



Calhoun: The NPS Institutional Archive
DSpace Repository

NPS Scholarship

Theses

2007-09

Direct-energy weapons : invisible and invincible?

Deveci, Bayram Mert

Monterey, California. Naval Postgraduate School

<https://hdl.handle.net/10945/3311>

Downloaded from NPS Archive: Calhoun



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

<http://www.nps.edu/library>



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

**DIRECTED-ENERGY WEAPONS: INVISIBLE AND
INVINCIBLE?**

by

Bayram Mert Deveci

September 2007

Thesis Advisor:
Second Reader:

Edward Fisher
Terry Smith

Approved for public release; distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2007	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE Directed-Energy Weapons: Invisible and Invincible?		5. FUNDING NUMBERS	
6. AUTHOR(S) Bayram Mert Deveci		8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited		12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) A military weapon is any tool used to increase the reach or power of a nation. Simply, it can be said that each era witnesses the deployment of new and powerful mass destruction weaponry. What will this century's most powerful weapon be? Directed-energy weapons, which offer advantages over conventional weapons by providing attack at the speed of light, precise targeting, rapid engagement of multiple targets, adjustable damage capacity, low operational cost, reduced logistic support, a nearly unlimited magazine, and wide area coverage for offensive and defensive purposes, seem to be at the forefront of the next revolution in military weapons. This thesis provides an understanding of the principles and techniques of directed-energy weapons. In addition, key directed-energy weapon (DEW) programs in laser weapons and RF directed-energy weapons (high-power microwaves) will be fully described, as well as a providing comparison of these DEW types from a military utility perspective. Last but not least, this study will assist in establishing a vision for how directed-energy weapons could revolutionize military affairs in the Turkish Armed Forces of the future.			
14. SUBJECT TERMS Directed-energy Weapons, High-power Microwave Weapons, RF weapons, Laser, HEL, Ground-based Laser, Airborne Laser, Space-based Laser, Soft-kill, Hard-kill		15. NUMBER OF PAGES 139	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

DIRECTED-ENERGY WEAPONS: INVISIBLE AND INVINCIBLE?

Bayram Mert Deveci
Captain, Turkish Army
B.S., Turkish Military Academy, 1997

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN ELECTRONIC WARFARE SYSTEMS
ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL
September 2007**

Author: Bayram Mert Deveci

Approved by: Edward Fisher
Thesis Advisor

Terry Smith
Second Reader

Dan Boger
Chairman, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

A military weapon is any tool used to increase the reach or power of a nation. Simply, it can be said that each era witnesses the deployment of new and powerful mass destruction weaponry. What will this century's most powerful weapon be? Directed-energy weapons, which offer advantages over conventional weapons by providing attack at the speed of light, precise targeting, rapid engagement of multiple targets, adjustable damage capacity, low operational cost, reduced logistic support, a nearly unlimited magazine, and wide area coverage for offensive and defensive purposes, seem to be at the forefront of the next revolution in military weapons.

This thesis provides an understanding of the principles and techniques of directed-energy weapons. In addition, key directed-energy weapon (DEW) programs in laser weapons and RF directed-energy weapons (high-power microwaves) will be fully described, as well as a providing comparison of these DEW types from a military utility perspective. Last but not least, this study will assist in establishing a vision for how directed-energy weapons could revolutionize military affairs in the Turkish Armed Forces of the future.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	AREA OF RESEARCH	2
B.	MAJOR RESEARCH QUESTIONS	3
C.	LITERATURE REVIEW	4
D.	IMPORTANCE AND THE BENEFITS OF THE STUDY	5
E.	ORGANIZATION OF THE THESIS.....	5
II.	TERMINOLOGY AND DE WEAPONRY BASICS.....	9
A.	BACKGROUND	9
B.	BASIC PRINCIPLES FOR DIRECTED ENERGY WEAPONS	11
C.	WHAT IS DIRECTED ENERGY (DE) AND DIRECTED-ENERGY WEAPONS?	14
	1. Key Definitions	14
	2. Directed-Energy Weapon Systems	15
	a. Particle Beam Dilemma.....	15
	b. Developments and Current Applications	17
D.	WHY DIRECTED-ENERGY WEAPONS?.....	19
	1. Advantages of Directed-Energy Weapons.....	20
	2. Limitations and Problems with Directed-Energy Weapons	21
E.	EFFECTS ON TARGETS	23
	1. Soft-Kill.....	24
	2. Hard-Kill.....	25
III.	LASER WEAPONS.....	27
A.	INTRODUCTION AND SCIENTIFIC BACKGROUND	28
	1. How Laser Weapons Work.....	28
	2. Propagation through the Atmosphere	30
	a. Absorption	30
	b. Scattering.....	31
	c. Turbulence	33
	d. Thermal Blooming	33
	3. Target Interaction.....	34
B.	LASER TYPES AND TECHNOLOGIES	35
	1. Chemical Lasers	35
	a. Hydrogen Fluoride.....	35
	b. Deuterium Fluoride	36
	c. Chemical Oxygen Iodine	36
	2. Solid-State Lasers.....	37
	3. Free-Electron Laser	37
C.	TACTICAL AND STRATEGIC LASER WEAPONS.....	38
	1. Ground-Based Lasers	40
	a. Tactical High-Energy Laser	40
	b. Mobile Tactical High-Energy Laser.....	41

2.	Airborne Lasers	42
a.	<i>Airborne Laser (ABL)</i>	42
b.	<i>Advanced Tactical Laser (ATL)</i>	43
3.	Space-Based Laser	44
D.	LASER COUNTERMEASURES AND PROTECTIVE TECHNIQUES.....	46
IV.	HIGH-POWER MICROWAVE WEAPONS	49
A.	PHYSICAL PRINCIPLES OF HIGH-POWER MICROWAVES.....	49
1.	Structure and Basic Considerations.....	49
2.	High-Power Microwave Sources	51
B.	OPERATIONAL CAPABILITIES	52
1.	How High-Power Microwave Weapons Affect Their Targets.....	53
a.	<i>Front-Door Coupling</i>	55
b.	<i>Back-Door Coupling</i>	55
2.	Lethality of High-Power Microwave Weapons	56
a.	<i>Upset</i>	56
b.	<i>Lock-up</i>	56
c.	<i>Latch-up</i>	57
d.	<i>Burnout</i>	57
C.	HIGH-POWER MICROWAVE WEAPONS AND ELECTRONIC WARFARE.....	57
D.	HIGH-POWER MICROWAVE APPLICATIONS AND TARGETS.....	60
E.	DEFENSE AGAINST HIGH-POWER MICROWAVE WEAPONS.....	63
V.	COMPARISON OF DIRECTED ENERGY WEAPONS.....	67
A.	ADVANTAGES AND DISADVANTAGES OF LASER WEAPONS.....	68
B.	ADVANTAGES AND DISADVANTAGES OF HIGH-POWER MICROWAVE WEAPONS.....	71
VI.	PRESENT AND NEAR FUTURE DIRECTED-ENERGY WEAPONS.....	77
A.	E-BOMBS	77
B.	ACTIVE DENIAL SYSTEM (USA)	79
C.	ZEUS (USA)	80
D.	VIGILANT EAGLE (USA).....	82
E.	STINGRAY (USA).....	83
F.	SABER 203 (USA).....	84
G.	ZM-87 PORTABLE LASER (CHINA)	85
H.	BRILLIANT (CANADA)	85
I.	PERSONNEL HALTING AND SIMULATION RESPONSE (USA)	86
VII.	THE IMPLICATIONS OF DIRECTED-ENERGY WEAPONS FOR THE TURKISH ARMED FORCES.....	89
A.	WHY SHOULD THE TURKISH ARMED FORCES INTEGRATE DEW	90
1.	Support All Levels of War	90
2.	Homeland Defense	92
3.	Effective Domestic Security	92

4.	Low Operational Cost.....	92
5.	Superior Information Warfare.....	94
6.	Non-lethal Warfare.....	94
B.	HOW DIRECTED-ENERGY WEAPONS BENEFIT TURKISH LAND FORCES.....	95
C.	HOW DIRECTED-ENERGY WEAPONS BENEFIT TURKISH NAVAL FORCES.....	98
D.	HOW DIRECTED-ENERGY WEAPONS BENEFITS THE TURKISH AIR FORCE.....	102
VIII.	CONCLUSIONS AND RECOMMENDATIONS.....	105
	LIST OF REFERENCES.....	109
	INITIAL DISTRIBUTION LIST.....	119

