are being considered. Another program of research is the Space Based LASER (SBL) that has essentially the same capabilities as the ABL, but from a space-based platform. While these programs focus on defensive measures, militarists would be derelict in duty for not planning for offensive use of DEWs, if only for attack deterrence.

**DEWS FOR HUMANITY’S SAKE**

DEWs offer more precision, greater destruction scalability, and lower energy production requirements than conventional chemical based weapons. “Because LASERs put considerably less destructive energy into a target. . . offensive applications of LASERs will most likely be dedicated to missions where their characteristics (e.g., precision, speed, numbers of engagements) are more important that pure destructive capability.” The ability to attack a precise target and only to the precise level of destruction desired makes DEWs the weapon of choice for limiting wars’ effects on unintended targets. This promotes the idea that DEWs are a more humane weapon, although the reality may be different based upon employment.

**DEWS SCIENCE FICTION TBD**

Future DEW applications are as unlimited as gunpowder was upon its invention. These future applications are the things of science fiction and children’s imaginations, or are they? Multiple DEW research programs offer much greater evolutionary changes to warfare. In 2005, Dr. Sheldon Z. Meth, program manager, Tactical Technology Advisor, wrote, “While I hesitate to admit that I am a Buck Rogers or Star Trek fan, I have to say it is fascinating how science fiction can anticipate reality. The potential exists for a weaponized LASER to be carried on a HMMWV, if not by a single soldier.” Less than three years later, the U.S. military considered deploying a HMMWV mounted ADS to Iraq.

Other U.S. DEW programs offer viable solutions and capabilities long sought after by many militarists and strategists. The Navy’s anti-projectile Mid-Infrared Advanced Chemical LASER
(MIRACL) looks to extend the Navy's capabilities by offering extended range fleet defense and as part of the triad for US missile defense systems. The Air Force' Personnel Halting and Stimulation Response (PHaSR) program focuses on using a LASER to "stun" a target. Now consider the possibilities; a DEW that has the ability to mark a person in a crowd by emitting energy into that person, but the person does not know he has been marked - asymmetrical warfare application to mark a target for tracking and further attack; the vaporizer, a DEW that transmits enough energy to completely disrupt a target's molecular structure so it is no longer a system, but simple molecules broken apart; the force-field, a DEW which fires continually providing a shield against incoming weapons. These applications have the potential to become reality and have significant implications to warfare.

**IMPLICATIONS TO WARFARE**

At the tactical level of warfare, DEWs present a significant threat to high-value weapons systems which can be attacked rapidly and near simultaneously, thereby reducing their inherent value. Weapons systems such as armored vehicles, tactical aircraft, and command posts represent these high-value targets. These systems, normally considered advantageous, will become far more susceptible to attack because of DEWs ability to penetrate traditional counter-measure systems such as jamming and anti-projectile. Additionally, the defense in depth becomes more vulnerable due to the speed at which these tactical targets can be destroyed. The development of DEW countermeasures is a generational gap behind DEWs development. This will create a near-term imbalance at the tactical level between an adversary that has not adopted new tactical methodologies to counter the DEW threat.

At the tactical level, DEWs simply represent a better weapon that militarists have to account for when considering how to fight. At the operational level, DEWs will change the concept of fighting. Given the speed at which DEWs can be delivered in the combined arms aspect of modern conventional warfare and a commander's ability to see more of his operational battlefield, he can use DEWs to achieve far greater results in the breakthrough and supporting his attack on objectives at a much faster tempo than previously possible. This increased tempo changes the game at the operational level of war;
the enemy will lack the opportunity to react in a timely fashion. This highlights the absolute requirement to have the advantage of gaining and maintaining the initiative or having effective DEW countermeasures in the form of physical systems and doctrine.

DEWs present the greatest implications at the strategic level of war. While the current capability and focus of DEWs are oriented on defense, they represent a direct threat to any nation state that relies upon a defense of its borders, deterrence by retaliation, or a layered defense in depth using force projection as a layer. Essentially, DEWs have the potential to negate common defensive measures and deterrence strategies. While future modern warfare will most likely resemble the current limited wars in Iraq and Afghanistan, a nation state must be prepared for the most dangerous type of warfare, if it hopes to avoid it.

At the strategic level, DEWs as anti-ballistic missile defense has the potential to un hinge a delicate balance between nuclear weaponized nations.

What concerned the Kremlin the most was the prospect, however remote, that the United States would be protected against Russian missile strikes, thus completely undermining the strategic balance between the two countries and destroying the concept of deterrence, which has done so much to prevent a military conflict between the major powers for more than 60 years. While U.S. Strategic Defense Initiative (SDI) is not promoted as offensive, all global competitors understand the ability to negotiate from a position of strength.

In addition to DEWs enabling SDI and upsetting the precarious balance of power among superpowers, DEWs have the potential to dramatically impact how the U.S. projects power, thereby effecting U.S. influence across the globe. *Joint Vision 2010* states “power projection, enabled by overseas presence, will likely remain the fundamental strategic concept of our future force." U.S. overseas presence is normally concentrated on bases or within our expeditionary naval forces. These concentrations present strategic high-payoff targets for potential adversaries armed with DEWs because the attack can be immediate and without warning. Therefore, a nation or organization demonstrating DEW capability, such as the ABL, SBL, or THEL, could likely conduct anti-access operations against traditional sources of strategic strength. While anti-access operations are possible with conventional
weapons, DEWs present significantly more advantages than the U.S. can currently counter, requiring us to rethink how we will maintain our military supremacy at the tactical to strategic levels.

**IT'S DISPERSION DUMMY**

"History has shown that, without investment in high-technology, fighting the next war will be done using the last war type technique."41 Despite current U.S. investment in DEW technologies, we have not invested the time required in revising our techniques for modern warfare with DEWs.

In almost every case, technologies are applied first in an attempt to improve the prevailing method of fighting. Then, once the full capabilities of new technologies are fully grasped, new methods of fighting emerge. Often these new methods then produce new organizations and training requirements as well as new demands on military leaders.42

Therefore, the challenge is to realize the implications of DEWs on modern warfare and adapt our ways of fighting the next war with efficiency, rather than trial and error possibly resulting in a defeat.

The U.S. military does not have to abandon current national or military strategies to prepare for modern warfare involving DEWs. We simply need to adapt current fighting doctrine to achieve the same strategic goals while amplifying our present military strengths. Adapting our current fighting methods and doctrine must focus on dispersion of the force. By dispersing our forces at all levels of war, we decrease our vulnerability to DEWs’ inherent advantages of engaging multiple targets at a much greater tempo.

The concept of dispersion as a tactic for warfare is not new, but many conventionalists dismiss dispersion as an effective method for defeating a conventional force, which leads to an inability to be prepared for the most dangerous type of warfare. Mao Tse Tung wrote, "In conventional tactics, dispersion of forces invites destruction; in guerrilla war, this very tactic is desirable both to confuse the enemy and to preserve the illusion that the guerrillas are ubiquitous . . ."43 This fear of dispersed forces being destroyed by a conventional concentrated force has permeated U.S. Army doctrine for years. 

*Field Manual (FM) 100-5 Operations* and even today's revised *FM 3-0 Operations* fail to even mention dispersion within the principles of war. (Appendix 6) Conversely, FM 3-0 highlights mass as one of the nine principles of war, which seemingly counters dispersion as an effective means of warfare. DEWs,
combined with the linking capability of modern U.S. forces, will enable dispersed forces to mass in accordance with the principle’s doctrinal definition.

The greatest challenge to developing mass with dispersed forces is the ability to link the forces’ actions. The U.S. military link is Command, Control, Communications, and Computers (C4). While many would consider this link to be highly vulnerable to attack, the same technology for DEW countermeasures is being researched for enhanced capability to wirelessly linked information... computers and other devices will process information on optical beams. The U.S. militaries’ indoctrinated mindset of unity of effort via centralized command and decentralized execution is the most important way it enables the forces to be linked. This indoctrinated ideology, if focused upon in training and doctrine, will enable us to amplify our current weapons systems; be prepared to incorporate near and long-term DEWs capabilities; and be prepared to fight dispersed against a dispersed or conventional adversary by using swarm tactics.

