Chapter 2

HISTORY AND DEVELOPMENT OF MILITARY LASERS

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INTRODUCTION

This chapter will examine the history of the laser, from theory to demonstration, for its impact upon the US military. In the field of military science, there was early recognition that lasers can be visually and cutaneously hazardous to military personnel—hazards documented in detail elsewhere in this volume—and that such hazards must be mitigated to ensure military personnel safety and mission success. At odds with this recognition was the desire to harness the laser's potential application to a wide spectrum of military tasks. This chapter focuses on the history and development of laser systems that, when used, necessitate highly specialized biomedical research as described throughout this volume. This presentation is neither exhaustive nor definitive, but describes numerous developmental and fielded laser systems that cover a range of militarily important applications.

Military advantage is greatest when details are concealed from real or potential adversaries (eg, through classification). Classification can remain in place long after a program is aborted, if warranted to conceal technological details or pathways not obvious or easily deduced but that may be relevant to future developments. Thus, many details regarding developmental military laser systems cannot be made public; their descriptions here are necessarily vague.

Once fielded, system details usually, but not always, become public. Laser systems identified here represent various evolutionary states of the art in laser technology, design, and application during their development. Emitted beam characteristics vary widely and are important to the specific application and assessment of potential hazards.

INVENTING THE LASER

"A splendid light has dawned on me about the absorption and emission of radiation."

—Albert Einstein, letter to Michele Angelo Besso, September 6, 1916[1(p82)]

Light amplification by stimulated emission of radiation ("laser") is the optical demonstration of Einstein's theorized "splendid light." Einstein realized that an atom in an excited state can be induced to make a downward transition while emitting a photon, if the atom is irradiated at a frequency that matches the atomic transition energy of the host material. Even so, in science, realization without proof is mere theory. Einstein's "splendid light" remained theory for several years.

Civilian Efforts

In 1928, at Kaiser Wilhelm Institute, Rudolf Ladenburg proved negative absorption (stimulated emission) near resonant wavelengths in neon gas.[2] However, Ladenburg's demonstration was of an uncontrolled emission, and nothing practical flowed from his proof. Another 26 years would pass before demonstration of a controlled stimulated emission. In 1954, at Columbia University, Charles Townes, Herbert Zeiger, and James Gordon stimulated ammonia gas with microwave radiation and created the first "maser" (microwave amplification by stimulated emission of radiation).

Three years later, Gordon Gould, a Columbia graduate student, coined the acronym "laser." In a notarized but unpublished paper, Gould described how a laser could be built, and was later awarded a patent just for his design. Historical credit for the invention of the laser went instead to Bell Labs researchers Charles H. Townes and Arthur L. Schawlow, whose detailed and published proposal for building what they called an "optical maser" created an instant stir when it appeared in *Physical Review* on December 15, 1958.[3]

The race to build the first laser began immediately, but there was no agreement about which of several candidate materials might be an acceptable host.[4] Townes led a team at Columbia to build a potassium-vapor laser. Similarly, Gould, at Technical Research Group, worked on alkali metal vapors. In the Soviet Union, Nicolay G. Basov concentrated on semiconductors. Ali Javan, at Bell Labs, worked to build a helium-neon gas laser. Schawlow, also at Bell Labs, considered ruby, but then dismissed it as unsuitable. Theodore Maiman, at Hughes Research Laboratory, became convinced that Schawlow was wrong to dismiss ruby as a host material. On May 16, 1960, Maiman used a cylindrical ruby crystal and a xenon flash lamp to generate a monochromatic beam of coherent radiation.[5] The ruby laser emitted a 0.5-millisecond pulse that approximated the pump lamp's emission duration with a primary emission wavelength of 694.3 nm. The pulse on higher-energy ruby lasers could linger from 1 to 5 milliseconds. These are relatively long pulses compared to what is possible through Q-switching. (Q-switched lasers emit short pulses. "Q" refers to the "quality" factor describing the state of a laser cavity.)

Military Interest

Researchers at the Defense Department's Advanced Research Projects Agency (ARPA) and military services' research and development (R&D) laboratories, including the Army's R&D labs at Picatinny Arsenal, New Jersey, and Ft Monmouth, New Jersey, quickly recognized that laser energy possessed a number of special properties, not least of which are spatial and temporal coherence. Coherent and almost parallel beams of light can achieve extremely high radiation densities when tightly pulsed and highly focused, creating transitory temperatures exceeding those on the sun's surface.

Even the low-powered, Q-switched ruby laser inspired excitement among those who understood its potential. Q-switching produces a more intense pulse. While output energy is somewhat decreased, the pulse duration is markedly shortened, resulting in a tremendous increase in emitted power density; a 10 ns pulse of 1 J represents a pulse of about 100 million W. The effect of such a pulse on target materials, whether rigid or elastic, is more "explosive" or ablative than long pulses. Thus, the transition from ruby to neodymium-doped yttrium aluminum garnet (Nd:YAG) as the preferred solid-state laser changed the potential not only for laser application, but also for resulting medical hazards.

ARPA and the military services' R&D laboratories naturally hoped that laser technology could be manageably scaled, powered, and packaged as deployable combat tools. The ultimate goal was development of a "ray gun." In 1968, Frederick Schollhammer obtained US Patent Number 3,392,261 for the "Portable Beam Generator," also known as the handheld laser ray gun.[6] Of course, owning a patent and making a product are two different things.

Impressive though they are, even today's most modern laser applications still pale in comparison to the power and efficiency of those depicted in science fiction. Early military applications were all the more benign by contrast. ARPA awarded seed money for research to develop and test new laser action materials ("lasants"). The original ruby lasant was applied to a number of applications with military potential. Within a year of Maiman's original achievement, the first prototype military laser device—an artillery laser rangefinder—had been designed and built. In much the same way that radar modernized air operations, some visionaries believed the laser could fundamentally change future battlefields across a wide spectrum of military functions.

MILITARIZING THE LASER

Although many nations have harnessed the potential of military lasers, none have done so as extensively as the United States. Prior to the development of the first laser, American military scientists had envisioned light-sourced applications to support distance measurement, target designation, and wireless guidance. Unfortunately, none of these applications could be achieved with noncoherent light sources. The laser provided a tight, collimated, and discrete wavelength beam that was immediately applied to support these and other applications:

Rangefinders

The first successful American military application of laser technology was for the purpose of distance measurement, or "rangefinding." The idea in this case was to employ the energy density of the laser beam, the strength of which guaranteed reflection back from almost any irregular surface of military interest. Using ruby, the first artillery laser rangefinder was built at the US Army's Pitman-Dunn Laboratory at Frankfort Arsenal, Pennsylvania. Dubbed the XM23, this device was the first of a larger family of rangefinders. The well-engineered ruby laser rangefinder was deployed within every main battle tank the US Army fielded until the introduction of the M1 Abrams tank series in 1978.

Although the ruby laser system was useful in early work, faster and cooler lasers were subsequently made possible through the use of Nd:YAG as a lasant. The switch to Nd:YAG was concurrent with the introduction of the M1 Abrams in 1978 and continued in the M1A1 (1985). A laser rangefinder known as the eye-safe laser rangefinder (ELRF) used erbium-doped glass as a lasant that did not exceed the radiation protection exposure limits. It was introduced with the M1A2 in 1986[7] (Table 2-1).

The mainstay for US ground as well as nontank vehicle laser rangefinders has been the neodymium-based AN/GVS-5. Since 1977, more than 8,000 such units have been fielded to Army and Marine Corps forward observers. The AN/GVS-5 delivers one ranging measurement per second and can be operated by battery or vehicular electrical power. This system's 7 × 50 mm sighting optics, multiple target indicator, and minimum range adjustment provide wide versatility and adaptability.

The LAV-AD (Light Armored Vehicle–Air Defense) and LAV-105 are both eight-wheeled armored cars. Each is augmented with a different laser rangefinder.

TABLE 2-1

US TANK RANGEFINDER SYSTEMS GROUPED BY THEIR LASER MEDIUMS AND TANK MODELS

Laser Medium	Ruby			Nd:YAG	Er:Glass
Tank Rangefinder System (Tank Model)	AN/VVS-1 (M60A2 Tank)	AN/VVG-1 (M551A1 Sheridan)	AN/VVG-2 (M60A3 Tank)	AN/VVG-3 (M1 and M1A1 Tank)	ELRF (M1A2Tank)

Er:Glass: erbium-doped glass
ELRF: eyesafe laser rangefinder
Nd:YAG: neodymium-doped yttrium aluminum garnet

The LAV-105 uses the AN/GVS-5, and the LAV-AD uses a transversely excited atmospheric carbon dioxide (CO_2) laser. The Avenger air defense system also uses a CO_2 laser.[8] Other rangefinders also exist (Table 2-2).