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1.	Directed-Energy Weapons on Different Platforms.....	6
Figure 2.	Thesis Roadmap.....	7
Figure 3.	Archimedes’s Burning Mirror.....	9
Figure 4.	Electromagnetic Spectrum.....	12
Figure 5.	Stimulated Emission Process.....	27
Figure 6.	Schematic Diagram of Laser Weapon Systems.....	29
Figure 7.	Atmospheric Absorption.....	31
Figure 8.	Rayleigh and Mie Scattering.....	32
Figure 9.	Energy Level Classification of Laser Weapons.....	40
Figure 10.	Ground-Based Laser Concept.....	41
Figure 11.	Airborne Laser (ABL).....	43
Figure 12.	Advanced Tactical Laser Platforms.....	44
Figure 13.	Space-based Laser.....	45
Figure 14.	Basic Set-up of a HPM System.....	50
Figure 15.	Range vs. Effects.....	54
Figure 16.	EW Systems and HPM Systems Coupling Methods.....	59
Figure 17.	HPM Weapons Close Air Support.....	61
Figure 18.	Required Laser Power Levels for Sample Targets.....	69
Figure 19.	E-bomb Warhead.....	77
Figure 20.	Lethal Footprint of an E-bomb.....	78
Figure 21.	Vehicle-mounted Active Denial System (V-MADS).....	79
Figure 22.	Zeus System.....	80
Figure 23.	Zeus Subsystems.....	81
Figure 24.	Vigilant Eagle System.....	82
Figure 25.	AN/VLQ-7 Stingray.....	83
Figure 26.	Saber 203.....	84
Figure 27.	ZM-87 Portable Laser.....	85
Figure 28.	BRILLIANT System.....	86
Figure 29.	The Personnel Halting and Stimulation Response (PHaSR).....	87
Figure 30.	Damage and Destroy Enemy Information Systems.....	94
Figure 31.	Defense against RAM.....	97
Figure 32.	Ship Defense Against ASMs.....	100
Figure 33.	Self-protection of Fighter Aircraft.....	102

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Advantages and Disadvantages of PB Weapons	16
Table 2.	Directed-Energy Weapon Developing Countries	18
Table 3.	Advantages and Disadvantages of DE weapons.....	23
Table 4.	Summary and Comparison of Laser Types.....	38
Table 5.	Laser Countermeasures Summary	48
Table 6.	Differences Between EW Systems and HPM Weapons.....	59
Table 7.	Potential HPM Weapon Applications and Targets	62
Table 8.	High-power Microwave Protective Techniques	65
Table 9.	Comparison of Laser and HPM Weapon Systems Advantages.....	74
Table 10.	Comparison of Laser and HPM Weapon Systems Disadvantages	75
Table 11.	Missile Costs.....	93
Table 12.	Land Applications of DE Weapons	98
Table 13.	Naval Applications of DE Weapons	101
Table 14.	Air Applications of DE Weapons	104

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First of all I want to express my gratitude to the Turkish Nation for providing me this opportunity to obtain my Master's degree in the United States at the Naval Postgraduate School.

I would like to express my sincere thanks to Professor Edward Fisher and Lt. Col. Terry Smith USAF, for their support, professional guidance and patience during the course of this thesis. Their knowledge in every aspect of this thesis led to the successful achievement and completion of this work.

I would also like to thank my mother Aysel Deveci and my father Yasar Deveci for their selfless and endless love and support throughout my life.

Lastly, and most importantly, I would like to thank my beautiful wife Sezin for all her understanding, support and love that she gave me while I struggled through completing my Master's degree at the Naval Postgraduate School as well as this thesis. I dedicate this work to the love of my life Sezin. Thanks my daisy!

THIS PAGE INTENTIONALLY LEFT BLANK

DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Turkish Republic, the Turkish Armed Forces, the Turkish Land Forces, the Turkish Naval Forces or the Turkish Air Force.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Our true mentor in life is science.

Mustafa Kemal Atatürk

The founder and the first president of the Turkish Republic

Consider a hypothetical scenario in which two countries are in conflict. Well aware of the value of asymmetric weapons, one country begins investigating directed-energy (DE) weapons and equips its armed forces with these weapons. In the event of an unwanted war, for defensive protection they intend to use high-power microwave (HPM) sources to disrupt the other's stealth aircraft, which are potentially more susceptible due to their wave-absorbing nature. Moreover, they plan to protect fighter aircraft with free electron laser (FEL) cannons against incoming missiles and shoot down the other's rockets and artillery fire with tactical high-energy laser (THEL) from the arsenal of a multi-platform, multi-mission, defense system.

For offensive applications, this DE conscious nation suppresses the other's air defense and command, control, communications, computer and intelligence (C4I) facilities with unmanned air vehicles (UAVs) loaded with radio frequency (RF) weapon payloads. Using a modularized sealed exhaust chemical oxygen iodine laser (COIL), they can disable the other's domestic critical infrastructure, transportation and communications systems with advanced tactical laser (ATL). In addition, agents use transient electromagnetic devices (TED) to cause detrimental effects on infrastructure such as financial institutions (i.e., banks, ATMs, and stores), airport facilities, and other critical entities.

The second country underestimates directed-energy weapon attacks by prioritizing conventional fighters and cruise missiles against their enemy's defenses. With the unique role of directed-energy weapons' combination of rapid reaction times, long ranges and speed-of-light engagement, unlimited magazine and precision, this second nation is susceptible to DE weapon attacks that can destroy these aircraft and missile systems. The high-power microwave signals from the DE equipped adversary's

installations cause over ninety percent of cruise missiles to fail en route to their targets. Following a DE equipped nation attack with an E-bomb, airborne laser (ABL), and/or advanced tactical lasers, there is little left of this second country's ground facilities and airborne defense systems, with the added condition that minimal collateral damage resulted from the DE-equipped country's attack.

A. AREA OF RESEARCH

Warfare is largely unwanted, but often unavoidable. Under the shadow of this reality, innovations in technology and the application of that technology to military operations combine to provide an opportunity to gain military advantage.¹ The rate of technological change in communications, computers, sensors, lasers and radio frequency weaponry is influencing and increasing the complexity of modern warfare.

Military communities have known of the detrimental effects of radio frequency energy on electronics since World War I. Incisive applications of electronic devices on military weapon and support systems are making the directed-energy weaponry approach the most promising weapons in the twenty-first century.

This study addresses what directed-energy (DE) weapons are, provides an understanding of the two basic types of directed-energy weapons, and offers a comparison of these two basic types. The thesis also examines why the Turkish Armed Forces should integrate directed-energy weapons into its force structure and how the Turkish Armed Forces could improve combat capabilities by using these weapons. This research will lead to more effective planning of directed-energy weapons usage for offensive and defensive strategies in any future conflict involving the Turkish Armed Forces.

¹ Army and General Staff Coll Fort Leavenworth KS School of Advanced Military Studies and Lincoln 2004, 1.

B. MAJOR RESEARCH QUESTIONS

This study researches the answers to the following questions:

Primary Question

- How can the Turkish Armed Forces use directed-energy weapons to improve its combat capabilities in the twenty-first century?

Subsidiary Questions

- What is directed energy and directed-energy weapons?
- What is soft-kill and hard-kill?
- What are the different types of directed-energy weapons?
- Why directed-energy weapons?
- What are the types of laser weapons?
- What is a ground-based laser?
- What is an airborne laser?
- What is a space-based laser?
- What are laser countermeasures?
- What are the structure and characteristic properties of high-power microwave weapons (HPMWs)?
- What are the applications and targets?
- What are the protective methods?
- What is the relationship between electronic warfare (EW) and directed-energy weapons?
- How can one compare laser and high-power microwave weapons?
- What are the advantages and disadvantages of each type of directed-energy weapon in general, and for the Turkish Armed Forces specifically?
- Why should the Turkish Armed Forces consider integrating directed-energy weapons into their force structure?
- What might be the offensive and defensive utilization of directed-energy weapons according to the Turkish Armed Forces missions and responsibilities?

C. LITERATURE REVIEW

Recent advances in technologies have made the development of directed-energy weapons technically feasible. After the third quarter of the last century, scientists have offered many logical and convincing explanations about why directed-energy weapons will be so dominant throughout the coming years.

Although early documents categorize particle beams as DE weapons, later studies just examine laser and high-power microwaves under the DE umbrella, and do not include particle beams in the discussion.

All the sources found in academic journals highlight the importance of directed-energy weapons and how they will change the battle space perspective of future wars. While some sources present these weapons simply as reflections of technological improvements, other researchers offer more complicated and technical discussions.