Swarming is not a new military concept. “Swarming occurs when several units conduct a convergent attack on a target from multiple axes. Attacks can either be long range fires or close range fire and hit-and-run attacks.” In Swarming on The Battlefield; Past, Present, and Future, militarist Sean Edwards provides numerous historical examples where swarming has been effective, even when employed by a conventional force on the operational level, for example Napoleon at Ulm. (Appendix 7) In 2006, Hezbollah demonstrated how a dispersed force, armed with conventional weapons and using conventional tactics at the small unit level, defeated Israeli Defense Force, employing concentrated combat power in the form of tanks, attack aircraft, and large unit combat formations. An additional benefit of dispersion and swarming attack is the enemy’s inclination to concentrate mass for defense, thus making his concentration more vulnerable to DEW attack. Swarming tactics do not require the U.S. military to abandon our traditional weapons systems in exchange for thousands of small teams on the battlefield. Conversely, the change can be implemented through greater dispersion of our current systems at all levels of war and most importantly, the infantry.
REIGN OF THE INFANTRY

Primacy of the infantry as the force that wins wars has been debated for decades, if not centuries, but the introduction of DEWs secures the infantry's role as the decisive force for modern warfare. Infantry, when operating in multiple small units across the battlefield, will be able to deliver much greater lethality, while overwhelming the enemy's ability to target all the small units before they can attack. Infantry dispersion will become the commander's method for defeating the enemy, even when the enemy is armed with DEWs. Dispersion becomes more important as a means to counter weaponry's increased lethality. Therefore, it is vital to restructure our current infantry organization to operate more independently at the small unit level, while retaining abilities to link them in action against an adversary.

Future infantry units need to be organized around small teams capable of operating independently with an area of responsibility of twenty square kilometers at a minimum. These units will need teams capable of independent operations within their area of operations (AO) which are tied to higher headquarters that are capable of supporting them logistically and directing reinforcements to their AO. This implies numerous tasks of training and equipping the small units; as well as, the higher headquarters' ability to see and employ the multiple small units. While today's current communications and computer systems enable such links between higher headquarters and the small units, the ability to support logistically and with reinforcements is lacking. Perhaps the most promising method to support these dispersed units is global positioning sensor (GPS) enabled air resupply. By enabling the small units to remain dispersed for longer periods of time, the higher headquarters commander can design operations that exploit his small teams' sustained influence throughout a greater AO. Reorganizing the infantry to support this level of dispersion, presents significant challenges to sustaining a dispersed force and modifying how we currently equip and train the force. While these are difficult challenges, failure to reorganize the infantry has the potential to expose and negate our current advantages to an enemy armed with DEWs.
In addition to the dispersed force being less vulnerable to enemy attacks, it also provides flexibility of employment across the spectrum of warfare, which makes reorganizing the infantry even more needed. Given recent U.S. involvement in Iraq and Afghanistan and budgetary constraints, many strategists are debating the need for large combat systems capable of countering a adversary in conventional war. The reality is that large scale conventional warfare is not the most likely war we will fight in the future, but remains the most dangerous. A counter argument for organizing the force for the most likely war, limited objectives and unconventional means, is that losing a war like Iraq will not jeopardize our existence as a nation, but unpreparedness to fight the most dangerous war could result in our defeat as nation. Therefore, instead of a complete force transformation, reorganization of the infantry, ready to employ and counter DEWs, is the most effective means to be prepared for the most likely and most dangerous types of warfare in the future.

**CONCLUSION**

Few combat systems inspire more confidence in our nation’s power than a naval fleet. So much so, that in our early history as a global power, President Theodore Roosevelt alluded to the U.S. Navy as his big stick in his often quoted “speak softly and carry a big stick” foreign policy manner. It is our history and nature to associate power with such large combat systems. DEWs represent a direct threat to our traditional concentrations of combat power, because of the synergistic effect created by their fundamental advantage of speed to attack multiple large combat systems near simultaneously. Unless we add depth to our strategic defense by reorganizing the infantry into small units operating across the spectrums of warfare at the operational and tactical levels, we will be vulnerable to adversaries with increased lethality offered by DEWs. Given that reciprocity between “means” will continue as long as warfare exists, the most logical action is to change the “ways” we plan to wage war. Reorganizing the infantry to operate with much greater dispersion will provide the strategic depth to our national defense and will enable the U.S. military to provide a force capable of meeting the most likely and most dangerous types of warfare in the future, regardless of the reciprocity continuum.
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ENDNOTES


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APPENDICES

Appendix 1 The Science Behind the LASER:

Early High Energy Laser Evolution

The connection between laser and microwave weapons runs deep, both in terms of the physics and the evolutionary history of these technologies.

The basic physics of the Maser and the Laser are the same. Dr Charles Townes, who codiscovered the Maser (Microwave Amplification by Stimulated Emission of Radiation) in 1953 at Columbia University, later collaborated with Dr Arthur Schawlow at Bell Labs to create, in 1958, the first Laser (Light Amplification by Stimulated Emission of Radiation).

Both Lasers and Masers act as amplifiers of electromagnetic radiation and, if equipped with mirrors to bounce this radiation back and forth inside the device, can act as oscillators and thus sources of electromagnetic radiation.

The inner workings of both devices rely on a phenomenon called 'stimulated emission' whereby an atom or molecule which has been excited to a given energy level, will emit that energy as a photon in the visible light or microwave bands, if it is hit by another photon with exactly that energy level. If you can excite a volume of gas or other material, within which a large proportion of atoms or molecules are of a specific type, with specific energy levels, shooting a single photon of that energy level into the volume will see a cascade effect, with a vastly larger number of like photons coming out the other end.

In practical terms such a device converts the energy used to excite the material, into a stream of light or microwave photons of a specific wavelength or colour. The process of exciting the device is termed 'pumping'.

Pumping can be achieved in a variety of ways, using light (flashlamps or other so called 'pump' lasers), electrical discharges (in gas lasers), electrical current (semiconductor lasers) or shockwaves in gas flows (Gas Dynamic Lasers or Chemical Lasers).

The earliest lasers of interest involved the use of crystal rods, for instance made of ruby, or discharges in argon or carbon dioxide gas. Because lasers produced light which was coherent and almost spectrally pure, that light could be easily focussed. By the mid 1960s researchers were producing many kiloWatts of power and burning holes into plates of metal and other materials.

Unfortunately crystal rod lasers and gas discharge tube lasers suffer a common problem, which is power conversion efficiency, typically at best several percent. As a result most of the power put in to pump the device is converted into waste heat. A period example is a gas discharge laser with a total length of 60 metres producing a mere 9 kiloWatts of power, yet wasting at least ten times as much.
THERMAL (GDL & CL) vs ELECTRICAL LASERS

GAS DYNAMIC LASER - GDL

![Diagram of GDL process]

ELECTRIC DISCHARGE LASER - EDL

![Diagram of EDL process]

CHEMICAL LASER - CL

![Diagram of CL process]

SCHEMATIC DIAGRAM OF A HIGH POWER LASER
Researchers needed a laser technology which was suitable for generating hundreds of kiloWatts or MegaWatts of power, and which had a conversion efficiency in the tens of percent, before any weapons application was feasible.

In the early sixties a number of physicists suggested it may be possible to pump a molecular gas to laser action by rapid heating or cooling. Further research showed that such cooling could be achieved through the expansion of a heated gas through a supersonic nozzle. In 1966, a team of physicists and engineers working for Avco Everett constructed and operated the world's first Gas Dynamic Laser (GDL), operating on a mixture of CO2, N2 and H2O. By 1970, continuous power outputs of 60 kiloWatts were being generated and a 1973 pulsed GDL delivered 400 kiloWatts for 4 milliseconds. It was then clear that High Energy Laser weapons were feasible.

This technology was the basis of the subsequent US Air Force Airborne Laser Laboratory and underpins the current chemical laser technology used in the YAL-1A ABL system.

Gas Dynamic Lasers, now termed Chemical Lasers (CL), bear in some respects more similarity to rocket engines than the commonly popularised rod laser. A laser propellant, comprising a suitable mix of chemicals, is combusted or reacted and the exhaust efflux is then directed into an expansion nozzle. The exhaust stream from the expansion nozzle contains highly energetic molecules, which due to the choice of propellants and added agents, have effectively been pumped to a state where laser action can occur. If a pair of aligned mirrors is placed to either side of the exhaust stream, laser action will occur as photons bounce between the mirrors, and power can be extracted if one of the mirrors is optically leaky.

While simple in principle, the design and construction of a Chemical Laser is anything but trivial. Combustors operate at temperatures as high as 1000 to 2000 deg C, depending on the laser fuel mix used. The expansion nozzles require very precisely controlled flow conditions to work, which results in
a complex exhaust system designed to produce the required pressure and flow rates. Some laser fuels and/or their exhaust efflux can be highly corrosive and/or toxic. Mirrors must have very low optical losses, since even a 1 percent loss in a 1 MegaWatt laser sees 10 kiloWatts of waste heat dumped into the mirrors.

The first chemical lasers built used carbon monoxide (CO) burned in oxygen-nitrogen, with water being added, to produce the same 10.6 micron band laser action used in carbon dioxide gas discharge lasers. CO burning in N20 and benzene (C6H6) burning N20 were also explored as fuels.

While a single laser, comprising a combustor, expansion nozzle and exhaust duct could produce respectable power levels, it was clear that many such devices needed to be cascaded to produce power levels suitable for weapons applications. This is why all contemporary Chemical Lasers use batteries of smaller lasers to produce the final high power output beam.