As military rangefinders transitioned from use of ruby to Nd:YAG lasant, an additional military application became possible. Because neodymium was cooler than ruby, neodymium permitted faster repetition rates. Although largely unnecessary for rangefinders, these faster rates were essential for target designation.

Target Designators and Markers

Target designation relies on beam reflection and fast repetition rates. A laser target designator emits a coded train of pulses to a designated point of reflectivity on the target. A seeker on the weapon identifies and locks onto the reflected, coded train of pulses. Guidance surfaces or steering jets then maneuver the delivery system (bomb, missile, or warhead) to strike the target at the designated point.

The US Army first began research into laser target designation in 1962. Simultaneously, the Army began research into laser guidance of smoothbore cannon projectiles. The US Air Force joined this effort and developed the first laser-guided bomb (BOmb, Laser, Target-117) (BOLT-117) in 1967. The BOLT-117 was essentially a gravity bomb equipped with a laser seeker, guidance logic, and attached control system. The system's signals steered the bomb by controlling its fins. Target designation for the bomb was achieved by laser designator (AN/ALQ-10) operated from a separate observation aircraft.[9,10]

In 1968, the BOLT-117 was field-tested in Vietnam.[9] Because the BOLT-117 was a "dumb bomb" adapted to a "smart task," this bomb was limited in terms of its seeker sensitivity, glide agility, and range. Although it needed an improved and integrated system in a more maneuverable body, its concept was compelling.

The limitations of the BOLT-117 were overcome by the GBU (Guided Bomb Unit)-10 Paveway, which was designed and built to be a laser-guided bomb.

TABLE 2-2

A COMPARISON OF US HANDHELD AND VEHICLE-MOUNTED LASER RANGEFINDERS

System	Known As	Platform Use	Medium
AN/GVS-5	GVS-5	Handheld	Nd:YAG
AN/PVS-X	MLRF	Handheld	Nd:YAG
AN/TWQ-1	Avenger	HMMWV Air Defense	TEA CO_2
LAV-105	LAV	Armored Car	Nd:YAG
LAV-AD	LAV-AD	Armored Car - AD	CO_2
AN/PVS-6	MELIOS	Handheld	Erbium

AD: air defense
CO_2: carbon dioxide
HMMWV: high-mobility multipurpose wheeled vehicle
LAV: light-armored vehicle
MELIOS: mini-eyesafe laser infrared observation set
MLRF: miniature laser rangefinder
Nd:YAG: neodymium-doped yttrium aluminum garnet
TEA CO_2: transversely excited atmospheric carbon dioxide

A prototype of the GBU-10 was successfully employed over North Vietnam in 1972.[9] Near Hanoi, four GBU-10s released during a single sortie scored four direct hits and dropped the Than Hoa Bridge, which had previously survived more than 800 attack sorties by dumb bombs over a 5-year period. As a proof-of-concept mission, the Than Hoa raid was a resounding success. The accomplishment was quickly followed by dropping Hanoi's equally vexing Paul Doumier bridge.[11]

The GBU-12, GBU-15, GBU-16, GBU-24, GBU-27, and GBU-28 succeeded the GBU-10.[10] These follow-on systems had maneuverable bodies and could be self-designated. This meant that the delivery aircraft could designate its own target, eliminating the need for an additional aircraft on station. Some of the aircraft and helicopter laser designators in the US inventory are listed in Table 2-3.

TABLE 2-3

LASER DESIGNATORS AND THEIR ASSOCIATED US AIRCRAFT PLATFORMS

System	Known As	Platform Association
AN/AVQ-9	Pave Light	OV-10 and F-4
AN/ALQ-10	Pave Knife	F-16
AN/AVQ-11	Pave Sword	O-2A and F-4
AN/AVQ-12	Pave Spike	O-2A, F-4, and F-111
AN/AVQ-13	Pave Nail	OV-10
AN/AAQ-14	LANTIRN	F-14, F-15E, and F-16C/D
AN/AVQ-14	Pave Arrow	O-2A and C-123
AN/AVQ-19	Pave Spectre	AC-130
AN/AAQ-22	Safire NTIS	UH-1N and P-3
AN/AVQ-25	Pave Tack	A-7D, A-10A, F-4, and F-111
AN/AVQ-26	Pave Tack	F-4, RF-4, and F-111F
AN/AAS-32	ATL	AH-1F
AN/AAS-33A	TRAM	A-6E
AN/AAS-35	Pave Penny	F-16, A-7D, A-10A, F-4, F-111, and OV-10A
AN/AAS-37	LRFD	OV-10
AN/AAS-38A	Nite Hawk	F/A-18
NTSF-65	NTS	AH-1W
TADS LTD	TADS	AH-64
M65	LAAT	AH-1F and AH-1S
MMS LRF/D	Mast Mount	OH-58D

ATL: advanced tactical laser
LAAT: laser augmented airborne tube-launched, optically tracked, wire-guided missile
LANTIRN: low-altitude navigation and targeting infrared for night
LRFD and LRF/D: laser rangefinder designator
LTD: laser target designator
MMS: mast-mounted sight
NTIS: navigational thermal imaging system
NTS: night targeting system
Safire: shipboard airborne forward-looking infrared equipment
TADS: target acquisition and designation sights
TRAM: target recognition attack multisensor

Smart bombs can also be designated from the ground. The AN/PAQ-1 laser target designator, which can be fitted with a night sight, was issued to Special Forces, Army artillery observers, and Air Force forward air controllers as early as 1972. In 1977, the modular universal laser equipment (MULE) was introduced. The MULE was an extremely adaptable piece of equipment used by artillery forward observers, naval gunfire spotters, and forward air controllers. Two years later, the ground/vehicular laser locator designator (G/VLLD, often referred to simply as the GLD, pronounced "glid") was fielded. This system could be man-packed, but its primary mount was the fire support team vehicle (FIST-V). Both the MULE and G/VLLD performed target location and laser designation for all fielded laser-guided munitions (LGM) in the US and North Atlantic Treaty Organization inventories.[10]

As the US Army worked to solve problems associated with cannon-launched guided projectiles (CLGPs), the Marine Corps adapted the air-to-ground missile AGM-65 Maverick to laser guidance as the AGM-65E,[12] dubbed the LMav (laser-guided Maverick) to differentiate it from other Maverick models guided by electro-optics, television, or infrared imaging. The Army would later field a helicopter-launched, antitank LGM known as the Hellfire, and later the Hellfire II, with 20 variants between them. The LGM can be fired from eleven different helicopters, six fixed-wing aircraft, four unmanned aircraft, and at least two naval craft.[13]

During this time, the Army also finally fielded its Copperhead antitank round. The M712 Copperhead laser-guided, 155-mm CLGP is fired from any model 155-mm Howitzer to within the general vicinity of the target. When the round reaches apex and begins its downward flight, a forward observer illuminates its target by laser. The Copperhead's seeker locks onto the reflected laser energy and steers itself to the target. The Copperhead is effective in locating both stationary and moving targets. However, its price tag limited its use to very high-value targets. Its last reported use was in 2003 during Operation Iraqi Freedom, after which a new family of smart projectiles incorporated global positioning system/inertial navigation system-guided bombs and precision artillery.[14]

In 1986, the compact laser designator was fielded for Army Special Forces and Navy Seals. At about the same time, military scientists began to analyze the concept of portable and handheld laser markers that could be used to illuminate or mark targets (Table 2-4). The Special Operation Forces laser marker was then developed to illuminate a target for hand-off to a laser designator. Officially known as the AN/PEQ-1, the Special Operations Forces laser marker was further developed to a whole family of target pointers, illuminators, and aiming lights. Members of this family are handheld, pistol-mounted, or rifle-mounted, and are monocular or binocular. Some can be used with night vision devices—the most recent being the AN/PEQ-16A/B. The laser target marker was used by ground-based forward controllers. The handheld systems LPL-30 (International Technologies Ltd, Rishon LeZion, Israel) and TD-100 (Target Designator-100) were developed to mark targets for identification using low-light viewing devices such as night vision goggles or low-light television.[6]

The purpose of laser designation, laser spot detection, and laser target marking systems is to support laser homing by illuminating targets to enable munitions to lock on and guide toward the point of beam reflectivity. The primary disadvantage of laser homing is that rain, fog, dust, and smoke can interfere with the laser beam or even completely obscure it, causing the munition's seeker to lose its lock and miss its target. This problem can be avoided through the use of another type of laser guidance known as laser beam "riding."