Most current scientific studies discuss just one type of directed-energy weapon and at this point in time do not include military applications in the discussion. Military writings mostly view these weapons with just only one service branch's point of view - Army, Navy or Air Force.

This thesis does not attempt to explain all types of directed-energy weapons, but instead presents their military applications for a nation's service branches (Army, Navy, and Air Force jointly). In summary, like other sources, this study concludes that directed-energy weapons technology has made sufficient progress in the last decades and countries that underestimate the asymmetric advantages of these weapons will find themselves at risk.

Further examination should be conducted on modeling and simulation tools as well as scenarios to improve the operational effectiveness of directed-energy weapons among real users. Additionally, self-defense and countermeasures against directed-energy weapons should be researched aggressively.

D. IMPORTANCE AND THE BENEFITS OF THE STUDY

Although this subject is very scientific and electronic warfare-focused, this thesis explains things simply and clearly with figures, graphs and tables so readers with little knowledge of the basic science will have little trouble understanding the principles behind directed-energy weapons. The reason for this approach is that the study is intended to be easily understood by non-engineers and other non-technical individuals with little or no electronic warfare (EW) training, education, or background. By adopting this approach, the author hopes to broaden the number of targeted readers.

The results of this thesis may be used to support ongoing efforts by the Turkish Armed Forces to apply electronic warfare against modern threats. This study should enhance the perspective and knowledge of electronic warfare officers, related project officers and technical personnel. Furthermore, research and results will assist the Turkish Armed Forces in evaluating future needs and requirements of electronic warfare systems.

E. ORGANIZATION OF THE THESIS

This thesis is composed of eight chapters. Chapter I provides an introduction to, and an overview of, directed-energy weapons by using an imaginary war scenario.

Chapter II presents the fundamental terminology before entering the high-power microwave and laser discussions, and provides the historical background for directed-energy weapons. Besides giving the definitions in order to understand directed energy and directed-energy weapons clearly, particle beams will be explained in this chapter. Current applications and countries working on directed-energy weapons will also be discussed.

Chapter III explains how lasers work and function within the atmosphere. Laser types and technologies are summarized. Well-known high-energy laser weapon systems, such as ground-based lasers, airborne lasers and space-based lasers, will be explained and demonstrated with figures, as in Figure 1. As a protective technique, laser countermeasures will be reviewed.



Figure 1. Directed-Energy Weapons on Different Platforms²

Chapter IV explains the structure and characteristics of high-power microwave weapons. High-power microwave lethality and the methods used to affect targets will be explained. Furthermore, potential targets and applications of high-power microwave weapons will be examined. This chapter also illustrates and discusses the relationship between electronic warfare and high-power microwave weapons.

Chapter V analyzes and compares the advantages and disadvantages of the two basic forms (laser and high-power microwave) of directed-energy weapons.

Chapter VI illustrates present and near future directed-energy devices from different countries in this area, along with figures.

Chapter VII answers the primary research question of how can the Turkish Armed Forces use directed-energy weapons to improve its combat capabilities in the twenty-first century.

Chapter VIII presents the conclusion and the recommendation of the study. Figure 2 shows the outline of the thesis.

² From Thompson and Goure 2003, 48.

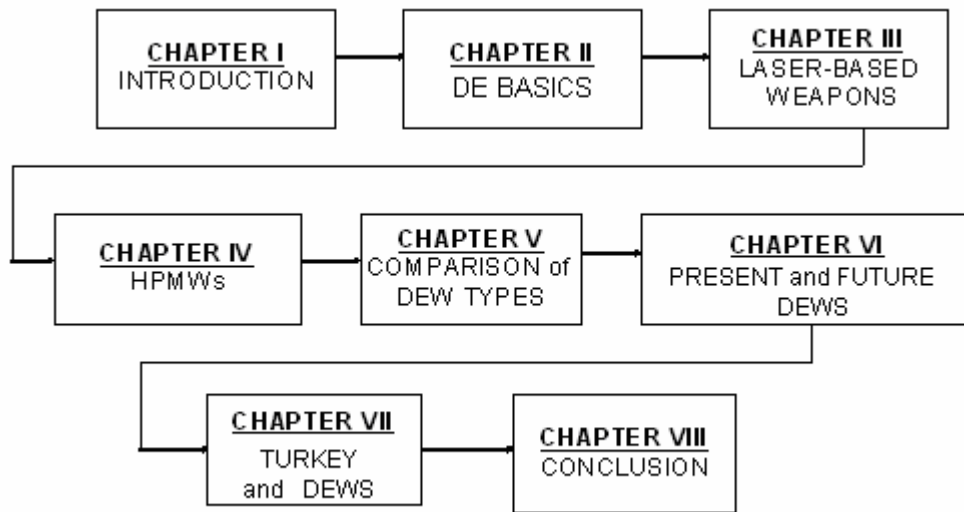


Figure 2. Thesis Roadmap

THIS PAGE INTENTIONALLY LEFT BLANK

II. TERMINOLOGY AND DE WEAPONRY BASICS

It is still a matter of wonder how the Martians are able to slay men so swiftly and so silently. Many think that in some way they are able to generate an intense heat in a chamber of practically absolute non-conductivity. This intense heat they project in a parallel beam against any object they choose, by means of a polished parabolic mirror of unknown composition, much as the parabolic mirror of a lighthouse projects a beam of light. But no one has absolutely proved these details. However, it is done, it is certain that a beam of heat is the essence of the matter. Heat, and invisible, instead of visible, light. Whatever is combustible flashes into flame at its touch, lead runs like water, it softens iron, cracks and melts glass, and when it falls upon water, incontinently that explodes into steam.³

A. BACKGROUND

Archimedes is said to have invented burning mirrors, turning them on ships to set them afire and helping defend his hometown of Syracuse when the Romans invaded in 214 BC.⁴ In the fifteenth century this scenario was painted by an Italian painter as shown in Figure 3. Later, in 1898 H.G. Wells used a directed-energy death-ray or heat-ray in his novel “The War of the Worlds.”



Figure 3. Archimedes’s Burning Mirror⁵

³ Wells 1898, 35.

⁴ Sforza and Zmuda 2003, 1.

⁵ From Beason 2005.

In 1861, Scottish physicist James Clark Maxwell proposed that the oscillation of an electric charge produced an electromagnetic field moving outward from its source at a constant speed, which demonstrated the connection between magnetism and electricity. A German scientist, Heinrich Rudolf Hertz, considered an electromagnetic wave to be a potential source that could be used to provide power and verified Maxwell's ideas. Maxwell's four equations describe the propagation and interaction known as electromagnetic radiation. An electromagnetic spectrum shows the different kinds of radiation, arranging them according to their frequency or wavelength, and includes radio waves, microwaves, infrared, visible and ultraviolet light, x-rays and gamma rays.

Prior to and during World War II, Albert Einstein's studies showed that atoms could absorb and emit radiation spontaneously, and in certain excited states, emit radiation. This discovery, which he named stimulated emission of radiation, allowed other scientists to advance on the path toward the laser (Light Amplification by the Stimulated Emission of Radiation). Einstein's discovery provided the basic foundation for the development of lasers, and this discovery opened an extensive array of military applications.

Before World War II, it was assumed that electromagnetic waves could be used to destroy airplanes. As a coincidental result of further studies, the radio for detection and ranging (radar) was discovered.⁶

The modern quest for effectively using electromagnetic energy for defense applications probably began around 1935, when the British Admiralty is said to have petitioned Sir Robert Watson-Watt to investigate the possibility of using a radar-like device to boil a pilot's blood.⁷ Early in World War II, British radar experts came up with an idea of developing a "super- interferometer," which could transmit microwaves intense enough to destroy enemy electronic networks.⁸

⁶ Guoqi Ni, Benqing Gao, and Junwei Lu 2005, 1.

⁷ Sforza and Zmuda 2003, 1.

⁸ National Air Intelligence Center Wright-Patterson AFB OH, Li, and Wang 1996, 3.

The first ruby solid-state laser was developed in 1960 at the Hughes Aircraft Corporation laboratory in California. Since its first invention, the laser has proven to be an extremely useful device for the military.

During the same time, high-power microwave technology has progressed. Soviet Union scientists were probably the first to successfully develop an HPM weapon, and were far ahead of other countries on the research of the source of HPMs. In 1979, they achieved a breakthrough in manufacturing an experimental gigawatt-level microwave emission triode, a device critical to controlling the extremely high power levels needed in microwave beam technology. Before its collapse, the Soviet Union had a large and diverse radio frequency (RF) weapons program and remnants of this work continue today within former Soviet countries.⁹ However, the U.S. has caught up and now leads all competition in this field.