While the carbon dioxide laser was the first in this class, it was soon followed by the Hydrogen Fluorine (HF), Deuterium Fluorine (DF) and Oxygen Iodine (COIL) lasers.

The HF laser uses atomic fluorine and molecular hydrogen to produce 2.7 - 2.9 micron band radiation, using typical fuels such as highly toxic SF6 or NF3, with hydrocarbons used to produce hydrogen. Its later sibling, the DF laser, uses ethylene (C2H4) burned with a nitrogen trifluoride (NF3) oxidiser, into which deuterium and helium are injected, to produce 3.6 to 4.2 micron band radiation.

The most significant of these three discoveries was the Chemical Oxygen Iodine Laser (COIL), invented by the US Air Force Weapons Laboratory in 1977, and now used in the YAL-IA system. The COIL emits in the 1.315 micrometer range, and uses chlorine gas and an aqueous mixture of hydrogen peroxide and potassium hydroxide to produce excited oxygen molecules, which are reacted with molecular iodine to produced the laser medium, and which is then passed through the expansion nozzles. Conversion efficiencies above 20% were demonstrated very early.
As is clearly evident, building a large laser may be the basis of a HEL weapon, but a considerable amount of hardware will be required to actually put it to use.

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2/12/2010 - WASHINGTON (AFNS) -- Missile Defense Agency officials demonstrated the potential use of directed energy to defend against ballistic missiles when the Airborne Laser Testbed successfully destroyed a boosting ballistic missile Feb. 11 over the Pacific Ocean.

The experiment, conducted at Point Mugu Naval Air Warfare Center-Weapons Division Sea Range off the central California coast, serves as a proof-of-concept demonstration for directed energy technology.

The Airborne Laser Testbed is a pathfinder for the nation's directed energy program and its potential application for missile defense technology.

At 8:44 p.m. PST Feb. 11, a short-range threat-representative ballistic missile was launched from an at-sea mobile launch platform. Within seconds, the Airborne Laser Testbed used onboard sensors to detect the boosting missile and used a low-energy laser to track the target. The Airborne Laser Testbed then fired a second low-energy laser to measure and compensate for atmospheric disturbance. Finally, the Airborne Laser Testbed fired its megawatt-class High Energy Laser, heating the boosting ballistic missile to critical structural failure. The entire engagement occurred within two minutes of the target missile launch, while its rocket motors were still thrusting.

This was the first directed energy lethal intercept demonstration against a liquid-fuel boosting ballistic missile target from an airborne platform. The revolutionary use of directed energy is very attractive for missile defense, with the potential to attack multiple targets at the speed of light, at a range of hundreds of kilometers, and at a low cost per intercept attempt compared to current technologies.

Less than one hour later, a second solid fuel short-range missile was launched from a ground location on San Nicolas Island, Calif., and the Airborne Laser Testbed successfully engaged the boosting target with its High Energy Laser, met all its test criteria, and terminated lasing prior to destroying the second target. The Airborne Laser Testbed destroyed a solid fuel missile, identical to the second target, in flight on February 3, 2010.
Appendix 3 High Energy LASERS:

Peace Through Light - the Airborne Laser Lab Program

By the early 1970s it was clear to the US DoD that an airborne laser weapon was feasible using existing laser technology, an idea which was actively promoted during the late 1960s by physicist Dr Edward Teller, co-inventor of the hydrogen bomb. This led to a series of experiments during the 1970s to demonstrate viability and identify problems.

The first was in 1973 when the USAF shot down a winged drone at their Sandia Optical Range, New Mexico, using a carbon dioxide GDL and a gimballed telescope. Subsequently, in 1976, the US Army employed an electrically pumped HEL to destroy a number of winged and helicopter drones at the Redstone Arsenal in Alabama. The USN, in March 1978, then engaged and destroyed an Army TOW missile in flight, using a chemical laser developed by DARPA/USN and a pointer-tracker developed by the USN. These tests were carried out at San Juan Capistrano near Camp Pendleton in California, as part of the Unified Navy Field Test Program.

The US Air Force launched their Airborne Laser Lab (ALL) program in 1976, under the motto 'Peace Through Light'. The aim of this effort was to construct a technology demonstrator, carried on modified NKC-135 Stratotanker serial number 55-3123, which could successfully track and destroy airborne targets.

The ALL system used a gas dynamic laser with CO2 - N2 - H2O propellants and a 10.6 micron operating wavelength. Pratt & Whitney Aircraft supplied the laser, Rocketdyne the combustor, Hughes the optical pointing and tracking system, Perkin Elmer the dynamic alignment system, with GD performing system integration.

The ALL system was complex enough to fill a KC-135A fuselage, with the HEL weapon located in the forward and centre fuselage areas, and test crew in the aft fuselage (USAF).
The ALL laser system combustors operated at 55 atmospheres of pressure, and at a 1900 K temperature, driving nickel plated nozzles with an output velocity of Mach 6. The optical resonator used one concave and one convex mirror, with beam extraction via an aerodynamic window, produced using high pressure nitrogen gas, with the efflux at 0.1 atmospheres of pressure. The ventral exhaust port, forward of the wing root under bomb bay like doors, used a corrugated titanium diffuser and vented gas at 870 K temperature, delivering a thrust of 4,000 lbf when operating. The supporting fuel system stored CO and N2O gas in stainless steel tanks, liquid Helium and Nitrogen in stainless steel tanks, with additional water coolant tanks for the mirror and combustors.

This laser produced a raw output of 456 kiloWatts of optical power in an 8 second sustained run, and an output from the optical aiming system of 380 kiloWatts, reported in 1979 literature. At a distance of 1 kilometre, the delivered power density was over 100 Watts/cm2.

The ALL project ran for eleven years, culminating in a series of trials during which five AIM-9 missiles were shot down, and a single BQM-34A Firebee drone destroyed.

While the ALL attracted much media attention as the world's first airborne laser weapon, its real value was in the enormous amount learned during the program. Several key problems rose to prominence.

The first was the issue of power losses in the optical feed, tracking and beam pointing system. Not only did waste heat have the potential to wreak havoc inside the system, but dust particles inside the system when hit by the intense infrared beam would be propelled at high velocity, as they partly vapourised, and damage optical surfaces. Cleanroom air quality was required.

It also became very evident that high precision target tracking equipment was needed, and the whole beam pointing system required extremely low jitter when tracking a target. The aim was to put a
'football sized' spot on the target and 'dwell' the beam for long enough to burn through the skin of the target and cause serious damage. Jitter in beam pointing significantly reduced effect, the problem getting worse with increasing distance.

This image shows a technician working on the optical telescope turret of the ALL HEL weapon. Note the array of ancillary optical sensors (USAF).
Beam propagation through the atmosphere presented anticipated and unanticipated problems. Water vapour molecules, water droplets and carbon dioxide molecules soaked up the beam, causing localised heating along the beam path which caused the beam to dissipate. This effect was termed 'thermal blooming' and would become more severe as beam power levels increased. A general limitation of all HEL weapons is an inability to penetrate cloud, dust clouds or haze, which scatter and soak up the beam's power very rapidly.

Target damage effects were another issue. Not only did the HEL laser beam have to operate at a wavelength which would experience a minimum of absorption by atmospheric molecules, but it also had to be capable of rapid absorption by structural materials making up the skin of the target. Aluminium for instance has around 98 percent reflectance for the 10.6 micron CO2 laser.

NKC-135A Airborne Laser Laboratory (USAF).

Other problems arose as a result of scintillation due to turbulence in the atmosphere, which is characteristically made up of pockets of air with slightly differing temperature. Slight temperature differences mean slight air density differences, which would cause the beam to refract (bend) every so slightly as it passed between two pockets of air. With thousands of such distortions along the beam path, this problem presented a difficult obstacle to achieving useful range, especially during low altitude operations, where the beam would be severely defocussed along the way.

The ALL NKC-135A was retired in 1984, and sent to the Wright-Patterson Air Force Museum in 1988.
The solution of the beam distortion problem paved the way for an operationally viable HEL weapon system.

At the end of the Cold War the SDI program was quietly killed off, but some key proposals survived. The Airborne Laser (ABL), envisaged as a follow-on to the ALL program, but with an operational role, was one of these. In 1996, the US Air Force awarded a US$1.1 billion contract to Boeing, TRW and Lockheed-Martin to develop a prototype ABL system, to be carried in a Boeing 747-400 aircraft. The ABL was to use a MegaWatt class COIL HEL weapon and a system to compensate for atmospheric distortion, to permit boost phase attacks on ballistic missiles.

A single ABL system would thus defend a footprint of hundreds of kilometres diameter, attacking and destroying launched ballistic missiles during their boost phase, when they are most detectable, slowest and most vulnerable due to heavy fuel load, pressurised fuel tanks and structural stresses.