Beam Riders

Beam rider sensors are located in the aft of the munition. Rather than looking forward at the target, beam rider sensors look back at the launching platform's laser and attempt to "ride" the laser beam itself. In this case, the laser need not actually illuminate the target at which it is aimed during the entire engagement. A gunner can "lead" a moving target, anticipating where the target will be when the missile closes on it. In theory, as long as the system operator (gunner) can see the target and can hold the beam on it in the final seconds before impact, the munition will continue to ride the beam until it strikes the target or loses sight of the beam.

Because the guidance beam is flat, without trajectory, the munition must likewise be capable of achieving and maintaining a flat flight path without trajectory. Only a missile (tube- or gun-launched) can do this. There are several examples of laser-beam rider autonomous missile[15–18] and gun-launched antitank guided missile[19–23] systems in foreign military arsenals. For example, Russia has at least six beam-riding, gun-launched antitank guided missiles and at least ten variants delivered by their family of 100-mm, 115-mm, and 125-mm guns, as well as three adjunct antitank guided missiles mountable on vehicles, watercraft, helicopters, and high-performance aircraft.[24]

The US military explored only initial development of adding such a system—the line-of-sight antitank (LOSAT)—to its own arsenal (Table 2-5). The LOSAT was a four-missile launcher mounted on a stretched high-mobility multipurpose wheeled vehicle (HMMWV), with a trailer carrying eight additional missiles. The LOSAT's guidance incorporated a CO_2 laser,[25] and the LOSAT's missiles rode the laser beam at hypervelocity (5,000 fps) to deliver long penetrator rod warheads. Only 12 delivery systems and 435 missiles were delivered before the LOSAT program was canceled in favor of a lighter-weight missile system.[26,27]

TABLE 2-4

US HANDHELD AND VEHICLE-MOUNTED LASER DESIGNATORS AND MARKERS BY MOUNT

System	Known As	Platform Use
AN/PAQ-1	LTD	Handheld
AN/TVQ-2	G/VLLD	FIST-V
AN/PAQ-3	MULE	Man-packed
LTM86 CLD	Clid	Handheld
AN/PEQ-1	SOFLAM	Handheld or mounted
AN/PEQ-2	ATPIAL	Mounted
LTM	LTM	Man-packed
LPL-30*	Commander's Marker	Handheld
TD-100	Marking Laser	Handheld

*This system name was originally trademarked by International Technologies, Ltd, Rishon, LeZion. Israel.
ATPIAL: advanced target pointer illuminator aiming laser
CLD: compact laser designator
FIST-V: fire support team vehicle
G/VLLD: ground/vehicular laser locator designator
LTD: laser target designator
LTM: laser target marker
MULE: modular universal laser equipment
SOFLAM: special operation forces laser marker

Multiuse Lasers

When it became obvious that a coupling of laser rangefinder and target designator tasks was a good idea, the first Army contract was awarded in 2002. The result was the human-portable AN/PED-1 lightweight laser designator rangefinder (LLDR 1), followed by the AN/PED-1A (LLDR 2) and AN/PED-1B (LLDR 2H). The variants include or are being upgraded to include the following capabilities: thermal imaging, day camera, laser designation, ELRF, electronic display, data export, and transmission; in the LLDR 2H, variants include digital magnetic compass and selective availability and antispoofing module GPS. With this system, US Army and Marine Corps forward observers and US Air Force terminal or forward air controllers can identify and target enemy assets in day, night, haze, smoke, fog, or rain at ranges up to 7 km.[28–30]

TABLE 2-5

SELECTED LASER BEAM RIDER MISSILE SYSTEMS BY COUNTRY, TYPE, AND MAXIMUM RANGE

Country	System	Type	Maximum Range
Sweden	RBS 70, RSB 70 NG, and RSB 90	SAM	7,000 m
Russia	AT-10* (9M117 Bastion – fired through rifled guns of T-55 tank)	ATGM and GLATGM	4,000 m
Russia	AT-11* (9M119/9M119M/9M119M1 Svir/Refleks /Invar – fired through smoothbore guns of T-64, T-72/T-80, T-84, and T-90 tanks and through Sprut-SD self-propelled AT gun)	ATGM and GLATGM	4,000 m (ATGM) or 5,000 m (GLATGM)
Russia	AT-12* (9M118 Sheksna – fired through smoothbore gun of T-62 tank series)	ATGM and GLATGM	4,000 m
Russia	AT-14* (9M133 Kornet with variants – adjunct to BMP-3, other APCs and IFVs, and boats)	ATGM	5,500 m (day) or 3,500 m (night)
Russia	AT-15* (9M123 Khrizantema with variants – autonomous tank destroyer- or helicopter-launched)	ATGM	6,000 m (claimed)
Russia	AT-16* (9K121 Vikhr – launched from ships, helicopters, and Su-25T aircraft; can also be launched against aircraft on frontal axis)	ATGM	8,000–10,000 m (day) or 5,000 m (night)
South Africa	ZT3 and ZT3A2 Ingwe – vehicle- and helicopter-mounted	ATGM	5,000 m
United States	LOSAT	ATGM	Classified

*NATO reporting name for military equipment of Russia and the former Soviet Union (https://en.wikipedia.org/wiki/List_of_NATO_reporting_names_for_anti-tank_missiles).
APC: armored personnel carrier
AT: antitank
ATGM: antitank guided missile
BMP: *Boyevaya Mashina Pekhoty*, Russian for "infantry fighting vehicle"
GLATGM: gun-launched antitank guided missile
IFV: infantry fighting vehicle
LOSAT: line-of-sight antitank
RBS: Robotsystem
SAM: surface-to-air missile

The US Marine Corps, with different coordination requirements, fielded the target location, designation, and hand-off system for use by Marine tactical air control parties, fire support teams, firepower control teams, and reconnaissance teams. The target location, designation, and hand-off system possesses additional capabilities for mission hand-off, but otherwise performs on par with the LLDR. Two configurations are fielded as military ruggedized tablets (MRTs): the MRT-A and MRT-B.[31]

Aiming Lasers

Although the handheld TD-100 laser marker (see Table 2-4) is often described as an "aiming laser," this term is now more commonly used to describe systems that are fitted onto weapons. These include the families of the AN/PAQ-4 and the AIM-1 systems (International Technologies Ltd), which fit many individual and crew-served weapons used by the US Army and Marine Corps. In a similar category are the handheld, clip-on, or finger-mounted ground commander's pointer and air commander's pointer. These pointers are small infrared aiming lasers that can be used with night vision devices to identify and illuminate targets at night. They are used by all US military services.[6] Other aiming lasers also exist (Table 2-6).

Laser Training Devices

Laser training devices have been in use since the late 1970s. The multiple-integrated laser engagement system (MILES) is a training system that provides a realistic battlefield environment for soldiers involved in direct fire, force-on-force training exercises that utilize tactical engagement simulation and eyesafe lasers.

TABLE 2-6

OTHER US LASER AIMING DEVICES BY SYSTEM MODELS

System Series	AN/PAQ-4	AIM-1*	GCP-1	ACP-2
Aiming devices	AN/PAQ-4, AN/PAQ-4A, AN/PAQ-4B, and AN/PAQ-4C	AIM-1, AIM-1/D, AIM-1/MLR, AIM-1/EXL, and AIM/MLR	GCP-1 and GCP-1A	ACP-2 and ACP-2A

*AIM-1 is trademarked by International Technologies, Ltd., Rishon, LeZion, Israel.
ACP: air commander's pointer
GCP: ground commander's pointer

As described in the US Army's Technical Bulletin 524, *Control of Hazards to Health From Laser Radiation* (2006), on occupational and environmental health, "[t]hese lasers are designed to be pointed at personnel during combat training. Although there is relatively little risk of eye injury from these lasers, the beams sometimes exceed the maximum permissible exposure (MPE) within a few meters (less than 10 m for the unaided eye)."[32(p48)] The subsequent system version, the MILES II, increased usability and training effectiveness by sensing hits, performing casualty assessment, and recording all "hit" events for after-action analysis. MILES 2000 is the latest in this family of devices.[8]

The technical bulletin also notes that "[h]azards from MILES devices are based on a 10-second exposure duration. A shorter exposure duration lessens the hazard but does not eliminate it."[32(p176)] However, repetitive or repeated exposures can create a cumulative exposure that exceeds the safe exposure limits.[32] The scope and environment of MILES-based training has been extended considerably by the air-to-ground engagement system/air defense, laser air-to-air gunnery system, and precision gunnery training system.[8] A list of laser training devices and their hazardous envelopes is available in Technical Bulletin 524.[32]

A different approach is followed for the indoor simulated marksmanship trainer (ISMT) series, which includes the infantry squad trainer. Training in this series involves the projection of images on a screen. The trainee fires a laser at the projected target to record a hit or miss. The ISMT-E (enhanced) employs 3-dimensional technologies and programmable training scenarios to expand every aspect of training, including the addition of new weapons or capabilities at any time.[33] Table 2-7 lists US laser training systems and their associated weapons.