In the 1980s, directed-energy (DE) weapons became more attractive for countering intercontinental ballistic missiles, with their lethal power projected against distant targets at nearly instantaneous speeds, and most importantly, by them not being adversely affected by gravity or atmospheric drag. The aim was to intercept and destroy strategic ballistic missiles before they reached their targets. This was not possible with the properties and state of kinetic energy weapons.

Every year seemed to bring important inventions in this field. In the last two decades, the capacity of these weapons has been proven. After years of investment, high-energy laser (HEL) weapons and RF weapons have reached laboratory maturity and are ready for military use. The coming era will witness these weapons in the theaters of war.

B. BASIC PRINCIPLES FOR DIRECTED ENERGY WEAPONS

For the purposes of this paper, the technical details of directed-energy (DE) weapons would add little value, but terminology is important to an understanding of how lasers and microwaves are different parts of essentially the same thing.

⁹ Air War College Maxwell AFB AL Brunderman 1999, 8.

Directed-energy weapons irradiate the target with electromagnetic energy. This makes these devices unique in the field of military weapons.

Electromagnetic energy is referred to as an electromagnetic wave because this energy repeats itself in a predictable manner over time and shares the same propagation properties as light. The time for a periodic signal to repeat itself is known as the period of the wave and the inversion of a wave's period is known as its frequency ($T = 1/\nu$). Frequency is measured as the number of vibrations per second and expressed in Hertz (Hz) in honor of Heinrich Rudolf Hertz. By common convention, wavelength, period, frequency, and the speed of light are denoted by the symbols λ , T , ν , and c respectively.¹⁰ The speed of light is a constant, and in a vacuum, it *always* travels at a speed of 299,792,458 meters per second, no matter how its speed is measured. Mathematically, the relationship among these quantities is

$$\lambda = \frac{c}{\nu} \tag{2.1}$$

or with the period

$$\lambda = c \cdot T \tag{2.2}$$

Consequently, if the wavelength is known, frequency or period can be determined.

Figure 4 shows the relationship between frequency and wavelength.

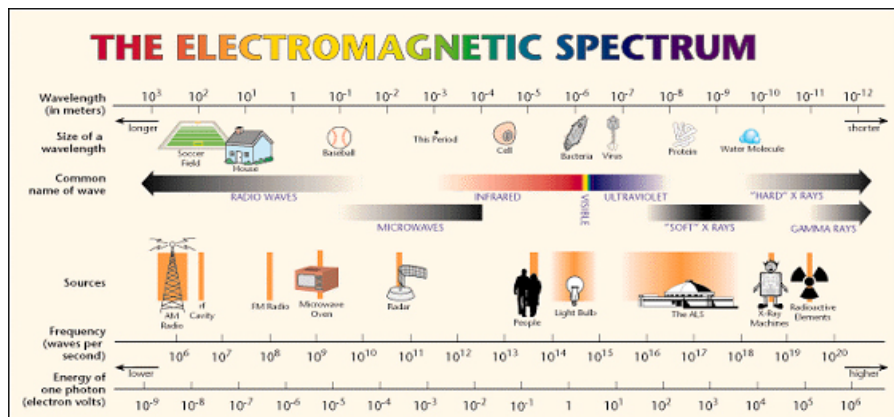


Figure 4. Electromagnetic Spectrum¹¹

¹⁰ Nielsen and National Defense University Press 1994, 83.

¹¹ From NASA 2006.

Although electricity and magnetism can be described as waves, another equally correct interpretation is to describe them as tiny, quantized packets of energy known as photons. The only difference between lasers and high-power microwaves, which are both made up of photons, is their energy level. In units of joules (named after James Prescott Joule) photon energy (E) is a function of frequency, and mathematically the relationship among these quantities is

$$E = h \cdot \nu \quad (2.3)$$

$$E = \frac{h \cdot c}{\lambda} \quad (2.4)$$

where h is a Planck's constant (named after Max Karl Planck) equal to $6,625 \times 10^{-34}$ Joule seconds.¹²

The basic function of a directed-energy weapon is to place sufficient fluence on a target (joules per square centimeter J/cm²) or irradiance (watts per square centimeter watts/cm²) to inflict lethal damage or disruption to critical components.¹³ The energy delivered to a target is determined by the following equation:

$$F = \frac{P \cdot \Delta t \cdot L}{A} \quad (2.5)$$

Fluence (F) is the energy deposited in joules per square centimeter (J/cm²); P is the directed-energy weapon's output power in watts (or Joules per second); Δt is the duration of the directed-energy weapons pulse in seconds; L is a dimensionless transmission number which delineates the percentage of the directed-energy weapons output that actually reaches the target (often called the Strehl number); and A is the DE weapon's effective spot size on the target. For example, to destroy soft targets (i.e., fabrics, plastics, etc...) approximately 1000 J/cm² are required. Extremely hard targets such as tanks might require 100,000 J/cm².¹⁴ Once the target has absorbed this energy, it will begin to heat up.

¹² Beason 2005, 28.

¹³ Scientific Advisory Board (Air Force) Washington DC 1995, vii.

¹⁴ Geis and Air University (U.S.). Center for Strategy and Technology 2003, 5.

Overall, directed energy and directed-energy weapons are a part of the electromagnetic spectrum, where microwaves have significantly longer wavelengths with lower frequencies than lasers. With their adjustable power and fluence capacity, instead of permanent hard-kill damage, directed-energy weapons are the new threat to highly sophisticated military systems.

C. **WHAT IS DIRECTED ENERGY (DE) AND DIRECTED-ENERGY WEAPONS?**

1. **Key Definitions**

Understanding the following important terms helps to better discuss the issues within later chapters.

Directed Energy (DE): An umbrella term covering technologies that relate to the production of a beam of concentrated electromagnetic energy or atomic or subatomic particles (Joint Publication 1-02, 161).

Directed-Energy Device: A system using directed energy primarily for a purpose other than as a weapon. Directed-energy devices may produce effects that could allow the device to be used as a weapon against certain threats; for example, laser rangefinders and designators used against sensors that are sensitive to light (Joint Publication 1-02, 161).

Directed-Energy Warfare: Military action involving the use of directed-energy weapons, devices, and countermeasures to either cause direct damage or destruction of enemy equipment, facilities, and personnel, or to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum through damage, destruction, and disruption. It also includes actions taken to protect friendly equipment, facilities, and personnel, as well as retain friendly use of the electromagnetic spectrum (Joint Publication 1-02, 161).

Directed-Energy Weapon: A system using directed energy primarily as a direct means to damage or destroy enemy equipment, facilities, and personnel (Joint Publication

1-02, 162). DEWs are a class of weapons whose intent is to disrupt, disable, and/or destroy an adversary's device or system by means of some intense electromagnetic (EM) environment.¹⁵

2. Directed-Energy Weapon Systems

Directed-energy weapons can be divided into the following three categories;

- Lasers, which excite atoms to release photons in powerful bursts of coherent light
- High-power microwave (HPM)/radio frequency (RF) weapons, which radiate electromagnetic energy in the high RF spectrum
- Particle beam devices, which use large numbers of atomic or sub-atomic particles moving at relativistic velocities approaching that of light

a. Particle Beam Dilemma

Particle beam weapons are the least mature of the three directed-energy weapon technologies and receive by far the least amount of research effort. Actually, since they are almost only capable of hard-kills and deliver kinetic energy into the target's atomic structure and they do not direct electromagnetic waves like lasers or high-power microwaves, particle beam weapons are not true directed-energy weapons.

There are two types of particle beam weapons: charged-particle beam weapons and neutral-particle beam weapons. A charged-particle beam (CPB) is made up of particles such as electrons, protons or heavy ions which possess an electrical charge. A neutral-particle beam (NPB) is made up of particles such as atomic hydrogen, deuterium or tritium that are electrically neutral. Neutral-particle beams interact very strongly with matter, therefore interactions with intervening gas makes the propagation of NPB through the atmosphere impractical. They are also limited to altitudes above 100 km. Charged-particle beams propagate only in the atmosphere (endoatmospheric) at altitudes less than about 200 km.

¹⁵ Naval Air Warfare Center Aircraft Div Frazier 2000, 5.