Ballistic missiles have thin load bearing skins, which are heavily stressed during the boost phase, while the missile boosters are largely filled with pressurised high energy propellants. Therefore even slight damage to the booster skin will cause catastrophic failure with results seen many times over during failed launches of satellite launch vehicles.
The ABL would be deployed in time of crisis to the borders of a nation threatening the use of ballistic missiles, and should they be launched, destroy them, ensuring that debris with WMD warheads falls on the launching party. At the time the ABL was conceived, these nations included Iraq, Iran and North Korea. With ongoing growth in Iran’s and North Korea’s arsenals, and their efforts to deploy nuclear warheads, the ABL could prove to be a vital asset if either of these nations achieves their aims.

One of the design aims of the ABL system was to carry enough laser fuel to destroy twenty to forty missiles during a single 12 to 18 hour sortie. The ABL would orbit near the border of a threat nation and engage missiles as soon as they clear the cloudbase and are within line of sight.

The capabilities of the ABL system have raised the prospect of another operational application, which is the Anti-Satellite (ASAT) role. In this role, the AL-1A would fly an intercept profile to intersect the ground track of a low orbit reconnaissance or surveillance satellite, or manned space vehicle, and damage or destroy it. While satellites are more robust structurally than ballistic missiles, the ABL delivers more power over the same distance when attacking an orbital target, due to the much lower atmospheric density along the beam path, compared to an atmospheric target. Satellites are also equipped with sensitive optics and vulnerable solar panels. Suffice to say even public debate on this application elicited loud complaints from non-US operators of military satellites.

In a crisis the ABL systems would be deployed to the borders of a nation threatening a ballistic missile attack, good candidates now being Iran and the DPRK. Orbiting at the tropopause, the ABL would detect, track, and attack ballistic missiles once they clear the cloudbase, with the debris falling back on the nation which launched the weapon. The latter is a critical consideration for WMD payloads. A design objective for the ABL is to carry enough fuel to destroy 20-40 missiles during an 12 to 18 hour sortie. Other roles canvassed for the ABL include attacks on low orbit reconnaissance satellites.

The airframe used to carry the ABL system is the YAL-1A which is a modified Boeing 747-400F freighter. This is a robust and mature 100 tonne payload class airframe, with a main deck which is comparable to the C-5 Galaxy in payload and capacity.
The YAL-1A ABL will be the first large laser weapon to become operational. Its purpose is to destroy ballistic missiles during the boost phase (Boeing).

The most notable external feature of the AL-1A is the nose mounted optical turret for the laser's primary mirror. The turret has a +/-120 degree field of regard in azimuth and is used to point the 1.6 metre primary laser mirror, produced by Corning Glass and Contraves. The roll shell is constructed from composite materials. When the laser is not in use, the 1.8 metre 150 kg window, built by Heraeus/Corning/Contraves, is rotated into a stowed position to protect the optical surface from abrasion by atmospheric dust particles, and birdstrike damage.

The main deck forward of the wing is separated from the aft main deck, which houses the laser system, by a full height bulkhead. The forward fuselage section houses the Battle Management system and the Beam
The Battle Management System (BMS) comprises the computers which manage the weapon system, the operator consoles for the weapon system, and supporting communications. Built around open systems COTS hardware and software, the system is the nerve centre of the ABL. It performs the identification, tracking, determines the priority and nomination of targets, and controls the engagement.

To do this, the battle management system relies on offboard sensors and an onboard infrared tracking and rangefinding sensor. The latter is a derivative of the legacy LANTIRN targeting pod, using the existing longwave FLIR sensor to tracking the missile, and a new carbon dioxide 10.6 micron band rangefinding laser and sensor, to supplement angle track data with accurate range. The intent is to produce an accurate trajectory projection for the target missile to facilitate 'prioritising' targets for attack. The sensor is mounted in a dorsal pod, carried on a short pylon.

The third subsystem in the forward fuselage is the Beam Control System (BCS). This is the critical component which ensures that the laser's power can be effectively delivered to the target. The BCS comprises the wavefront sensor and control system for beam distortion control, the systems for beam jitter control, beam alignment and beam 'walk' control, calibration hardware, and target acquisition and tracking equipment. The deformable mirror has 341 actuators which update the shape of the mirror at 1,000 Hz frequency - this means 1/1000 sec is required not only to measure the distortion but also to calculate and control the mirror actuator.

The lower forward cargo hold is retained and intended for carrying equipment to support deployments.

The aft main deck area carries the HEL subsystem and supporting hardware. Immediately aft of the wing are the two supporting lasers, built by Raytheon and Northrop-Grumman. These are the Tracking Illuminator Laser (TIL) and Beacon Illuminator Laser (BIL), both diode pumped solid state devices. The TIL is used to illuminate the target to facilitate fine tracking, while the BIL is used to measure atmospheric distortion to compensate beam wavefront shape, via the wavefront sensor.
Aft of these are the main laser power stages, using 1.315 micron band COIL technology. Plastics, composites and titanium are used extensively to save structural weight. Despite this, each of the six laser modules weight around 1.5 tonnes. Each of the modules vents exhaust efflux via six ventral exhaust ducts and ports (see photo).
The laser stages are complex. The gaseous atomic oxygen fuel for the COIL is produced in a reactor which mixes Helium (He) hydrogen peroxide liquid ($\text{H}_2\text{O}_2$) and potassium hydroxide (KOH) producing waste heat and potassium chloride (KCI). The hydrogen peroxide is recycled in a closed loop system until it has been exhausted. US sources claim that 1,200 USG of propellant is to be carried.

The atomic Oxygen produced is then mixed with gaseous Iodine (I), to produce the excited Iodine required for laser operation. The gaseous mix is then flowed through a supersonic expansion nozzle, which also acts as the laser cavity.

![Ventral aft fuselage exhaust ports for the COIL laser.](image)

The high power beam is flowed through all six laser stages gaining power with each stage, for an aggregate output of the order of a MegaWatt of continuous wave power. The full power beam is directed via a system of mirrors to the beam control subsystem and then the optical turret in the nose.

In an operational environment the AL-1A would be positioned into an orbit near enough to cover the territory of interest and loiter awaiting target tracks. Surveillance systems such as orbital early warning satellites, AEW&C where equipped with suitable radar, and UAVs would detect the initial launch of the missiles, relaying this data via Link-16 to the AL-1A. Once the ABL system is cued, the aircraft positions for a shot - if required the aircraft will turn to face the threat sector to afford the best possible field of regard for the laser weapon.

As the ballistic missiles break through the overcast, their enormous heat signatures would be detected by the LANTIRN sensor and coarse tracking initiated. The BMS would attempt to establish missile trajectories as early as possible to determine priority for engagement. While the US Air Force have not disclosed how they intend to do this, it is reasonable to speculate that the value of the target and the distance to the missile would both be factors in the beam scheduling algorithm. Not unlike phased array radars used for missile defence, there is a finite time window to attack each target and a finite amount of laser time available within this window. Therefore judicious scheduling of laser use is essential to provide opportunities for reattack if needed. More distant targets will require that the laser 'dwell' on the target much longer to achieve effect, compared to nearer targets.

Once a coarse track for a specific missile has been established and the laser scheduled to shoot, the turret is slewed to point at the target and the TIL illuminator is lit up to initiate fine tracking. Once the fine track is established, the BIL beacon is lit up to generate continuous data on atmospheric distortion along the
beam path. With the BIL operating the COIL laser is engaged and a multi-MegaWatt beam of 1.315 micron infrared radiation is put on to the target. In a viable engagement scenario, this would lead, within seconds, to the breakup of the target missile. Once this has happened, the system is cued to the second highest priority target and the same engagement sequence repeated. This would continue until laser fuel is exhausted or all of the targets killed, or out of reach.

What defences exist against the ABL? Given the signature size of a ballistic missile, detection and tracking is unavoidable once the missile clears any cloud. At that point the only defence lies in improving the missile’s resistance to laser attack.

Years ago a physicist remarked to this author that this was ‘simple, you cover the missile with a mirror coating to reflect the laser’. This is of course easier said than done, since any dirt, dust, moisture droplets, ice particles or other material on the surface of even a perfect mirror will vapourise and the superheated plasma will eat into the surface, destroying its reflectivity. At best mirror surfaces increase required laser dwell time to destroy the target.

Another strategy proposed has been to impart a rotation to the missile, effectively causing it to spin around its longitudinal axis, to minimise local exposure time to the laser, the idea being that through the remainder of each rotation the skin would cool. But this strategy also at best delays the inevitable, and could at best impact required dwell time.

A third strategy proposed has been the use of ablative surface coatings which would evaporate and so both cool the surface and block the beam in a layer of superheated vapour. A variation on this theme is the use of highly heat resistant skin materials. Both of these strategies would significantly add to the cost and weight of a missile, impacting deployable numbers and useful warhead size.