In addition to all of the applications described above, lasers have many other uses on, behind, and above the modern battlefield. These include remote explosive ordnance detonation, chemical and biological dispersion detection, secure communications, and laser radar (known both as LADAR and LIDAR).

SEARCHING FOR HIGH-ENERGY LASER WEAPONS

When lasers were still very new, ARPA arbitrarily defined a high-energy laser (HEL) as one that could produce an output energy of 10 kW. That criterion was quickly raised to 100 kW, and then to 400 kW. Within the Department of Energy, the megawatt-class laser was considered a HEL. As a practical matter, the term "HEL" is one whose output causes the destruction or mission-neutralization of a target, whether it is an electro-optical missile seeker, a helicopter in attack mode, an intercontinental ballistic missile in flight, or a satellite in orbit. For example, mounted on a tracked vehicle, a single-kW (but more likely 10-kW) laser might be considered a HEL. However, for the purposes of this section, "HEL" will refer to any laser that satisfied or exceeded ARPA's original definition (10 kW).

Rumors in the press and intelligence channels have suggested that Soviet laser weapons were used in remote skirmishes from China to Afghanistan.[34–36] In 1975, American early-warning satellites were reportedly temporarily blinded by Soviet HELs. US defense officials denied that lasers were involved but not that US satellites were temporarily blinded.[37] For those who understood the military's increasing dependence on satellites, the potential ramifications of an antisatellite capability were horrific to contemplate and would constitute a tremendous vulnerability in US strategic deterrence.[38]

Not surprisingly, the United States has investigated the possible development of US HEL weapons. As early as 1962, scientists at the Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico, were tasked with calculating the laser energy that would be required to destroy an intercontinental ballistic missile. At the time, there were no lasers in existence that could possibly deliver the energy necessary to meet this objective.[39] However, the CO_2 laser was invented

TABLE 2-7

US LASER TRAINING SYSTEMS AND PLATFORM ASSOCIATIONS

System	Platform Association
MILES, MILES II, and MILES 2000	Individual and crew-served weapons
AGES/AD family	Chapparal, Vulcan, Stinger, and TADS
AN/ASQ-193 LATAGS	Various
PGTS	TOW and Dragon
TWGSS/PGS (AGES II)	Kiowa (.50 cal); Apache Hellfire (20 mm)
M55 Trainer	All tanks, M2/M3 BFV, and M551
Javelin FTT	Javelin AT system
ISMT/IST	11 individual and crew-served weapons
ISMT-E	15+ individual and crew-served weapons

AD: air defense
AGES: air-to-ground engagement system
AT: antitank
BFV: Bradley fighting vehicle
FTT: field tactical trainer
ISMT: indoor simulated marksmanship trainer
IST: infantry squad trainer
LATAGS: laser tactical air gunnery system
MILES: multiple integrated laser engagement system
PGS: precision gunnery system
PGTS: precision gunnery training system
TADS: target acquisition and designation sights
TOW: tube-launched, optically tracked, wire-guided
TWGSS: tank weapons gunnery simulation system

in 1964, and by 1967, a CO_2 gas dynamic laser (GDL) could produce more than enough energy (10 kW) to cause severe damage to the human body. Other countries may have pursued development of such a lethal weapon, but the United States, instead, remained focused on its goal to develop a laser system that could only be used to destroy missiles. Several types of these laser systems are described below.

Tri-Service Laser

By early 1968, Pratt & Whitney's XLD-1 and AVCO Corporation's MK-5 (both were CO_2 GDLs) achieved output beams of 77 kW and 138 kW, respectively. These systems created expectations of grossly higher output energies as a matter of course. Indeed, the XLD-1 would achieve 455 kW output in May 1969 and exceeded 500 kW in 1970. However, in December 1968, AVCO's MK-5 appeared to be the more powerful device. The armed services purchased the MK-5 scaled up to 150 kW and named it the Tri-Service laser (TSL).[39]

The TSL program became a 4-year odyssey that culminated in December 1972 at Sandia Optical Range, Kirtland Air Force Base. There, researchers at the Air Force Weapons Laboratory mated the 100- to 150-kW beam of the TSL-1 CO_2 GDL with the Hughes Aircraft field test telescope and held it on a moving target that was approximately 3-in. square for several seconds at a distance of 1,760 m. This feat was followed 11 months later with the successful use of the same system to shoot down a 12-ft drone flying 200 mph over Sandia Range.[39]

Airborne Laser Laboratory

With these objectives met, the next logical step was to install a HEL in an airframe as a weapon testbed. In March 1972, the Air Force Weapons Laboratory took possession of a Boeing NKC-135A aircraft and instrumented it with a 400-kW CO_2 GDL. The system was integrated with a Hughes optical pointing and tracking system and a Perkin Elmer dynamic alignment system to become the Airborne Laser Laboratory, a program platform that lasted 11 years and was successfully used to shoot down five AIM-9B Sidewinder air-to-air missiles in 1983.[39]

Mobile Test Unit

The US Air Force was not alone in its efforts to develop HEL capability (Table 2-8). The US Army mounted an AVCO 30-kW CO_2 electric discharge laser in a modified Marine Corps LVTP-7 (landing vehicle, tracked, personnel-7) amphibious assault vehicle. Christened the "mobile test unit" (MTU), this system successfully disabled a 300-mph fixed-wing drone and a tethered helicopter drone at Redstone Arsenal, Alabama, in 1976. Technically, this system was a medium-powered laser, not a HEL, but the MTU demonstrated what could be done with less. Unfortunately, it nearly filled the interior of the vehicle in which it was mounted and, at that time, was neither scalable nor robust enough for Army standards. Despite its successful "hard kill" engagements to structurally destroy drones and helicopters, the Army's MTU program ended inconclusively in 1978.[39]

Mobile Army Demonstrator and Multipurpose Chemical Laser

In 1981, the mobile Army demonstrator (MAD), a 100-kW deuterium-fluoride laser, was built as a prototype for an air defense weapon against missiles

TABLE 2-8

COMPARISON OF US HIGH-ENERGY LASER TESTBEDS

Program	Platform	Type Laser	Output	Successful Engagements
TSL-1	Fixed	CO_2 GDL	150 kW	Drones
ALL	KC-135A	CO_2 GDL	400 kW	Sidewinder AA missiles
MTU	LVTP-7	CO_2 EDL	30 kW	Drones and helicopter
MAD	*	DF	100 kW	*
UNFT	Fixed	DF	400 kW	TOW missiles, helicopter
MIRACL	Fixed	DF	2.2 MW	Drones, missiles, and satellite

*In 1981, the MAD was built as a 100-kW deuterium-fluoride laser prototype for an air defense weapon against missiles under the Strategic Defense Initiative (SDI) umbrella. The MAD was scheduled to be scaled up to 1.4 MW, but deuterium-fluoride technology then proved unsuitable for a mobility mission. The effort was omitted from the SDI budget in late 1983. It was later continued under its new name, the Multipurpose Chemical Laser.
AA: air-to-air
ALL: airborne laser laboratory
CO_2: carbon dioxide
DF: deuterium-fluoride
EDL: electrical discharge laser
GDL: gas dynamic laser
LVTP: landing vehicle, tracked, personnel
MAD: mobile Army demonstrator
MIRACL: midinfrared advanced chemical laser
MTU: mobile test unit
TOW: tube-launched, optically tracked, wire-guided
TSL: tri-service laser
UNFT: unified Navy field test

under the Strategic Defense Initiative umbrella. The MAD was scheduled to be scaled up to 1.4 MW, but deuterium-fluoride technology then proved unsuitable for a mobility mission, so the effort was omitted from the Strategic Defense Initiative budget in late 1983. With Army funding to Bell Aerospace Textron, the MAD laser survived under a new name: the multipurpose chemical laser.[40]

Unified Navy Field Test Program

While the US Army tested the MTU, the US Navy entered the HEL arena. In 1978, the Navy mated a 400-kW TRW Inc (Cleveland, OH), deuterium-fluoride HEL with a Hughes pointer-tracker. Dubbed the Unified Navy Field Test Program, this system destroyed four out of five tube-launched, optically tracked, wire-guided antitank missiles in flight. Later, a UH-1 Iroquois helicopter was targeted and destroyed.[38,39]

Midinfrared Advanced Chemical Laser

The midinfrared advanced chemical laser (MIRACL)[41] was built in the mid-1970s by TRW for the Navy at White Sands Missile Range, New Mexico. Located at the High-Energy Laser Systems Test Facility, MIRACL was the first megawatt-class, continuous wave, chemical laser built in the United States. The MIRACL system is a closed-loop, 2.2-MW, deuterium-fluoride HEL. In the late 1970s, the Navy tested and proved the pointing and tracking technology then under development for MIRACL's partner, the Sea Lite beam director (Hughes Aircraft Company, Westchester, CA). Sea Lite has a 28,000-lb, 1.8-m aperture gimbaled telescope and optics that can focus from 400 m to infinity while tracking a small cross-section missile flying directly at it. MIRACL and Sea Lite have a long record of successful tests against highly dynamic targets, including 500-mph drones, supersonic Vandal missiles, and satellites in orbit[37,41] (see Table 2-8).