To form a NPB, hydrogen or deuterium gas is subjected to an enormous electrical charge that ionizes the gas molecules, and the ions are then accelerated down a long vacuum tunnel by an electric field of hundreds of megavolts. At the end of the tunnel, electrons are stripped from the ions. This results in a beam of neutral particles that shoots toward the target. ¹⁶

NPB weapons deliver kinetic energy into the target’s atomic structure. At low power, this kinetic energy produces electronic upset that disrupts the electronic circuits; at higher power, this produces burnout damage, which destroys sensitive electronics.

Table 1 shows the advantages and disadvantages of the particle beam weapons.

Advantages and Disadvantages of PB Weapons	Advantages	Disadvantages
	All weather capability	Altitude limitations
	Beam penetration	Complicated beam control
	Beam velocity	Huge power supply
	Rapid aim capability	Line-of-sight (LOS) device
		Sensitive targeting information
		Size and weight Problems

Table 1. Advantages and Disadvantages of PB Weapons

¹⁶ Bolkcom and Tatman 1997, 7.

Due to the disadvantages shown in Table 1, such as weight, size, and power challenges, particle-beam weapons are not considered as feasible weapons in the coming decades. Today, and in the decades to come, directed energy is generally focused on lasers and microwaves. The next two chapters will explain and illustrate these two categories of directed-energy weapons in detail.

b. Developments and Current Applications

In recent years, technological developments in microelectronics have made integrated circuits and super high-speed circuitry widely used in today's high precision and extremely accurate weapons systems. These systems produce sophisticated, smart, stealthy, compact and intelligent weapons.

Since kinetic energy weapons are no longer capable of fully dealing with these types of complex electronic equipment and advanced technologies, it is necessary to develop a new generation of weapons. This emergence has been driven by or affected by at least the following three factors:

- Increased application of automated electronic systems in military and civilian operations,
- Increased use of the electromagnetic spectrum,
- After more than twenty years of effort, an understanding of the susceptibilities of both military and commercial systems to directed-energy weapons is maturing.¹⁷

Major innovations have been made in the form of improved laser materials, high-power microwave sources, antennas, sensors, optical materials, and many engineering areas related to directed-energy weapons. The technology needed to implement these weapons in a compact size for integration on combat platforms was absent at the end of the last century, but directed-energy weapons technology has advanced vastly and is now maturing rapidly.¹⁸

¹⁷ Sforza and Zmuda 2003, 49.

¹⁸ Scientific Advisory Board (Air Force) Washington DC 1995, v.

Different countries have focused on the investigation of directed-energy weapons. In reviewing the published literature, the United States is clearly the leader in this science, with China, Russia, Ukraine, Germany, the United Kingdom, Israel, Australia, and France advancing in the field, while Japan, South Korea, Sweden, Taiwan, Pakistan, and India are emerging powers.^{19 20 21}

Table 2 (which was derived from the three previous reference sources) identifies the countries that are investigating, developing, or producing directed-energy weapons under three development levels: major, medium-scale, and emerging.

Development Level	Countries
Major	United States
Medium-Scale	China, Germany, France, United Kingdom, Israel, Australia, Ukraine, Russia
Emerging	Japan, South Korea, Sweden, Taiwan, Pakistan, India

Table 2. Directed-Energy Weapon Developing Countries

The significance of directed-energy weapons is that they provide a range of strategic and operational capabilities in both offensive and defensive military operations. Basic strategic and operational offensive applications are:

- Suppression of enemy air defense (SEAD)
- Attack against ground, air and maritime targets
- Electronic suppression and disablement of command, control, communications, computers, and intelligence (C4I) systems
- Close air support (CAS)

¹⁹ Air War College Maxwell AFB AL Brunderman 1999, 23.

²⁰ United States. Congress. Joint Economic Committee 1998.

²¹ Sforza and Zmuda 2003, 49.

- Battlefield air interdiction
- Space control and anti-satellite operations
- Suppressing or damaging visible, infrared, and microwave sensors
- Asymmetric strikes
- Dispersion of crowds, rioters (non-lethal anti-personnel attacks)
- Speedboat pursuit

Basic strategic and operational defensive applications are:

- Ballistic missile (BM) and surface-to-air missile defense
- Counter-artillery and rockets
- Air defense
- Counter-electronics against targeting and sensor systems
- Fleet defense
- Aircraft self-protection
- Protection of armored vehicles
- Neutralization of explosive traps and minefield cleaning
- Critical infrastructure protection
- Stopping of motor vehicles
- Surveillance of coastal waters

The host platforms can be ships, large or tactical aircraft that include helicopters, ground vehicles, ground bases and spacecraft. Directed-energy weapons have passed the stages of laboratory prototypes and even trial production for some applications. There is no doubt that they will become a major force multiplier due to their significant advantages over traditional kinetic weapons (see Table 3).

D. WHY DIRECTED-ENERGY WEAPONS?

To reach deployment, a new weapon system must either show significant capability or cost advantages over existing systems or address a priority requirement that cannot be met by incremental improvements to an existing system.²²

²² National Defense University Washington DC Center for Technology and National Security Policy and Zimet 2002, 3.

1. Advantages of Directed-Energy Weapons

There are several reasons for the growing interest in directed-energy weapons. The attraction of the military to these weapons is clear when considering the unique properties they bring to the strategic, operational, and tactical battlefield.

The first and most obvious advantage is that directed-energy weapons deliver lethal energy at the speed of light. This significant advantage enables instant reaction to fast, highly maneuverable targets. That means many of the problems associated with aiming and discharging existing weapons are effectively eliminated, because virtually no time elapses between firing a directed-energy weapon and its impact on the target.²³

Avoidance of collateral damage or adjustable energy is the second advantage of directed-energy weapons. Today's war mentality prefers the option to inflict non-lethal attacks prior to the use of lethal force. In contrast to kinetic and chemical weapons that might have devastating and unintended collateral effects, flexible engagement levels dependent upon the transmitted power and irradiation time makes the DE weapons unique and valuable.

A third important aspect of the directed-energy weapons is that they are extremely precise. Directed-energy weapons allow the attackers employing them to select the specific part of a fast-moving target that they wish to strike. In fact, with sufficient tracking and characterization, this unprecedented precision will accomplish surgical strikes with no collateral damage or fratricidal effects on friendly forces.²⁴

A fourth important feature of directed-energy weapons is their freedom from gravitational limits. Directed-energy beams are essentially immune to gravity due to their lack of mass, which also frees them from the kinematic and aerodynamic constraints that limit traditional weapons.²⁵

²³ Thompson 2002.

²⁴ Thompson and Goure 2003, 5.

²⁵ Spencer, Carafano, and Heritage Foundation (Washington, D.C.) 2004, 4.

A fifth key feature of the directed-energy weapons is that they are area weapons that can engage multiple targets within a hostile area with minimal prior information on threat characteristics. They can affect all targets in that area and can be rapidly retargeted to provide protection in several directions.²⁶

A sixth directed-energy weapon advantage is their deep magazines, which need only fuel and battery chargers, as well as low operating costs. For example, a tactical high-energy laser shot is estimated to cost about \$8,000, whereas firing a Patriot (PAC-3) missile costs \$3.8 million; an AIM-7 Sparrow missile costs approximately \$125,000; and a Tomahawk cruise missile costs roughly \$600,000. Although the beam-generating system may be expensive to build and maintain, the price of engagements is minimal because the system expends only energy.²⁷

A final unique characteristic of directed-energy weapon is their all-weather attack capability to reach virtually untouchable targets. They are unaffected by weather and can penetrate deep into the earth, enabling attacks on buried bunkers, as well as targets in space.²⁸

2. Limitations and Problems with Directed-Energy Weapons

Directed-energy weapons offer new ways of fighting that will change current doctrines, tactics, and strategies. As with the introduction of any new systems, directed-energy weapons also have limitations and drawbacks that will tend to mitigate their fast growth.

The first problem facing directed energy is operating under real-world conditions. While a new technology like directed-energy weapons are being transitioned out of the laboratory to the real battlegrounds, there might be relatively simple countermeasures that can restrict the effectiveness of directed-energy weapons that have been overlooked by those working in the laboratories and that may be relatively simple to implement.

²⁶ Air Univ Press Maxwell AFB AL and Walling 2000, 14.

²⁷ Spencer, Carafano, and Heritage Foundation (Washington, D.C.) 2004, 4.

²⁸ Naval War Coll Newport RI Joint Military Operations DEPT and Jersey 2003.