A fourth strategy proposed has been the use of higher rocket thrust per payload so the missile climbs out of the atmosphere in a much shorter time, thus reducing firing opportunities for the laser. If the missile can complete its boost phase in half the time, the time available for attack is halved, which during a massed launch would allow some fraction of missiles to get past the laser. As with the preceding strategy, cost/numbers becomes a major issue since a much bigger missile first and second stage is required for the same warload.

Let us assume that a player develops a fast burn, spinning ballistic missile with an ablative coating, covered by a mirror coating. What it means is that more ABL platforms will need to patrol a given area to ensure that the increased dwell time does not allow any missiles to escape. The attacker will have to spend a lot more on his missiles. Like all missile defence technologies, the ABL drives up the cost of mounting a successful missile attack, to the point where it may not be economically viable. Suffice to say the intensive interest of China and Iran in cruise missiles indicates that the ABL, and ground based interceptor missiles, are already having impact well before they have even achieved full operational capability.

The ABL program has been controversial, to say the least. As it is directly competing for funds with capabilities such as interceptor missiles, be they silo, warship or air launched, there is an added element to the controversy, as all players attempt to maximise their slice of the budgetary pie.

The COIL laser achieved ‘First Light’ in November, 2004, with an initial test run. However, significant integration and testing remains before the system will be viable for operational use. This February the buy of five production airframes was put on hold, until such time as the capabilities of the prototype could be proven. Current planning envisages a trial shot against a target ballistic missile in late 2008.

Recent US reports indicate that many problems remain to be resolved. One is that of atmospheric dust particles in the main beam, termed ‘fireflies’. Given the intensity of the beam, dust particles vapourise and the plasma exacerbates local turbulence and soaks up energy from the beam, reducing effective range. It also has the potential of interfering with the fine tracking function, which relies on infrared reflections off the target.

There has been considerable speculation on the use of the ABL for other roles, excluding the previously mentioned ASAT role. One idea has been to use the ABL to attack cruise missiles. If these are high flying supersonic weapons like the Kh-22 Burya/Kitchen flying a relatively flat trajectory, then the ABL will be highly effective. If they are low flying cruise missiles in the class of the Tomahawk or ALCM, then effectiveness is apt to be poor. The same is true of low flying aircraft targets or surface targets. The
reality is that the troposphere, below 36,000 ft, is a poor propagation environment with a lot of water vapour and dust particles, or water droplets in cloud. The tropospheric 'soup' absorbs and dissipates the energy in the laser beam a lot faster than the dry/cold/thin stratosphere does. Physics are physics and cannot be easily beaten. The result will be very poor effective range, and an unusable weapon if any cloud gets between the laser and the target. Much the same constraints apply if the target is an aircraft. A high flying UAV, reconnaissance aircraft or even hypersonic vehicle is extremely vulnerable to the ABL. A low flying aircraft is not.

In perspective the AL-1A ABL is a revolutionary weapon which once mature will render ineffective arsenals of short, intermediate and intercontinental ballistic missiles, and high flying aircraft and cruise missiles, where conditions permit the ABL to operate within lethal range of the target. How soon the ABL matures into an operationally viable system remains to be seen.

The Tactical High Energy Laser (THEL)
The THEL is a laser weapon jointly developed by the US and Israel, with the program initiated in 1996. The THEL is to be built in two configurations, the static baseline THEL and relocatable Mobile THEL (MTHEL).

The design aim of the THEL systems is to provide a point defence weapon which is capable of engaging and destroying artillery rockets (Katyushas), artillery shells, mortar rounds and low flying aircraft.

The THEL demonstrator was trialled repeatedly between 2000 and 2004, destroying 28 122 mm and 160 mm Katyusha rockets, multiple artillery shells, and mortar rounds, including a salvo attack by mortar.

The demonstrator THEL system was built around a deuterium fluoride chemical laser operating at 3.8 microns wavelength. The combustor in this laser burns ethylene in toxic and corrosive Nitrogen Trifluoride gas to produce the excited deuterium fluoride lasing medium, which is then mixed with deuterium and helium, and fed into expansion nozzles similar to that of other chemical lasers, like the carbon dioxide GDL and COIL. A complex exhaust diffusion and pressure equalisation system must be used, including a neutralisation stage to soak up the highly corrosive and toxic deuterium fluoride exhaust efflux gas.

The first deuterium fluoride laser to be trialled was the US Navy's MIRACL, or Mid-Infrared Advanced Chemical Laser, which was coupled to the Sea Lite Beam Director optical turret. This research system was trialled extensively since 1983 at the High Energy Laser Systems Test Facility (HELSTF Directorate) at White Sands in New Mexico. This was a MegaWatt class weapon.

The THEL program yielded excellent trial results, using a phased array radar to track incoming targets and direct the beam. Unlike the ABL, the THEL is a relatively short range weapon used for the terminal defence of a local area, not unlike a point defence SAM or AAA system.
The Sea Lite beam director was coupled to the MIRACL deuterium fluoride laser, demonstrating the technology later used in the THEL demonstrator (US Navy).
THEL optical turret subsystem. Note the cassegrainian primary aperture (US Army).

A 160 mm Katyusha artillery rocket engaged by the THEL system.
THEL/MTHEL phased array engagement radar.

THEL engagement scenario.
MTHEL is a repackaged and mobile derivative of the THEL demonstrator.
The sheer bulk of the demonstrator made it impractical for operational deployment, leading to the second generation MTHEL system. MTHEL was to initially have been in three semitrailers, but now appears to have been repackaged into a single container sized semitrailer. A prototype was intended to be deployed by 2007, but more recent reports indicate funding difficulties and thus uncertainties in timelines.

The THEL/MTHEL system was developed by a team including TRW/Northrop-Grumman, Ball Aerospace, Elbit/El-Op, IAI/Elta who developed the radar and fire control system, RAFAEL and Tadiran.

Like the ABL, the THEL/MTHEL suffers the same weather and propagation limitations imposed by atmospheric physics. While Israel, with dry desert climatic conditions may be optimal for THEL operations, the same is not apt to be true for humid tropical environments, or northern temperate environments, where moist air, fog, low cloud and similar propagation impediments are much more common.

In operational terms a key limitation of this design lies in the expensive and toxic exotic fuel mix. At several thousand dollars per shot in fuel expenditure, the Deuterium Fluoride laser is problematic for a system to be deployed en masse.

In strategic terms the impact of the THEL is yet to be determined, unlike the ABL which is set to change the game fundamentally. The current MTHEL development effort is sustained and yields a viable product, it is apt to become a feature of ground based air defence over the coming decade. At the time of writing
funding had been stopped for this effort, the focus shifting to electrically pumped solid state laser technology.

High Energy Laser Technology Demonstrator

The High Energy Laser Technology Demonstrator (HEL TD) is a follow on effort by the US Army to demonstrate a mobile multi-hundred kiloWatt class laser using solid state laser technology. The budget justification for the effort, running until 2013, is thus:

"A. Mission Description and Budget Item Justification: This applied research program element (PE) investigates advanced technologies for Future Force High Energy Laser (HEL) weapons technology, and, where feasible, exploits opportunities to enhance Current Force capabilities. The major effort under this PE is the development of a multi-hundred kilowatt (kW) Solid State Laser (SSL) laboratory demonstrator that can be integrated into a HEL weapon system to provide increased ground platform-based lethality. HEL systems have the potential to address the following identified Army capability gaps: 1) Defeat In-Flight Projectiles such as rockets, artillery, mortars, anti-tank guided missiles, and man-portable surface-to-air missiles; 2) Ultra-Precision Strike with little to no collateral damage; 3) Disruption of Electro-Optical (EO) and Infra-Red (IR) sensors; and 4) Neutralizing mines and other ordnance from a stand-off distance. HELs are expected to complement conventional offensive and defensive weapons at a lower cost-per-shot than current systems. At weapon system power levels of greater than 100kW, SSL technology has the potential to enhance survivability by addressing the capability gaps identified above. This SSL technology effort addresses technical issues such as high average power output from compact and more efficient lasers; precision optical pointing and tracking; laser effects degradation due to atmospheric effects; lethality against a variety of targets; and effectiveness against low-cost laser countermeasures. The multi-hundred kilowatt laser and additional HEL technology components will be refined and upgraded to transition into an integrated SSL weapons system demonstrator that will be developed in PE 0603004A (Weapons and Munitions Advanced Technology) Project L96. Project NA5 funds congressional special interest items. Work in this PE is related to, and fully coordinated with, efforts in PE 0602890F and PE 0603924F (High Energy Laser Joint Technology Office), PE 0605605A (DoD High Energy Laser Systems Test Facility), and PE 0603004 (Weapons and Munitions Advanced Technology) Project L96. The cited work is consistent with Strategic Planning Guidance, the Army Science and Technology Master Plan (ASTMP), the Army Modernization Plan, and the Defense Technology Area Plan (DTAP). Work is performed by the U.S. Army Space and Missile Defense Command (SMDC), in Huntsville, AL, and the High Energy Laser Systems Test Facility, White Sands Missile Range, NM."
Northrop-Grumman and Boeing have been contracted for this effort. Boeing will integrate the beam control subsystem on a Heavy Expanded Mobility Tactical Truck (HEMTT).