Although some of the US HEL systems could have been adapted as weapon systems, none were developed as such. Rather, these systems were testbeds built to demonstrate and delimit specific types of technology and packaging. Testing revealed that the HELs were too large, heavy, expensive, and hazardous. Deuterium-fluoride systems discharge deadly waste gases, which was a primary fault of the MAD system originally intended for deployment; gases from the MAD were found dangerous to unprotected personnel in the immediate vicinity of its discharges. All HEL systems also created extreme heat and were technologically difficult to operate.

SEARCHING FOR LOW-ENERGY LASER WEAPONS

As noted above, the US Army's medium-energy MTU laser program ended inconclusively in 1978, despite successful hard-kill engagements against drones and helicopters. Although discontinued, the MTU program demonstrated what could be achieved by lasers with energy less than that produced by very high-energy laser systems.

Certain foreign developments and activities prompted the United States to conclude that although low-energy lasers (LELs) were incapable of producing hard kills, the LELs could certainly be applied to achieve "soft kills." Soft kills are successful attacks against a variety of essential enemy systems and components (eg, sensors; computer functions; software and memory; electrical integrity; command, control, and communications nodes; or biological functions) sufficient to cause system failure or degradation to the point of unreliability. For example, a LEL system might be used to inflict serious damage to the gunner's aiming sights on an enemy tank, which, in turn, could effectively degrade the ability of the gunner to engage any distant target. An enemy tank that cannot attack or defend its tactical effective range is effectively "dead."

The most desirable soft targets susceptible to degradation by LELs consist of all types of optics, including low-light and night vision equipment, electro-optic sensors, aircraft canopies and windscreens, and, quite incidentally, human eyes. It takes more energy to degrade all but the latter, so although low energy by definition, the safest LEL weapons require a "one-two punch" involving different energy levels. Table 2-9 compares US LEL weapons and countermeasure systems described below.

Close-Combat Laser Assault Weapon

In the early 1980s, the US Army commenced development of a laser system known as the close-combat laser assault weapon (C-CLAW), nicknamed "Roadrunner." The C-CLAW used modestly low-powered lasers to attack and neutralize electro-optic sights, night vision equipment, and helicopter canopies. The system employed the primary frequency of pulsed CO_2 at 1 kW and both the primary and doubled frequencies of Nd:YAG. As a consequence of the latter, the system was quite capable of inflicting severe damage to enemy eyes, although these were not its intended targets. The goal was to build a 900-lb system to be mounted adjunct on an armored vehicle, but by 1983, the system had grown too heavy (3,000 lb) and was too expensive to meet specifications. As a result, the C-CLAW program was canceled.[36]

Stingray

Around the same time, the US Army contracted with Martin Marietta for a new system, the AN/VLQ-7, or "Stingray," an adjunct, bolt-on system designed for the M2 Bradley infantry fighting vehicle and other assault platforms.[8,36,42] The Stingray uses advanced technology and risk-assessment assumptions to locate, acquire, and target enemy optical systems in focal alignment with the system. In a target-rich environment where a single target must be selected among several, the assumption is made that the greatest threat to a given vehicle or platform is the one that has its gunnery or guidance optics trained on the vehicle or platform.

TABLE 2-9

US LOW-ENERGY LASER WEAPONS AND COUNTERMEASURE SYSTEMS, PLATFORMS, AND TARGETS

System	Known As	Platform	Targets
C-CLAW	Roadrunner	Armored vehicle	Optics
AN/VLQ-7	Stingray	Bradley	Optics
AN/ALQ-191	Cameo Bluejay	AH-64	Optics
AN/ALQ-179	Coronet Prince	Various airframes	Optics
Jaguar	Jaguar	M1A2 Abrams	Optics
Outrider	Outrider	HMMWV and LAV	Optics

C-CLAW: close-combat laser assault weapon
HMMWV: high-mobility multipurpose wheeled vehicle
LAV: light-armored vehicle

The Stingray employs a very low-power laser to scan the battlefield with energy pulses. When a focal plane is determined to be in alignment with the Stingray, indicating that it is acquiring or tracking the system, some of the Stingray's emitted laser energy will be reflected back to and detected by the system at an intensity well above the background scatter. The principle is much the same as that responsible for the retroreflection of a flashlight or headlight beam in an animal's eyes at night. The light reflected back is only visible when the animal (or optical system) is looking directly at the emitter.

When the Stingray detects optical reflection, the system centers its crosshairs on the point of intense reflectivity and fires a more powerful laser at the targeted optic. This more powerful laser degrades, damages, or destroys the enemy optical system. The Stingray then returns to its previous search mode to identify additional targets. The Stingray's search laser is not hazardous to enemy eyes at tactical ranges, but its weapon laser is.[36,42,43] As a safety precaution, the Stingray is programmed with a library of common animal optical cross-sections of reflectivity and thus will not react to retroreflection from these animal eyes.

The Stingray has been extensively tested and produced in limited numbers. It was deployed during the Persian Gulf War but was not used because the receiving unit had neither trained with it nor integrated its tactical employment into its battle drills. The Stingray has since been mothballed and production canceled, but its effectiveness did not go unnoticed.

Cameo Bluejay

In 1987, a similar program was initiated to develop an airborne optical countermeasure system for AH-64 attack helicopters. Officially the AN/VLQ-191, more commonly known as Cameo Bluejay, this system applied some of the same assumptions and technologies as the Stingray[36,43] but incorporated growth requirements that could not yet be met. The Cameo Bluejay program was suspended in 1989 to await technology evolution.

Coronet Prince

Other, similar systems also exist (see Table 2-9). The Coronet Prince (AN/ALQ-179) is a US Air Force pod-mounted adjunct system similar to the Stingray in concept. The Coronet Prince is a LEL countermeasure system designed to locate, target, and neutralize enemy air defense systems dependent upon optical and electro-optical acquisition, tracking, or guidance.[36,43]

Outrider

The Outrider is another Stingray derivative, this one developed by the Marine Corps. The Outrider can be mounted on a HMMWV, light-armored vehicle, or other high-mobility wheeled vehicle and can be used to augment reconnaissance forces. The Outrider could also be deployed with an armored spearhead force to protect the advancing armor by locating and degrading immediate optically guided or adjusted threats.[42,43]

Jaguar

The Jaguar system began development in 1985 and passed validation testing in 1988. This system was designed for use as an adjunct antioptics system with the M1A2 Abrams tank. The Jaguar was known to use a laser, but that is all that can reliably be said of it.[36]

Other Attempts to Produce Weapons-Mounted Lasers for the Battlefield

Despite the many aforementioned examples of laser countermeasure and weapon systems, no one has yet managed to build the handheld laser ray gun envisioned by Frederick Schollhammer. Attempts have been made, however. When the US Army first expressed interest in acquiring a rifle-mounted laser weapon for the purpose of attacking sensors and vision, at least two companies answered the call, followed by a military response.

Dazer

Allied Corporation produced the Dazer,[43] a potentially tunable LEL, based on an Alexandrite analogue, with a frequency spread of 700 to 815 nm. The Dazer system was powered by a battery backpack and designed to attack sensitive sensors such as low-light television, night vision equipment, and human eyes. As its name implied, Dazer was designed to temporarily "dazzle" vision but not to produce permanent blindness.