Fratricide is probably the second biggest drawback in using this technology. Some directed-energy weapons are not very discriminating. Radiating at an enemy will not only affect the target system, but also anything else in the beam's path. Any friendly forces within the footprint of the beam will be at significant risk.²⁹

A third great limitation of some types of directed-energy weapons is that they are highly susceptible to degradation by the atmosphere in the presence of obscurants, whether natural or manufactured, such as dust, clouds, rain and smoke.

Another potential limitation is damage or performance-degrading assessments. Due to little directly-observable feedback from the target as to the effects of a hit, one may not know positively if a directed-energy weapon has been successful.³⁰

The last concern regarding directed-energy weapons is related to their usage against allied forces. High-powered microwave weapons may be relatively simple for terrorist forces (and others) to acquire and use in an asymmetric manner. In order to counter this, all electronic platforms and weapon systems must be hardened and shielded. Table 3 summarizes the advantages and disadvantages of directed-energy weapons.

Like their strengths, directed-energy weapons weaknesses differ from those encountered by current technologies and contribute to the impression that these weapons are very different. Like all other weapons, directed-energy weapons have limitations and problems. However, their potential influence on the current battlefield strategies far outweighs their limitations.

²⁹ Air War Coll Maxwell AFB AL and Brunderman 1999, 20.

³⁰ Bayer 1986, 46.

Advantages and Disadvantages of Directed Energy Weapons	Advantages	Disadvantages
	Adjustable damage capacity	Atmospheric obscurants
	Attack at the speed-of-light	Countermeasure problems
	Deep penetration into hidden targets	Danger of fratricide
	Freedom from gravity	Difficult damage assessment
	Low operational cost	Relatively new technology
	Nearly unlimited magazine	
	Precise targeting	
	Rapid engagement of different targets	

Table 3. Advantages and Disadvantages of DE weapons

E. EFFECTS ON TARGETS

There are various means of affecting targets using directed-energy weapons. The following discussion includes some of the commonly used terms to discuss these various means.

Deny is a temporary action, and it is defined as the ability to eliminate the enemy's operational capacity without inflicting harm, whereas degrade means to achieve this impact with minimal injury on the enemy systems. Deny and degrade are both similar in that they both are non-permanent and affected systems will return to normal operation within a period of time.

The concept of damage involves moderate injury to incapacitate the enemy systems for a certain period of time. This action may be permanent, depending upon the severity of the attack.

Finally, destroy reflects the idea of permanent injury on the enemy systems which would be require total replacement.³¹

In principle, depending on some conditions such as distance between the weapon and target, generated power, and target-hardening level, directed-energy weapons affect their targets through either a soft-kill or a hard-kill.

1. Soft-Kill

A soft-kill is achieved when the effects of a directed-energy weapon stops operation of the target system temporarily. As is understood from their definitions above, deny, degrade, and some damage effects are the practical methods of a soft-kill mechanism. Disrupting the electronics of a guided missile, causing it to miss its target, or suppressing or damaging visible, infrared, and microwave sensors might be given as examples of a soft-kill. The results are a temporary loss of function, but they can seriously compromise operational success.

A soft-kill by directed-energy weapons against human targets means painful stimulation of human nerves, hearing or skin. After brain tissue absorbs an electromagnetic pulse, it slightly but rapidly expands and produces a supersonic wave which is received by the inner ear. If this pulse of energy exceeds a certain threshold and the supersonic wave is too strong, the human ear will not function.³² The Active Denial System, discussed in a later chapter, is an example of a directed-energy weapon which uses a soft-kill mechanism by heating up the skin's surface.

³¹ Air Univ Press Maxwell AFB AL and Walling 2000, 28.

³² National Air Intelligence Center Wright-Patterson AFB Oh and Zhihao 1996, 4.

2. Hard-Kill

Like conventional weapons, directed-energy weapons can defeat their targets by causing physical damage to the structure of the targets. A hard-kill is achieved when sufficient energy is delivered into the target system, such that it is permanently damaged or destroyed.³³ Destroying a ballistic missile with an airborne laser during its boost phase by heating, melting, or vaporizing its skin is an example of a hard-kill. A hard-kill can include:

- Structural damage
- Melting of components
- Shorting out electronics
- Fusing and immobilizing moving parts

Directed-energy weapons have adjustable kill mechanisms as well as both hard-kill and soft-kill capacities, which makes them unique in comparison to kinetic energy weapons. Instead of only destroying targets, directed-energy weapons have soft-kill potential which enables temporary damage and degradation.

³³ Kopp and Pose, 5.

THIS PAGE INTENTIONALLY LEFT BLANK

III. LASER WEAPONS

Thirty years ago the vision of directed-energy weapons, using high energy lasers (HEL) and high power microwaves (HPM), was first seriously engaged by the military. Within a decade the capability of these weapons to destroy or disable targets had been proven, and numerous demonstrations of lethal effect, on increasingly difficult targets, have been carried out since then.³⁴

Albert Einstein was the first to describe the procedure that atoms could emit and absorb radiation. He later named this monumental innovation as the stimulated emission of radiation and that research led to the foundation for the development of laser systems. In stimulated emission processes, electrons stimulated by an incoming photon undergo a transition to a lower energy state. When a photon collides with an atom that is already excited, the atom releases two new outgoing photons identical to the incoming photon, at the same phase, frequency, and direction of propagation. Figure 5 shows an illustration of a stimulated emission process where E_2 has a higher energy state than E_1 .

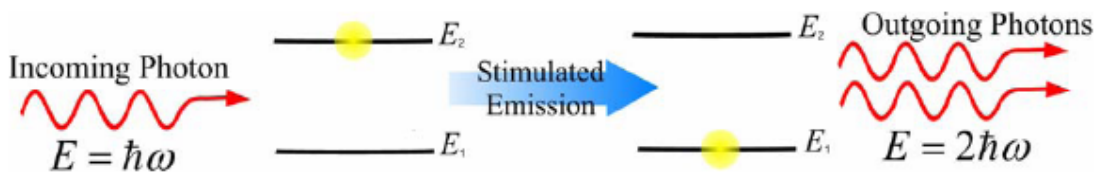


Figure 5. Stimulated Emission Process³⁵

In 1954, Charles Townes and Arthur Schawlow created the maser (Microwave Amplification by Stimulated Emission of Radiation) well before theorizing the laser. The technology of a maser is very similar to that of a laser, but differs in that it does not use visible light. The maser gave new life to the idea of stimulated emission, thus leading the way for laser technology. In 1960, while working at Hughes Research Laboratories, Theodore H. Maiman developed the ruby laser, which is considered the first successful

³⁴ Scientific Advisory Board (Air Force) Washington DC 1995, v.

³⁵ From Mansfield 2005, 53.

optical or light laser (Light Amplification by the Stimulated Emission of Radiation).³⁶ This first solid-state laser invention opened an entirely new vision for directed-energy weapons.

A. INTRODUCTION AND SCIENTIFIC BACKGROUND

1. How Laser Weapons Work

A laser is a device that produces an intense unidirectional beam of coherent light. Unlike ordinary light, as generated by the sun or a light bulb, that scatters energy in a random fashion, the laser beam is coherent and almost uniform in wavelength, and travels in a single direction. These unique characteristics of the laser beam makes it important for military applications as will be described shortly. Lasers operate in the infrared, visible and ultraviolet sub-ranges of the electromagnetic spectrum.

Lasers have at least three common components:

- A lasing medium or an amplifying medium that increases the intensity of the light beam (gas, liquid, solid, semi-conductor)
- A method of stimulation or pumping (pulse discharge, electricity, or chemical reaction)
- A resonant cavity (reflective mirrors)

Laser lethality is largely a function of the fluence delivered on a target that must in turn couple with the target and exceed some failure threshold. Fluence is directly related with beam quality and beam control, which are the key technical challenges for laser systems.

Beam quality is a measure of how effective the laser is in putting its light into a desired spot size (or area) at the target location. Once a laser beam is generated, it has to be the best possible quality so it will have the highest intensity when it reaches the distant target.³⁷

³⁶ Steward 2006, 214.

³⁷ Department of Defense Laser Master Plan 2000, 2.

Beam control is another major problem that tries to eliminate beam breakups. When laser energy is projected miles away, the beam is disrupted by the turbulent atmosphere. This is overcome by using adaptive optics that support the usage of low-power laser systems to illuminate a target. The idea behind the adaptive optics is to neutralize the adverse effect of the atmosphere, thus allowing lower-power systems.