**Advanced Tactical Laser (ATL)**

The ATL program is an effort to exploit the technology developed for the ABL to provide a cheaper and smaller system, suitable for carriage on aircraft such as the AC-130 Spectre or V-22 Osprey, as a close air support weapon. In January 2006, U.S. Air Force’s 46th Test Wing provided Boeing with a C-130H Hercules for trials of the prototype weapon, claimed to be in the MegaWatt class, using COIL technology. The intent was to mount the laser prototype in the aircraft and perform lethality trials in 2007 against a range of ground targets. L-3 Communications/Brashear developed the optical turret, and the laser is being built by AFRL at Kirtland Air Force Base in Albuquerque, New Mexico. The laser was successfully fired in May, 2008.
The Solid State High Energy Laser

An alternative HEL technology now under development is the solid state electrically pumped laser, popularised extensively in 2002 as part of the Joint Strike Fighter marketing campaign.

This category of laser is based on the humble laser diode, which first emerged twenty years ago as a technology for use in optical fibre communications. Laser diodes are evolved siblings of the common Light Emitting Diode (LED), found in household appliances and now even battery powered torches. Light emitting diodes, usually made from Gallium based alloys, generate light as a result of electrical current flow through a minute semiconductor junction, which has been doped with additives which become excited by the electrical conditions in the junction. An LED is an incoherent and relatively broad emitter, compared to a laser. Current LED technology spans colours from infrared through to blue. The distinction between an LED and Laser Diode is that the latter is fabricated with a miniature optical resonator, to induce oscillation and thus laser action. To narrow the bandwidth of the cavity, most communications laser now also include a diffraction grating in the design, in addition to the resonant cavity. A simple description of a laser diode is that it is a special type of LED, designed to exhibit laser action. At this time Laser diodes are manufactured in vast quantities for CD and DVD burners, and also for communications and industrial applications.

The solid state laser effort led by the US Air Force at the Air Force Research Lab aims to develop a 25 kiloWatt weapon, scalable to 100 kiloWatts, and suitable for carriage by aircraft, ground vehicles and ships as a close in weapon. The attraction of this technology is that electrical power is easy to supply, and toxic propellants are not required.

The idea behind the these high power lasers is to couple together a very large number of much smaller laser diode modules, which are then use to pump the laser medium with energy. This a essentially a scaled up equivalent to the laser diode pumped 1.55 micron eyesafe rangefinding lasers now in use.

The principal problems currently faced with this technology are cost, scalability and power handling capability. Conversion efficiency from electrical power to optical output for these systems is typically of the order of 10%, which means that 90% of the electrical power put into the laser is converted into waste heat, which needs to be removed. The individual laser diodes are also not very powerful, typically emitting around one Watt each. A laser rated at 25 kW with a 10% conversion efficiency would require 250,000 diodes. At $10 per diode, this results in a multimillion dollar investment in lasers alone. Public reports on
Joint High Power Solid State Laser

The JHPSSL effort is intended to develop a family of electrically power high power solid state lasers suitable for 100 kiloWatt class weapons applications, primarily for land and sea based point defence systems. The JHPSSL program is jointly funded by the Army Space and Missile Defense Command, Huntsville, Alabama; Office of the Secretary of Defense - Joint Technology Office, in Albuquerque, New Mexico; the Air Force Research Laboratory at Kirtland Air Force Base; and the Office of Naval Research in Arlington, Virginia.

Northrop Grumman demonstrated early 2008 a 15.3 kiloWatt laser module for this program (refer image). Textron systems have been contracted to produce a competing JHPSSL design, using proprietary ThinZag laser ceramic Neodymium doped Yttrium-Aluminum-Garnet (Nd:YAG) slab technology.

High Energy Liquid Laser Area Defense System

The High Energy Liquid Laser Area Defense System (HELLADS) effort was launched following a research breakthrough by DARPA, in 2003, with a budget of around US$75M. Its aims were described by the US DoD thus:

'The goal of the High Energy Liquid Laser Area Defense System (HELLADS) program is to develop a high-energy laser weapon system (~150 kW) with an order of magnitude reduction in weight compared to existing laser systems. With a weight goal of less than 5 kg/kW, HELLADS will enable high-energy lasers (HELs) to be integrated onto tactical aircraft and will significantly increase engagement ranges compared to ground-based systems. The HELLADS program has completed design of a revolutionary high energy laser that supports the goal of a lightweight and compact high energy laser weapon system. An objective system laser module with integrated power and thermal management will be fabricated and demonstrated at an output power of 15 kW. Based on the results of this demonstration, additional laser modules will be developed and integrated with a beam control subsystem to produce a 150 kW laser weapon system demonstrator. The performance of the demonstrator will be characterized in a laboratory environment.

Program Plans:
- Develop and test a 15 kW objective system laser module with integrated power and thermal management subsystems.
Complete preliminary design of a 150 kW laser weapon system.
Complete detailed design and fabricate a 150 kW laser weapon system.
Demonstrate performance of a 150 kW HELLADS system.

In practical terms, HELLADS is to produce a 750 kg laser capable of producing 150 kilowatts of power, compact enough to be carried by aircraft, ground vehicles and UAVs. The technology is a liquid laser, where the lasing medium is a fluid containing the active chemical species pumped for laser action. No details of the design concept have been released so far, but it is reasonable to speculate that the liquid is actively cooled thus avoiding the problems inherent in solid state lasers. The pump mechanism has not been disclosed. If pumping is performed using laser diodes, it is reasonable to speculate that the liquid also cools the pump lasers.

General Atomics is the prime contractor, with Lockheed-Martin providing integration. HELLADS will like the ABL use a wavefront sensor and active mirror technology for beam wavefront correction. A demonstration is planned for 2007.

High Power Fibre Laser (HPFL) - Optical Fibre Laser Technology

Optical fibre lasers are a recent technological development, devised to provide low noise amplification for long haul submarine optical fibre communications systems. The technology is currently being developed further for weapons applications by Raytheon, following a demonstration conducted with the AFRL and Sandia in June, 2006.

The impetus for the development of fibre lasers lay in reducing the cost and complexity of repeater amplifiers for fibre cable links, especially for rapidly evolving, complex high speed waveforms. Eliminating complex and inflexible electro-optical repeaters in links allow costs to be significantly improved and the longevity of a cable installation significantly extended. Performance upgrades in many instances will require only the replacement of the line terminal equipment at either end of the link, rather than the chain of repeaters.

By the early 1980’s a race was underway in the fibre research community to find suitable laser technology for adaptation to the unique fibre environment. Early research explored Raman effect amplification and adaptations of established semiconductor lasers. Both proved to be disappointing, with Raman effect designs requiring unreasonably large pumping power due to their low efficiency, and semiconductor lasers having high signal distortion.

The breakthrough came in the mid 1980s when a research group in Southampton in the UK devised a rare earth ion doping technique for silica fibres, building on the same 1960s research which led to the now standard military Nd:YAG laser, used for bomb guidance. The first Erbium Doped Fibre Amplifier (EDFA) paper was published in 1987. The next important development was the 1.48 micron InGaAsP laser diode, the pump power source required to optically excite the Erbium ions embedded in the glass, to amplify at 1.55 microns. Japan’s NTT published their results in 1989. With a compact and efficient pump source and doped fibre technology the practical EDFA became a reality.

To build one, the starting point is a spool of Erbium doped optical fibre of a suitable length. The input, where the EDFA is coupled to the end of a fibre link, uses a wavelength selective coupler. The coupler is used to feed the flow of pumping photons from the pump laser into the EDFA. These photons propagate along the fibre, exciting it. The "signal" photons pass through the coupler into the EDFA, and are amplified in number as they pass through the excited fibre. When they reach the output end of the spool, they are fed into an optical splitter. Most of the photons go into the next segment of the fibre link, but some are split off to feed a local optical detector. The electrical output from the detector is then used in a negative feedback loop to control the power level produced by the pump laser. In this manner the EDFA gain can be quite precisely controlled.

While conceptually the EDFA is fairly simple, the laser physics and system design issues can be quite complex. Commercially available EDFA technology at this time covers a wide range of packaging and performance specifications, and a number of different pumping wavelengths and pumping designs. Current designs commonly employ a two stage arrangement, using silica glass, combinations of silica glass and fluoride glass, or fluoride glass fibres alone.