Cobra

McDonnell Douglas produced a similar rifle-mounted system dubbed Cobra, based on a different frequency range and using different output energy. Cobra weapons were developed and tested in the 1980s but were never integrated into the US armed forces.[43-45]

TABLE 2-10

US LOW-ENERGY RIFLE-MOUNTED LASER WEAPONS, DEVELOPMENT STATUS, AND TARGETS

System	Known As	Status	Targets
Dazer	Dazer	Prototype	Electro-optics and eyes
Cobra	Cobra	Prototype	Electro-optics and eyes
AN/PLQ-5	LCMS	Canceled	Electro-optics and eyes

LCMS: laser countermeasures system

Laser Countermeasures System

The Army initiated a new program to develop a human-portable laser countermeasures system (LCMS) from the ground up. Initially classified as the AN/PLQ-5, the LCMS was a rifle-mounted laser system that resembled the Cobra and employed three wavelengths.[43-45] In 1995, the LCMS program was restructured. Its weapon was removed in response to the Department of Defense prohibition on blinding lasers (1995).[46] US efforts to field a rifle-like "ray gun" are summarized in Table 2-10.

Nonweapon Low-Energy Lasers on the Modern Battlefield

Target Location and Observation System

Although the LCMS itself was canceled, a good deal of its technology investment was salvaged by transition to the man-packed target location and observation system (TLOS), designated AN/PLQ-8. TLOS used a gallium-aluminum-arsenide (GaAlAs) diode array that allowed individual soldiers to find threat optical and electro-optical surveillance devices and provide covert illumination for fire direction, improved night vision sighting, and landing zone marking. However, since TLOS emissions exceeded radiation protection exposure limits, the TLOS was not widely fielded.[47]

Saber 203 Laser Illuminator

The US Air Force also developed a "dazzle" device, known as the Saber 203 Laser Illuminator.[43] This device uses a semiconductor laser fitted into an unmodified M-203 40-mm grenade launcher attached to a standard M-16 rifle. Saber 203 illuminates an opponent with harmless, low-power laser light to an effective range of 300 m, which impairs an adversary's ability to fire a weapon or otherwise threaten friendly forces. Saber 203 can also be used as a laser designator and can counter night vision devices. In 1995, it was used successfully by US Marines in Somalia.[48]

LX-5 Laser Diode Illuminator

The US Air Force also developed the LX-5 Laser Diode Illuminator, which is a compact, lightweight system for illuminating the battlefield at night. The LX-5 operates in the near-infrared range and is used with night vision goggles. The system uses 230 W of power at 28 V and provides up to 9.5 W of illumination, adjustable from spot to floodlight size. Completely self-contained, the LX-5 can be operated by battery pack or platform electrical system.[49]

Pocket Laser Communicator

Among the most novel and innovative applications of laser technology is the US Air Force's pocket laser communicator (PLC). This prototype is meant for secure communications between aircraft in formation but could be adapted for ground maneuver units when radio jamming is encountered. In 1978, laser line-of-sight transmissions of data up to 1 gigabit per second were demonstrated at White Sands Missile Range over a 12-mile distance. The PLC is a lightweight, compact laser device capable of transmitting and receiving secure voice line-of-sight communications without radio transmission. Its effective range is 0.6 miles, but this can be increased to as much as 1.2 miles by using a narrow beam.[50,51]

The PLC system consists of a transmitter, receiver, and headset. The transmitter contains a diode laser that operates at near-infrared wavelengths and does not interfere with night vision equipment. Additional wavelengths are also being investigated. The PLC's transmitter is about the size of a miniature flashlight and can function as an infrared illuminator. A lens is used to vary beam size from a pinpoint to a floodlight. The receiver contains the electronics, battery, and infrared detector and is powered by a 9-V, rechargeable battery that allows 4 hours of operation. The receiver weighs about 8 oz and is roughly the size of a cassette tape. Two different headsets are available. One is a lightweight, adjustable model that covers one ear and has a small, adjustable microphone. The second is a combined earphone and microphone that is inserted into the ear and operates on the principle of bone conduction.[50,51]

Rapid Optical Beam Steering

The rapid optical beam steering (ROBS) system is a one-of-a-kind laser radar system operating at White Sands Missile Range. ROBS utilizes a 0.5-m aperture optical system, two tunable 3- to 5-μm imaging cam-

TABLE 2-11

OTHER US LOW-ENERGY LASER DEVICES AND THEIR FUNCTIONAL OBJECTIVES

System	Function	Objectives
TLOS	Illuminator	Illumination, sighting, and marking
Saber 203	Illuminator	Riot and security police crowd control
LX-5	Illuminator	Surface illumination from air
PLC	Communicator	Secure line-of-sight voice
ROBS	Laser Radar	High-resolution target tracking
LNS/LINS	Navigation	Laser ring gyro and global positioning
CAINS	Navigation	Carrier aircraft LINS
LST	Target Tracker	Relates target location to self

CAINS: carrier aircraft inertial navigational system
LINS: laser inertial navigational system
LNS: laser navigation system
LST: laser spot tracker
PLC: pocket laser communicator
ROBS: rapid optical beam steering
TLOS: target location and observation system

eras, and a CO_2 laser radar for range and Doppler measurements. The optical system is based on a roving fovea design, enabling signal target tracking over large angles at a high-track update rate and rapid retargeting among multiple targets. Although this is currently a singular system, it hints at what is possible.[52] A transportable ROBS system was under development in 2003.

Laser Navigation Systems

A host of laser navigation systems, laser inertial navigation systems, and laser inertial navigation attack systems have also been in use by the military for many years. These systems employ a three-axis ring laser gyroscope and laser inertial navigation system. Carrier aircraft use one of several generations of carrier aircraft inertial navigation systems.

Laser Spot Tracker

Numerous laser spot trackers are also in service. Normally aircraft associated, these devices lock onto the reflected energy from a laser-marked or designated target and define the direction of the target relative to itself. The pilot can then self-designate the target for an LGM, relay target coordinates, or select another type of precision or conventional munition for delivery to the target. Once the laser spot tracker achieves target lock, the operator who designated the target can cease designation activity and exit the area or designate another target. Table 2-11 presents a few of the many other uses to which low-energy lasers can be applied on the modern battlefield.

RETURNING TO HIGHER ENERGIES

Early efforts in the 1970s to develop HEL systems were quite successful in demonstrating that HELs could be used to destroy dynamic aerial targets. Although the technology demonstrator systems were large and heavy, their effectiveness was not lost on the military. By the mid-1990s, a multitude of technologies had matured to inspire yet another round of HEL development projects in the United States.

Nautilus

A US Army program known as Nautilus was launched as the first step toward fulfilling an April 1995 mission needs statement for the development of a tactical air defense system.[53] Nautilus was a demonstration program, which evolved into two concepts: (1) a static (immobile) system, the tactical high-energy laser (THEL) and (2) a mobile system, the mobile tactical high-energy laser (MTHEL).

Tactical High-Energy Laser

Nautilus used a fraction of the available energy from the MIRACL to test acquisition, pointing, and tracking equipment that would be mated to a scaled-down MIRACL and called the THEL. In February 1996, only 9 months after the program had begun, Nautilus successfully destroyed a short-range rocket in flight. Later that same year, the United States agreed to make THEL available to Israel and thus began a joint effort.[53,54]

THEL underwent a series of successful tests, but packaging the THEL was no easy task. It had a large footprint and essentially was a permanent installation. The logical next step was to package the system components so they could be moved and set up whenever and wherever the situation demanded.

Mobile Tactical High-Energy Laser

Much has been written about the MTHEL. Concept renderings have been produced and widely publicized in a multivehicle configuration. In whatever breadboard or prototype configuration MTHEL was eventually tested, it performed 28 in-flight kills of Katyusha rockets and engaged and destroyed multiple artillery projectiles in flight.[55]

Technical details of the THEL and MTHEL have been kept as closely guarded secrets, despite much speculation. The fact that MIRACL was used in early tests suggests involvement of a deuterium-fluoride laser. It is probable that THEL and MTHEL are beneficiaries of the US Army's investment in the multipurpose chemical laser program of the mid-1980s. These technologies were shared with Israel. However, THEL's large footprint and MTHEL's reported lack of ruggedness, coupled with a toxic and corrosive fuel and extreme heat evacuation, brought the programs to a close.