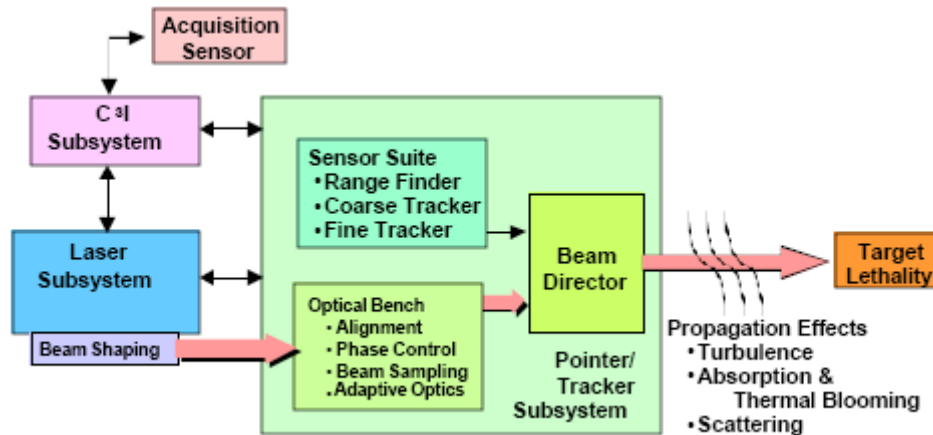


Figure 6. Schematic Diagram of Laser Weapon Systems³⁸

A basic laser system continuously locates and tracks the target with a standard rough target acquisition system. Fine target acquisition is used for the identification and tracking of targets thru an on-board active optics and electronics imaging system that delivers laser illumination to the target. After the fine target acquisition system works to lock onto and track the target in the continuous tracking mode, generation of the effective laser pulse is initiated. This pulse generated by the master oscillator is used to illuminate the target. When the laser beam is scattered by the atmosphere, the scattering radiation is reflected back and measured by the laser system so that the system can then calibrate the degree of atmospheric distortion. This return pulse contains information about the influence of atmospheric turbulence. Next, the deformation of the laser pulse generated by the atmospheric turbulence is calculated. The final stage involves sending this pulse back to the target once again, accounting for atmospheric turbulences to reconstruct the

³⁸ From Defense Science Board Washington DC, Welch, and Latham 2001, 4.

original pulse waveform and energy with the added feature of beam collimation that will focus delivered fluence on a small cross-section of the target, perhaps focusing on critical optics and electronics. Final amplification and high-output fluence level is performed by high-power laser systems before the final transmitted pulse is sent to the target with the objective of destructive effects. In order to focus the beam energy on the target at a distance of several miles the influence of the atmospheric turbulence has to be fully compensated.³⁹ A common laser weapon's work chart is showed schematically in Figure 6.

2. Propagation through the Atmosphere

The study of the propagation of laser radiation through the atmosphere is important so as to be able to identify the optimum wavelength for efficient laser weapons to reach the target with sufficient energy. Lasers require high-intensity beams to propagate long distances under a wide range of atmospheric conditions. The intensity of the beam is degraded by these atmospheric effects with the result of lost photons from the projected beam. The major atmospheric interactions considered are absorption, scattering, turbulence, and thermal blooming.

a. Absorption

Absorption is the process where the incident radiation is absorbed by the medium, which will shorten the maximum distance for fluence levels to achieve the desired effects. The primary atmospheric components that contribute to absorption are water, carbon dioxide, diatomic oxygen (O₂) and ozone. These molecules absorb the electromagnetic radiation and convert it to molecular vibration and rotation.⁴⁰

³⁹ Weise et al. 2004, 44.

⁴⁰ Weichel 1990.

There is no way to control the content of the atmosphere through which the beam is intended to propagate, therefore the best alternative is to choose a wavelength of light that is not greatly affected by this absorption process. A solution is to choose specific atmospheric “windows” where the selected laser wavelength is not greatly affected by absorption.

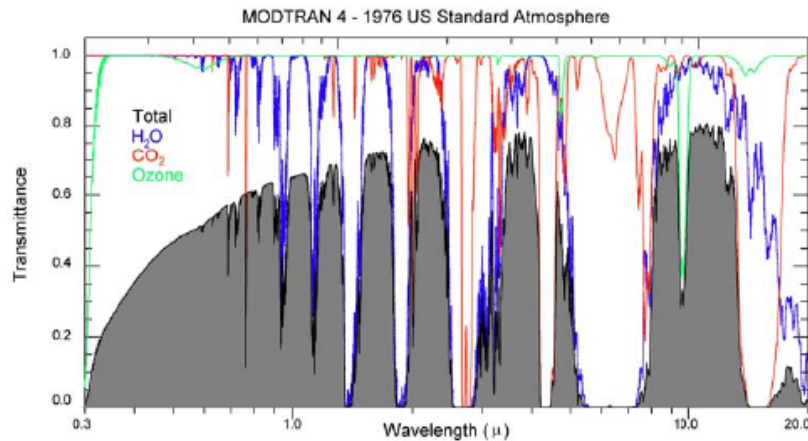


Figure 7. Atmospheric Absorption⁴¹

Figure 7 presents a graph of the transmittance (the amount of energy allowed to pass through the atmosphere) as a function of wavelength. This figure shows there are narrow absorption bands at specific frequencies over a wide range of wavelengths. Therefore, the choice of laser wavelength to ensure high transmittance is critical for laser propagation.

b. Scattering

Atmospheric scattering is another important energy loss mechanism in the propagation of a laser beam that will shorten the maximum distance for desired effects. Here, electromagnetic radiation (photons) interacts with scattering centers in the atmosphere, such as aerosols (water, sea salt, organic matter, dust, soot, urban pollutants), and the energy is redistributed in directions that do not contribute to the intended use of the laser. There are three different kinds of scattering:

⁴¹ From Olsen 2005, 65

- Rayleigh scattering
- Mie scattering
- Non-selective scattering

Rayleigh scattering (Figure 8) refers to the scattering of light off of molecules in the air. The radiation from Rayleigh scattering is emitted in all directions, causing a loss of energy in the light field as it propagates through the atmosphere.

Mie scattering (Figure 8) is the scattering type when the scattering centers are roughly comparable to the size of the incident wavelength. These types of Mie scatterers are typically suspended aerosol particles or very small droplets of water. The radiation of incident energy is again in all directions, similar to Rayleigh scattering, but Mie scattering also results in much more scattered energy being radiated in the same direction as the incident photon (see the notional figure in the center and on the right side of Figure 8).

Finally, non-selective scattering is the mechanism that results when the size of the scatterer is much larger than the wavelength. Non-selective scattering is the mechanism that describes what happens to light incident or passing through atmospheric phenomena such as fog, haze, and clouds. The term non-selective means that this type of scattering is independent of the wavelength. Non-selective scattering is very destructive as most of the incident energy is dissipated in the collisions that occur with the large mass.

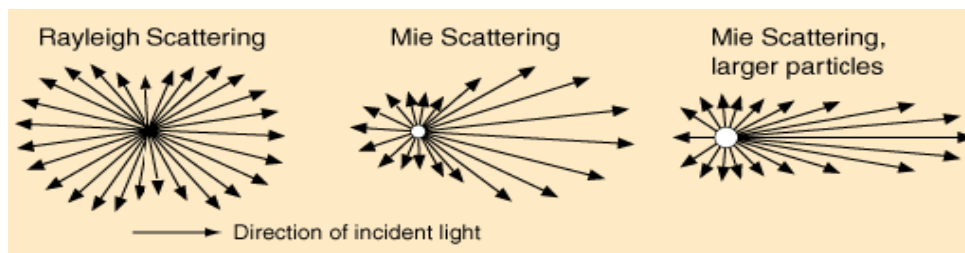


Figure 8. Rayleigh and Mie Scattering⁴²

⁴² From Niles 2005, 30.

c. Turbulence

Turbulence is another adverse atmospheric effect on laser beams, causing deformation of the beam. It is associated with temperature and density fluctuations in the atmosphere. These two fluctuations cause variations in the index of refraction of the air and cause fluctuations in the direction of the propagating light.

The beam will encounter regions of higher and lower temperature and the sizes of the regions of temperature fluctuation may be smaller than the beam itself. This will bend different portions of the beam front in diverse directions. These temperature changes and turbulence are lowest during the hours of darkness, whereas there is usually a large rise right after sunrise.⁴³

d. Thermal Blooming

Thermal blooming is distortion of a propagating beam caused by the heating of the air around it due to the high energy density of its laser beam. This nonlinear phenomenon creates plasmas in the air and causes loss of beam energy because of energy absorption.