Noise figures for communications fibre lasers typically vary between 4.5 and 9 dB (competitive with GaAs
electrical receivers), gains between 25 and 40 dB, and output power levels between 13 and 20 dBs. Around 2000 commercial designs optimised for 1.3 micron systems, using praseodymium doped fluoride fibre amplifier (PDFFA) technology, emerged, achieving similar performance to 1.55 micron EDFAs.

The fundamental physics of a High Power Fibre Laser (HPFL) do not differ from a communications fibre laser. The differences lie in power levels, and where applicable, operating wavelengths, typically in the 1.5 micron to 1.8 micron range.

DARPA funded experiments performed post 2000 demonstrated that the technology was feasible for high power applications, and in 2003 a single fibre single mode fibre laser delivered an output power of 1 kiloWatt, putting the technology into the domain of viable weapons. Pump efficiency in such lasers has been as high as 80%, as a result of which only 20% of optical power fed into the fibre needs to be removed as waste heat. Efficiency of the design will be mostly limited by the efficiency of the pump lasers.

US research effort in this area aims to produce laser power outputs of the order of a 100 kiloWatts or more, which is suitable for point defence weapon applications. To achieve this, power per fibre must be increased, and optical hardware to combine the output of multiple HPFLs is required. Effective cooling of pump lasers and the HPFL spools is also required.

The attraction of HPFLs is in their exploitation of mature commercial technologies, compactness, and electrical pumping compared to chemical lasers.

Raytheon Laser Area Defense System (LADS)
Raytheon's LADS is intended to provide a short range point defence weapon as a replacement for the Phalanx CIWS, utilising existing Phalanx hardware and systems. Cite:

"Raytheon has completed a series of activities that culminated in an early demonstration of LADS. The LADS unit consisted of an Air Force Research Laboratory (AFRL) 20-kilowatt IPG Photonics fiber laser and a bench-mounted beam director secured to the top of a Phalanx mount. AFRL testing verified the ability to propagate the laser beam and achieve the desired effect for a 60 mm mortar in a real-world environment. Sandia National Laboratories provided explosive test chambers, targets and an outdoor range for live-fire testing of LADS against operational mortars. This series of tests was analyzed by AFRLs Directed Energy Directorate, which substantiated predictions that a mortar could be destroyed at ranges greater than 550 meters. The laboratory and field testing anchored the high-fidelity directed energy weapon system effectiveness model."

A particular attraction for this class of weapons is what the US Navy label the "deep magazine" effect - as long as electrical power is available to drive such a laser, it will be capable of engaging targets, unlike guns and missiles which are limited by munitions load, and chemical lasers, which are limited by unique fuel supply.
Appendix 4 - The Science Behind Adaptive Optics, SDI, and the Adaptive Mirrors:
The Star Wars Breakthrough – Adaptive Mirrors

The much maligned Reagan era Strategic Defense Initiative or 'Star Wars' program, intended to drive the Soviets to bankruptcy, yielded one very important dividend for the world of HEL weapons – the adaptive mirror.

At the time of the ALL experiments, solutions were in sight for most if not all of the practical problems encountered with HEL weapons. Lasers could be scaled, optics made larger, tracking systems more accurate and longer ranging. The problem of penetrating the turbulent and thermally inhomogenous atmosphere was not solved.

To penetrate the atmosphere without defocussing beam distortion, the beam itself would have to be 'pre-distorted' as it leaves the optics of the HEL weapon, so that the wavefront of the beam arrived at the target undistorted and precisely focussed. While this is a simple idea in concept, it is harder in practice, as the motion of the HEL platform, motion of the target and movement of the air mass force the need for the pre-distortion of the beam to change continuously. Any solution thus has to include apparatus for continuously measuring the distortion along the path to the target, and a mechanism to continuously distort the HEL beam. Two technologies were developed to solve this problem.

One is the adaptive or deformable mirror which has up to hundreds or thousands of miniature actuators, each of which can locally raise or depress the surface of the mirror, to distort the beam in a controlled fashion. These 'rubber mirrors' are capable of distorting the wavefront in a controlled fashion, with enough accuracy to compensate for atmospheric problems.

The second technology is a form of Lidar (laser radar) which is used to continuously measure the distortion along the beam path to the target. These systems will illuminate the target with a lower power laser operating at a wavelength which is similar but not identical to the HEL weapon. This laser illumination is backscattered off the target and then fed into a device called a wavefront sensor, which measures the distortion across the whole cross section of the beam path to the target. The most commonly used device, the Hartmann-Shack wavefront sensor, uses an array of tiny 'lenslets' placed infront of an imaging device like a CCD. If the wavefront is perfectly flat, a dot appears centred beneath each of the lenslets. If part of the wavefront is distorted over the position of a lenselet, the dot's position moves in a manner specific to the direction and size of the distortion.

Hartmann-Shack Wavefront Sensor

Hartmann Shack Wavefront Sensor (Kiepenheuer-Institut für Sonnenphysik)
In a HEL weapon system, the Lidar and wavefront sensor are used to continuously measure the distortion along the beam path, and produce corresponding commands to the actuator array used in the deformable main mirror, which reflects the high power HEL beam to the target.
Physicists Slow Speed of Light

By William J. Cromie

Gazette Staff

Light, which normally travels the 240,000 miles from the Moon to Earth in less than two seconds, has been slowed to the speed of a minivan in rush-hour traffic -- 38 miles an hour.

An entirely new state of matter, first observed four years ago, has made this possible. When atoms become packed super-closely together at super-low temperatures and super-high vacuum, they lose their identity as individual particles and act like a single super-atom with characteristics similar to a laser.

Such an exotic medium can be engineered to slow a light beam 20 million-fold from 186,282 miles a second to a pokey 38 miles an hour.

"In this odd state of matter, light takes on a more human dimension; you can almost touch it," says Lene Hau, a Harvard University physicist.

Hau led a team of scientists who did this experiment at the Rowland Institute for Science, a private, nonprofit research facility in Cambridge, Mass., endowed by Edwin Land, the inventor of instant photography.

In the future, slowing light could have a number of practical consequences, including the potential to send data, sound, and pictures in less space and with less power. Also, the results obtained by Hau's experiment might be used to create new types of laser projection systems and night vision cameras with power requirements a million times less than what is presently possible.

But that's not why Hau, a research scientist at both Harvard and the Rowland Institute, originally set out to do the experiments. "We did them because we are curious about this new state of matter," she says. "We wanted to understand it, to discover all the things that can be done with it."

It took Hau and three colleagues several years to make a container of the new matter. Then followed a series of 27-hour-long trial runs to get all the parts and parameters working together.

"So many things have to go right," Hau comments. "But the results finally exceeded our expectations. It's fascinating to see a beam of light almost come to a standstill."

Members of Hau's team included Harvard graduate students Zachary Dutton and Cyrus Behroozi. Steve Harris from Stanford University served as a long-distance collaborator.

Making a Super-atomic Cloud

The idea of this new kind of matter was first proposed in 1924 by Albert Einstein and Satyendra Nath Bose, an Indian physicist. According to their theory, atoms crowded close enough in ultra-low temperatures would lock together to form what Hau calls "a single glob of solid matter which can produce waves that behave like radio waves."
This so-called Bose-Einstein condensate was not actually made until 1995, because the right technological pot to cook it up in did not exist. Vacuums hundreds of trillions of times lower than the pressure of air at Earth's surface, and temperatures almost a billion times colder that that in interstellar space, are needed to produce the condensate. Temperatures must be lowered to within a few billionths of a degree of absolute zero (minus 459.7 degrees F), where atoms have the least possible energy and all but cease to move around.

Hau and her group started with a beam of sodium atoms injected into a vacuum chamber and moving at speeds of more than a thousand miles an hour. These hot atoms have an orange glow, like sodium highway and street lights.

Laser beams moving at the normal speed of light collide with the atoms. As the atoms absorb particles of light (photons), they slow down. The laser light also orders their random movement so they move in only one direction.

When the atoms are slowed to a modest 100 miles an hour or so, the experimenters load the atoms into what they call "optical molasses," a web of more laser beams. Each time an atom collides with a photon it is knocked back in the direction from which it came, further slowing it down, or cooling it.

The atoms are now densely packed in a cigar-shaped clump kept floating free of the walls of their container by powerful magnetic fields.

"It's nifty to look into the chamber and see the clump of cold atoms floating there," Hau remarks.

In the final stage, known as "evaporative cooling," atoms still too hot or energetic are kicked out of the magnetic field.

The stage is now set for slowing light. One laser is shot across the width of the cloud of condensate. This controls the speed of a second pulsed laser beam shot along the length of the cloud. The first laser sets up a "quantum interference" such that the moving light beams of the second laser interfere with each other. When everything is set up just right, the light can be slowed by a factor of 20 million.