Airborne Laser

About the same time Nautilus was hailed a technical success, the US Air Force received $1.1 billion in funding to begin building the military airborne laser (ABL), designated officially as the YAL-1A (Boeing, Seattle, WA). ABL's predecessor, the Airborne Laser Laboratory, had used a 400-kW CO_2 GDL in a militarized Boeing 707. ABL used a megawatt-class chemical oxygen-iodine laser in a militarized Boeing 747-400F. The ABL was designed to detect and destroy theater ballistic missiles in the powered boost phase of flight immediately after missile launch. Infrared, wide-field telescopes installed along the length of the aircraft's fuselage would detect the missile plume from a loiter altitude of 40,000 feet at ranges up to several hundred kilometers.[56,57]

The ABL's pointing and tracking system would track the target missile, compute its launch location, and predict impact location. The turret at the nose of the aircraft would then swivel toward the target missile and a 1.5-m beam director inside the aircraft nose would focus the ABL beam onto the target missile. By heating a spot on the missile's fuel tank or an arc around the missile's circumference, the beam could then lock onto and destroy the missile near its launch area within seconds. However, unsolved technical problems, failure to meet range requirements, and budgetary reality finally caught up with the ABL, which was canceled in December 2011.[58]

Advanced Tactical Laser

In 2002, the Special Operations Command entered into a contract with Boeing to install an underbelly turret on a Lockheed C-130 Hercules to direct a 100 kW air-to-ground laser, which became officially known as the advanced tactical laser. A scaled-down chemical oxygen-iodine laser was produced, tested, and fitted into the aircraft. The turret was developed by L-3 Communications (New York, NY) and Brashear (Pittsburgh, PA); prototype testing began in 2007 and continued into 2009. Although the tests were favorable against 3 x 3-foot stationary targets and moving vehicles, the program has disappeared. Its disappearance is generally credited to a 2008 Air Force Scientific Advisory Board's conclusion that the advanced tactical laser testbed was not operationally useful. By 2010, development and testing presumably ceased (no further advancements were cited in the open literature).[57,59,60]

Aero-Optic Beam Controller

The airborne laser concept is not entirely dead. The Defense Advanced Research Projects Agency (DARPA, successor to ARPA) and the Air Force Research Laboratory are now pursuing another airborne laser project. Capitalizing on a breakthrough in aero-adaptive optics dubbed the aero-optic beam controller turret, the unusual approach is to perfect a protruding, 360° turret that can deliver a focused beam to enemy aircraft and missiles above, below, and behind the aircraft using high-energy lasers. Two major components (and a lot of minor ones) are still needed: (1) an airframe and (2) a laser. However, these component issues have not hampered aero-optic beam controller development. The decision to terminate the ABL has divorced the concept from the chemical oxygen-iodine laser, while concurrently freeing an aircraft defensive laser from the size and expense of a militarized and heavily modified Boeing 747-400 host. DARPA's thinking is that there are plenty of other lighter, scalable, and cooler lasers to select from, and if the right laser does not exist today, it might exist tomorrow.[61]

High-Mobility Multipurpose Wheeled Vehicle Laser Ordnance Neutralization System

Technologically reliable and using considerably less energy than required for air defense is the HMMWV laser ordnance neutralization system, often called Zeus. Zeus's initial development was by the Air Force as the mobile ordnance disrupter system, using a 0.3 kW Nd:YAG and 0.8 kW CO_2 laser fitted into an M113A2 armored personnel carrier. The program then transitioned to the Army, and a 0.5 kW laser was packaged on a HMMWV. In March 2003, the 0.5 kW Zeus was deployed to Afghanistan at the request of the vice chief of staff of the Army. During a 6-month period, it destroyed 200 ordnance items.

In early 2004, Zeus was upgraded to 1 kW, and later that year, the laser was replaced with a 2 kW Yb:glass, diode-pumped fiber laser weighing 2,000 lb less than its predecessor. In 2006, Zeus was deployed to Iraq, where it had mixed success because it often could not burn through materials hiding improvised explosive devices. The latest generation of Zeus uses a 10 kW solid-state heat capacity neodymium-doped glass disc laser. Zeus applies remote viewing of the doubled frequency of neodymium, which is visibly green, to point its otherwise invisible primary wavelength onto unexploded ordnance. The 10 kW laser then burns through the metal body of the munition and causes detonation from a distance of 200 or more meters. The Zeus program is now managed by the US Army Space and Missile Defense Command.[62–64]

High-Energy Laser Technology Demonstrator and Mobile Demonstrator

In 2007, Boeing was awarded a contract to begin development of a truck-mounted laser weapon system to counter rockets, artillery, and mortar rounds (C-RAM); unmanned aerial vehicles (UAVs); and cruise missiles. A prototype of the HEL technology demonstrator (TD), or HEL TD, was delivered exactly 4 years later at Redstone Arsenal, Alabama, and then underwent rigorous component testing and tweaking at the Army's solid-state laser testbed experiment site at White Sands Missile Range. In the next phase of its development, the system was renamed the HEL mobile demonstrator (MD), or HEL MD. Currently using a 10 kW solid-state laser, HEL MD was initially envisioned to be boosted to 50 kW and eventually to 100 kW; these goals have been increased to 60 kW and 120 kW.

The Army intends to upgrade the system with Lockheed Martin's 60 kW fiber laser. The HEL MD is completely self-sustaining on an eight-wheeled, heavy, expanded mobility tactical truck and is designed to be parked for stationary site defense; however, the HEL MD needs a target cue from a local or networked radar system to acquire a target. The 2015 demonstrator requires a driver and a system operator (gunner) to operate the system with a laptop computer and an X-Box (Microsoft, Redmond, WA) console.[65,66]

The 100 kW milestone target has been achieved by Textron Defense Systems (Providence, RI) and Northrop-Grumman Corp (Falls Church, VA). In early 2010, under the Joint Technology Office's Joint High-Power Solid-State Laser Program, each team demonstrated average power levels in excess of 100 kW under laboratory conditions. Textron announced its achievement on the same day the Army awarded Northrop Grumman a contract to install its laser at the solid-state laser testbed experiment site at the Army's High-Energy Laser System Test Facility at White Sands, where the laser will be aligned with the THEL beam control system for performance demonstrations.

Northrop Grumman's solid-state laser (SSL) also achieved a turn-on time of less than 1 second and attained 5 minutes of continuous operation with very good beam quality and efficiency. SSLs are important because they are pumped by electric diodes, not noxious or toxic chemical reactions fueled by tons of precursors, and create far less heat than chemical lasers. If a platform can generate the required electricity, it can fire its SSL laser. Therefore, it is assumed that the new requirement of 120 kW can be achieved.[67,68]

Excalibur

DARPA is funding a 21-element optical phased array (OPA) that combines three identical 10-cm diameter clusters of seven tightly packed fiber lasers. The array allows each individual fiber to correct for atmospheric turbulence at levels comparable to larger, conventional optical solutions. Power efficiencies of 35% have been achieved in near-perfect beam quality with precise targeting at 6.4 km at kW levels thus far. Tests were conducted at several tens of meters (100–200 m) above ground level, where the density of Earth's atmosphere can degrade laser beam quality and propagation. The goal is a 100 kW package 10 times lighter and more compact than previously tested, comparable laser systems. Cooling at the 100 kW level is still an obstacle, but DARPA assesses the OPA technology as extremely promising and will pursue it.[69]

High-Energy Liquid Laser Area Defense System

Meanwhile, General Atomics (GA) (San Diego, CA) has developed a third generation (Gen 3) tactical laser weapon module with a single laser oscillator producing a single beam with 75 kW output. The module was built under DARPA's high-energy liquid laser area defense system (HELLADS) architecture, which requires a 150 kW laser that can be installed in a tactical aircraft for air-to-ground engagements, weighs less than 5 kg/kW, and has a volume of 3 cm^3. To meet HELLADS requirements, two Gen 3 laser oscillators can be coupled together to produce a single 150 kW beam and still beat all HELLADS size and weight requirements, or combine four to produce a 300 kW beam. The Gen 3 is powered by a compact lithium-ion battery that can be recharged by any mobile platform. The current module is sized for installation in GA's Avenger unmanned aerial vehicle, but GA intends to place the Gen 3 in competition for multiple programs and program upgrades, including the HEL MD when it progresses to the 120 kW requirement.[70,71]

Potential Shipboard Lasers

A shift in attention from chemical lasers to SSLs has reduced the size, weight, and complexity of systems, with rewards similar to those projected by DARPA in the airborne domain. For example, there is no longer any need for enormous stores of hazardous chemical fuels. SSLs require one fuel—electricity—which surface vessels can generate in abundance. Also, the problem of heat evacuation has potentially been reduced by orders of magnitude.