The process is described in detail in the Feb. 18 issue of the scientific journal Nature. (Warning: Don't try this at home.)

**Relativity and the Internet**

Slowing light this way doesn't violate any principle of physics. Einstein's theory of relativity places an upper, but not lower, limit on the speed of light.

According to relativity theory, an astronaut traveling at close to the speed of light will not get old as fast as those she leaves behind on Earth. But driving at 38 miles an hour, as everyone knows, will not affect anyone's rate of aging.

"However, slowing light can certainly help our understanding of the bizarre state of matter of a Bose-Einstein condensate," Hau points out.

And a system that changes light speed by a factor of 20 million might be used to improve communication. It can be used to greatly reduce noise, which allows all types of information to be transmitted more efficiently. Also, optical switches controlled by low intensity light could cut power
requirements a million-fold compared to switches now operating everything from telephone equipment to supercomputers.

But what about the cost and exotic equipment needed for such improvements? "Technologies that push past old limits are always expensive and impractical to begin with; then they become cheaper and more manageable," Hau says matter-of-factly. She sees the possibility that slow light will lead to "significant advances in communications ten years from now, if we get to work on it right away."

What will she do next?

Hau sweeps her hand over a roomful of equipment and explains how things are already being set up to slow light speed even more, to one centimeter (less than a half-inch) a second. That's a leisurely 120 feet an hour.

Hau will give a lecture on her experiments at 4:30 p.m. on Monday, Feb. 22, at Room 250, Jefferson Laboratories.
Appendix 6 - Principles of War as listed in Field Manual 100-5 Operations (1993) and restated in Field Manual 3-0 Operations (2001):

THE FOUNDATIONS OF ARMY OPERATIONS
Fundamental to operating successfully across the full range of military operations is an understanding of the Army’s doctrinal foundations—the principles of war and the tenets of Army operations.

THE PRINCIPLES OF WAR
The nine principles of war provide general guidance for the conduct of war at the strategic, operational, and tactical levels. They are the enduring bedrock of Army doctrine. The US Army published its first discussion of the principles of war in a 1921 Army training regulation. The original principles adopted by the Army, although slightly revised, have withstood the test of time. Today’s force-projection Army recognizes the following nine principles of war:

Objective
Direct every military operation toward a clearly defined, decisive, and attainable objective. The ultimate military purpose of war is the destruction of the enemy’s armed forces and will to fight. The ultimate objectives of operations other than war might be more difficult to define; nonetheless, they too must be clear from the beginning. The linkage, therefore, between objectives at all levels of war is crucial; each operation must contribute to the ultimate strategic aim. The attainment of intermediate objectives must directly, quickly, and economically contribute to the operation. Using the analytical framework of mission, enemy, troops, terrain, and time available (METT-T), commanders designate physical objectives such as an enemy force, decisive or dominating terrain, a juncture of lines of communication (LOCs), or other vital areas essential to accomplishing the mission. These become the basis for all subordinate plans. Actions that do not contribute to achieving the objective must be avoided.

Offensive
Seize, retain, and exploit the initiative. Offensive action is the most effective and decisive way to attain a clearly defined common objective. Offensive operations are the means by which a military force seizes and holds the initiative while maintaining freedom of action and achieving decisive results. This is fundamentally true across all levels of war. Commanders adopt the defensive only as a temporary expedient and must seek every opportunity to seize the initiative. An offensive spirit must therefore be inherent in the conduct of all defensive operations. The side that retains the initiative through offensive action forces the enemy to react rather than act.

Mass
Mass the effects of overwhelming combat power at the decisive place and time. Synchronizing all the elements of combat power where they will have decisive effect on an enemy force in a short period of time is to achieve mass. To mass is to hit the enemy with a closed fist, not poke at him with fingers of an open hand. Mass must also be sustained so the effects have staying power. Thus, mass seeks to smash the enemy, not sting him. This results from the proper combination of combat power with the proper application of other principles of war. Massing effects, rather than concentrating forces, can enable numerically inferior forces to achieve decisive results, while limiting exposure to enemy fire.

Economy of Force
Employ all combat power available in the most effective way possible; allocate minimum essential combat power to secondary efforts. Economy of force is the judicious employment and distribution of forces. No part of the force should ever be left without purpose. When the time comes for action, all parts must act. The allocation of available combat power to such tasks as limited attacks, defense,
delays, deception, or even retrograde operations is measured in order to achieve mass elsewhere at the decisive point and time on the battlefield.

**Maneuver**
Place the enemy in a position of disadvantage through the flexible application of combat power. Maneuver is the movement of forces in relation to the enemy to gain positional advantage. Effective maneuver keeps the enemy off balance and protects the force. It is used to exploit successes, to preserve freedom of action, and to reduce vulnerability. It continually poses new problems for the enemy by rendering his actions ineffective, eventually leading to defeat. At all levels of war, successful application of maneuver requires agility of thought, plans, operations, and organizations. It requires designating and then shifting points of main effort and the considered application of the principles of mass and economy of force. At the operational level, maneuver is the means by which the commander determines where and when to fight by setting the terms of battle, declining battle, or acting to take advantage of tactical actions. Maneuver is dynamic warfare that rejects predictable patterns of operations.

**Unity of Command**
For every objective, seek unity of command and unity of effort. At all levels of war, employment of military forces in a manner that masses combat power toward a common objective requires unity of command and unity of effort. Unity of command means that all the forces are under one responsible commander. It requires a single commander with the requisite authority to direct all forces in pursuit of a unified purpose. Unity of effort, on the other hand, requires coordination and cooperation among all forces even though they may not necessarily be part of the same command structure toward a commonly recognized objective. Collateral and main force operations might go on simultaneously, united by intent and purpose, if not command. The means to achieve unity of purpose is a nested concept whereby each succeeding echelon’s concept is nested in the other. In combined and inter-agency operations, unity of command may not be possible, but the requirement for unity of effort becomes paramount. Unity of effort coordination through cooperation and common interests is an essential complement to unity of command.

**Security**
Never permit the enemy to acquire unexpected advantage. Security enhances freedom of action by reducing vulnerability to hostile acts, influence, or surprise. Security results from the measures taken by a commander to protect his forces. Knowledge and understanding of enemy strategy, tactics, doctrine, and staff planning improve the detailed planning of adequate security measures. Risk is inherent in war; however, commanders must not be overly cautious. To be successful, commanders must take necessary, calculated risks to preserve the force and defeat the enemy. Protecting the force increases friendly combat power.

**Surprise**
Strike the enemy at a time or place or in a manner for which he is unprepared. Surprise can decisively shift the balance of combat power. By seeking surprise, forces can achieve success well out of proportion to the effort expended. Rapid advances in surveillance technology and mass communication make it increasingly difficult to mask or cloak large-scale marshaling or movement of personnel and equipment. The enemy need not be taken completely by surprise but only become aware too late to react effectively. Factors contributing to surprise include speed, effective intelligence, deception, application of unexpected combat power, operations security (OPSEC), and variations in tactics and methods of operation. Surprise can be in tempo, size of force, direction or location of main effort, and timing. Deception can aid the probability of achieving surprise.
Simplicity
Prepare clear, uncomplicated plans and concise orders to ensure thorough understanding. Everything in war is very simple, but the simple thing is difficult. To the uninitiated, military operations are not difficult. Simplicity contributes to successful operations. Simple plans and clear, concise orders minimize misunderstanding and confusion. Other factors being equal, the simplest plan is preferable. Simplicity is especially valuable when soldiers and leaders are tired. Simplicity in plans allows better understanding and troop leading at all echelons and permits branches and sequels to be more easily understood and executed.
### Table 2.1

#### Historical Swarming Cases

<table>
<thead>
<tr>
<th>Case Study, Specific Battle or Mission:</th>
<th>Swarmer or Defensive</th>
<th>Swarmer Description</th>
<th>Nonswarmer Description</th>
<th>Uniqueness of Example</th>
</tr>
</thead>
<tbody>
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<td>Heavy infantry in legions</td>
<td>Horse archer against unsupported legions</td>
</tr>
<tr>
<td>Turks vs. Crusaders, Battle of Dorylaeum, 1097</td>
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</tr>
<tr>
<td>Woodland Indians vs. U.S. Army, St. Clair's Defeat, 1791</td>
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</tr>
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<td>Boers vs. British, Battle of Majuba Hill, 1881</td>
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<tr>
<td>Somalis vs. U.S. Commandos, Mogadishu, October 3-4, 1993</td>
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<td>Tribal militia (light infantry)</td>
<td>Light infantry, light vehicles, helicopter gunships</td>
<td>Peacekeeping operation</td>
</tr>
</tbody>
</table>

**NOTE:** Cataphracts are heavy cavalry armed with lance, bow, and sword.