Three types of lasers are currently being developed for potential shipboard use: (1) fiber SSLs, (2) slab SSLs, and (3) free electron lasers. Fiber and slab SSLs are mature technologies that appear very promising.[57,72,73] Using these, the US Navy has been pursuing development of three systems: (1) the tactical laser system, (2) the laser weapon system, and (3) the maritime laser demonstration. All three systems have been tested against over-water surface and aerial threat-representative targets at various times since 2009.[57,73]

Tactical Laser System

The tactical laser system is a 10 kW laser developed under contract to be integrated into the MK 38 Mod 2 close-in antiaircraft or small surface vessel ship-defense machine gun system. The system is referred to as the MK 38 tactical laser system with an output power of 10 kW supplied by a Boeing SSL fiber laser. System integration is by BAE Systems, Farnborough, United Kingdom.[73–75]

Laser Weapon System

The AN/SEQ-3 (XN-1) Laser Weapon System (LaWS) is a 30 to 33 kW fiber optic SSL that integrates six 5.4 kW lasers into a converged beam-on-target at tactical ranges regarded as close (maximum range is classified). The system can use a stand-alone or Phalanx-integrated close-in weapon system (General Dynamics, West Falls Church, VA); is currently installed on the USS *Ponce*; and is serving in the Persian Gulf at the time of this writing. The captain of the USS *Ponce* received permission to use LaWS operationally if the situation warrants such engagement. The system is operated using a standard monitor and gaming control system. The LaWS is potentially scalable upward to about 100 kW, but this has not been demonstrated. Navy leadership has said the follow-on system, rated at 100 to 150 kW, will go to sea for demonstration trials by FY 2018.[57,69,73,76–79]

Maritime Laser Demonstration

The Maritime Laser Demonstration (Northrop Grumman, Falls Church, VA) utilizes seven 15 kW slab SSLs that coherently create a single beam of about 105 kW. The Maritime Laser Demonstration is presumed scalable to 300 kW using current technologies.

Solid-State Laser Technology Maturation Program

The deployment, demonstration, and operational status of the Navy's LaWS has resulted in its extended deployment in the Persian Gulf, where it drew the attention of Iran. In early July 2015, the USS *Forrest Sherman* (DDG-98) and its attached helicopter came under repeated laser targeting by an Iranian flagged merchant vessel. As a result of this and other laser incidents, Navy Secretary Ray Mabus concluded that the Navy should have a single group in charge of all directed energy to understand how each project met the Navy's overall needs. The Navy's SSL Technology Maturation (SSL TM) program was initiated to produce a 100 to 150 kW laser for at-sea testing in 2018, to provide increased effectiveness against small boats and UAVs. This is another program in which the GA Gen 3 laser module may be considered.[69,70,72,73]

Ground-Based Air Defense Directed Energy On-the-Move

Included in the programs the Navy secretary alluded to is the Navy's pursuit of a C-RAM (now called C-RAMD to include drones) capability, secondary to anti-UAV and anticruise missile capability, on a land vehicle for the Marine Corps, but one quite unlike the Army's HEL technology demonstrator or HEL MD. Whereas the Army's HEL HD and HEL MD are stationary site defense systems when deployed, the

Marines require a system that performs its mission while moving. The requirement is named ground-based air defense directed energy on-the-move (the unwieldy G-BAD DE OTM acronym is usually shortened to G-BAD).

The initial testbed will be installed on a HMMWV, but the final expeditionary HEL system is to be installed on the four-wheeled joint light tactical vehicle (JLTV) being built for the Army, Marine Corps, and Special Operations Command as a new vehicle and, where applicable, the eventual replacement for the HMMWV. Raytheon (Waltham, MA) has been contracted to deliver a fully integrated, short-range laser weapon system with a minimum power output of 25 kW. The laser weapon itself must not exceed 2,500 lb and must be able to fire at full power, cumulatively or continuously, for 2 minutes, followed by a 20-minute cool-down and recharge to 80% total capacity. The envisioned weapon system (completion expected in 2020) is not a one-vehicle system but will consist of the laser weapon vehicle, a volume-surveillance radar vehicle, and a fully integrated command, control, and communications element with target acquisition, tracking, and fire-control capabilities. The latter two elements may be able to network to more than one laser weapon system, although this has not been publicly stated as a requirement.[63,77,80]

TABLE 2-12

RECENT HIGHER-ENERGY LASER SYSTEM TYPES AND PURPOSES

System	Laser Type	Energy	Purpose
THEL	DF	HEL	Antimissile and antiartillery
MTHEL	DF	HEL	Antimissile and antiartillery
ABL	COIL	HEL	Antitheater ballistic missile
ATL	COIL	100-kW	Air-to-ground tactical support
ABC	To be determined*	To be determined*	Antimissile and antiaircraft
Zeus HLONS	Nd:Glass SSHC	10-kW	Unexploded ordnance
HEL TD/MD	Fiber SSL	10-kW	Counter rocket, artillery, and mortar
Excalibur	Fiber SSL	Classified	Aerial and surface
HELLADS	Classified	75-kW	Air-to-ground engagements
TLS	Fiber SSL	10-kW	Close-in ship defense
LaWS	Fiber SSL	33-kW	Close-in ship defense
MLD	Slab SSL	105-kW	Close-in ship defense
SSL TM	Fiber/Slab SSL	150-kW	Close-in ship defense
GBAD DE OTM	Fiber SSL	25-kW	C-RAM, UAV, and cruise missile

*The ABC is a 360° turret that can deliver a focused beam to enemy aircraft and missiles above, below, and behind the aircraft using high-energy lasers. Laser system type has not been determined.
ABC: aero-optic beam controller
ABL: airborne laser
ATL: advanced tactical laser
COIL: chemical oxygen-iodine laser
C-RAM: counter-rocket, artillery, mortar
DF: deuterium-fluoride
GBAD DE OTM: ground-based air defense directed-energy on-the-move
HEL MD: high-energy laser mobile demonstrator
HEL TD: high-energy laser technical demonstrator
HELLADS: high-energy liquid laser area defense system
HLONS: high-mobility multipurpose wheeled vehicle laser ordnance neutralization system
LaWS: laser weapon system
MLD: maritime laser demonstration
MTHEL: mobile tactical high-energy laser
Nd:Glass: neodymium glass
SSHC: solid-state heat capacity
SSL TM: solid-state laser technology maturation
THEL: tactical high-energy laser
TLS: tactical laser system
UAV: unmanned aerial vehicle

Raytheon's contract award grew out of an earlier demonstration program, the laser area defense system (LADS), which used an Air Force Research Laboratory 20 kW IPG Photonics (Oxford, MA) fiber laser and a beam director mated to a Phalanx mount. The Naval Surface Warfare Center selected Kratos Defense & Security Solutions (San Diego, CA) to develop the LaWS. Raytheon's 20 kW fiber SSL has grown to 25 kW for the G-BAD.[57]

Table 2-12 provides a succinct summary of recent higher energy laser programs. Serious HEL programs also exist for shipboard defense against surface-skimming antiship missiles and ground-based anti-satellite weapons. At present, these efforts exist only as research programs, but history has shown that such programs can lead to successful application. Indeed, the successes of early research are still obvious today in midenergy laser projects and systems.

SUMMARY

The invention of the laser was very quickly and successfully applied to military tasks involving line of sight from laser to target, including rangefinding, target illumination, marking, and designation. The latter evolved concurrently with the ability to place laser seekers on maneuverable munitions. These applications involved low-energy lasers. Weapons required higher energies.

America's initial search for high-energy laser weapons embodied a willingness to try anything. Early quests were exploratory programs that solved important engineering problems concerning coupling, pointing, tracking, beam quality, and dynamic focusing, to name but a few. But the lasers themselves were large and somewhat fragile and posed problems associated with their excessive heat, dangerous gases, recovery time, and complex logistical requirements. Much was learned in the process.

Low-energy weapons can be described as blinders and dazzlers, both of which were designed to serve as countermeasures to optical systems. Blinders used a scanning laser to acquire on-axis optical or electro-optical targets and a more energetic laser to damage the optics. Dazzlers used a rifle-mounted low-energy laser to temporally disrupt sensors, optics, and eyes at tactical ranges; at close range, these lasers could cause permanent eye damage. These weapons were mothballed or discontinued due to a policy decision stemming from the United Nations Vienna Protocol IV of 1995.

As technologies matured, higher-energy lasers were again investigated, this time with an expectation of fielding a system. The first efforts were again too large, too complex, too dangerous, too expensive, or a combination thereof. Only at the lower end of high energy were successful systems deployed, due entirely to breakthrough advances in solid-state laser technologies.

The United States has not been alone in its efforts to develop lasers for use on the battlefield. The former Soviet Union (now Russia), France, Germany, the United Kingdom, and China are five of the nine or ten nations that have tried or succeeded in developing laser weapons. As far as is known, all have abandoned the search for a megawatt class of weaponry and, instead, have found promise in the revolution in SSLs, especially fiber SSLs.

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Note: *Most of the sources used in the preparation of this chapter are internet links to information resources not found in journal articles, reports, or books. These sources serve as pieces of a historical puzzle, supporting the author's telling of the story of laser developments over time. As a historical review, this chapter provides an accessible compilation and needed literature resource that future authors can cite.*

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