Several environmental factors affect thermal blooming, most importantly altitude and crosswinds. The net effect of increasing the altitude of a laser platform is to lessen thermal blooming. The reason is that aerosol content of the atmosphere, and therefore the absorption of beam energy, is larger at lower altitudes. Additionally, crosswinds blowing perpendicular to the beam (including those generated by the motion of the laser platform) mitigate thermal blooming by blowing the heated, expanding gases out of the way.⁴⁴

Thermal blooming can be controlled in a variety of ways, such as reducing the intensity of the beam. However, intensity reduction will spread out the beam. Beam spreading is undesirable, and for a destructive application can be controlled by increasing the size of the beam at the director. The greatest amount of fluence on a target due to a

⁴³ Nielsen and National Defense University Press 1994, 121.

⁴⁴ Forden 1997, 45.

large beam at the director focuses the beam at the target. As the beam focuses, the local intensity (delivered fluence) increases which results in the thermal blooming threshold being exceeded. As a consequence, beam spread can be limited with sophisticated director optics, but can not be eliminated.

3. Target Interaction

The effectiveness of laser weapons basically depends on a relationship between target hardness, atmospheric distortions, wavelength, beam quality, and lasing duration. Damage capacity of a laser weapon increases when the output power of the weapon as well as dwell time is increased. On the other hand, it decreases when the wavelengths of the laser beam and the range are increased.

There are two ways that laser weapons can destroy a target: thermal kill and mechanical kill (impulse kill).

Thermal kill occurs when thermal energy directed by a laser weapon remains at the same point on a target, is absorbed by the target surface, and therefore results in Joulian heating. If the beam does not remain fixed on the same spot for long enough, a heated target's surface might cool.⁴⁵ Heating begins as soon as the laser light is absorbed at a target's surface.⁴⁶ As the laser beam intensity on the target continues to rise, the coupled effect results in melting that ends with drilling a hole through the target's surface. With enough precision and dwell time, vaporization follows melting.

Mechanical kill or "impulse kill" occurs when very intense, short laser pulses interact with a target's surface, creating a shock wave that penetrates the target, possibly causing structural collapse and destroying internal mechanical components.⁴⁷ Mechanical kill may require less energy (fluence) to damage or degrade a target's performance than thermal kill, but requires higher intensities and shorter pulse widths.⁴⁸

⁴⁵ DiMaggio 1985, 19.

⁴⁶ Nielsen and National Defense University Press 1994, 181.

⁴⁷ DiMaggio 1985, 19.

⁴⁸ Nielsen and National Defense University Press 1994, 175.

B. LASER TYPES AND TECHNOLOGIES

Although most lasers may seem to be similar in appearance, they are very different with regard to performance parameters and properties. Among these types of variation, it is the intended target and operating environment that largely determines the required performance properties such as energy or wavelength.

Lasers are often differentiated by the kind of lasing medium, which can be gas, liquid, semiconductor, or solid state. Three major kinds of laser appear to have applications for directed energy weapons: chemical, electric (solid-state), and free-electron lasers.

1. Chemical Lasers

Chemical lasers use chemical reactions to excite atoms and provide the pumping energy. The lasing molecules in a chemical laser obtain their energy from the process that creates them. Chemical lasers use the reactions of gases or liquids to create the excited energy states necessary for laser emission.⁴⁹ They offer high energy levels in the megawatt range, but their military applications require large platforms to haul the large quantity of chemicals, in terms of volume, weight and fuel logistical problems. Potential chemical laser types are hydrogen fluoride (HF), deuterium fluoride (DF), and chemical oxygen iodine lasers (COIL).

a. Hydrogen Fluoride

In a hydrogen fluoride (HF) chemical laser, atoms of hydrogen (H) combine with the atoms of fluoride (F) to produce an excited molecule of hydrogen fluoride (HF). When this excited HF molecule returns to its normal stable state in the laser cavity, it emits light at a wavelength of about 2.7 microns, which will not propagate well in the earth's atmosphere but is useful for applications in space.⁵⁰

⁴⁹ Air University Press Maxwell AFB AL and McCarthy 2000, 16.

⁵⁰ Schroerer 1987, 13.

b. Deuterium Fluoride

The deuterium fluoride (DF) laser operates on the same basic principles as the hydrogen fluoride laser. Rather than molecular hydrogen, deuterium, which contains a neutron as well as a proton in its nucleus, reacts with atomic fluorine. Since the deuterium atoms have a greater mass than hydrogen atoms, they produce a longer wavelength laser light, in approximately the 3.8 microns region, where the atmosphere is more transparent.

Mid-Infrared Advanced Chemical Laser (MIRACL) is an example deuterium fluoride device that has successfully downed target drones and missiles via the use of a megawatt-class beam operating at a wavelength of 3,800 nanometers and with a power output in excess of 1 megawatt.^{51 52 53}

c. Chemical Oxygen Iodine

Reactants for this type of laser include hydrogen peroxide, chlorine, and iodine. The lasing action is achieved by a chemical reaction between chlorine and hydrogen peroxide that produces oxygen molecules in an electronically excited state. Excited oxygen molecules transfer their energy to iodine atoms by collisions, which raise the iodine atoms to an excited state. The excited iodine atom is responsible for lasing at a wavelength of 1.3 microns, which is shorter than the output of either the hydrogen fluoride or deuterium fluoride laser.⁵⁴

This shorter wavelength allows the focusing of the beam to the target with smaller optics than the longer wavelength systems. The shorter wavelength also assures that diffraction will not limit the weapon's range, especially at longer ranges. Finally, a

⁵¹ Air University Press Maxwell AFB AL and McCarthy 2000, 18.

⁵² Schroerer 1987, 14.

⁵³ Thompson and Goure 2003, 7.

⁵⁴ Possel and Air University (U.S.). Center for Strategy and Technology 1998, 8.

chemical oxygen iodine laser (COIL) is subjected to significantly less atmospheric absorption than the hydrogen fluoride laser, which maximizes the fluence distance of the system.

2. Solid-State Lasers

Solid-state lasers use a non-conductive glass or crystalline material that is doped with a species, such as neodymium or erbium, as the active medium. The prime example of such a solid-state laser would be the original ruby laser.⁵⁵

A solid-state laser relies only on material properties and prime (electrical) power and does not require flowing exotic gases or relativistic electron beams. For this reason, the system could be inherently smaller and less complex than other laser types. Solid-state lasers also operate at about 1.06 microns, lower wavelengths than the COIL, which further simplifies the optics.⁵⁶

Although solid-state lasers have fine beam wavelengths, their largest challenge is power levels because of heat removal due to output efficiency limitations. The wasted heat in the laser medium increases the temperature and degrades the beam quality.

3. Free-Electron Laser

Free-electron lasers (FEL) generate streams of electrons from superconducting radio frequency accelerators to create a tunable beam. This represents a unique way of creating laser radiation without the use of chemicals, crystals, or any of the traditional ways of generating laser beams.

Although they are currently limited to implementations at the kilowatt level and have the most complexity of the three laser alternatives, free-electron lasers are certainly the most attractive option for their potential to have adjustable, transmissible wavelengths, and for their potential cost effectiveness.

⁵⁵ Air University Press Maxwell AFB AL and McCarthy 2000, 16.

⁵⁶ National Defense University Washington DC Center for Technology and National Security Policy and Zimet 2002, 4.

Table 4 summaries and compares there major types of laser.

Type of Laser	Wavelength	Advantages	Disadvantages
HF	2.7-3.3 μm	<ul style="list-style-type: none"> • Most developed • Megawatt level 	<ul style="list-style-type: none"> • Size and weight
DF	3.5-4.2 μm		<ul style="list-style-type: none"> • Safety requirements
COIL	1.3 μm		<ul style="list-style-type: none"> • Sophisticated logistics
SSL	1.06 μm	<ul style="list-style-type: none"> • Less complex • Compact • Less sensitive to shock • Low electric energy requirements • High efficiency 	<ul style="list-style-type: none"> • Cooling problem • Kilowatt level
FEL	Tunable	<ul style="list-style-type: none"> • Selectable wavelength 	<ul style="list-style-type: none"> • Most complex • Kilowatt-level limits • Large systems

Table 4. Summary and Comparison of Laser Types

C. TACTICAL AND STRATEGIC LASER WEAPONS

Due to the unique nature of its coherent and intense light, lasers could easily be used as directed-energy weapons. Although rather ambiguous, laser weapons can be divided into three categories according to their power and energy levels, or the sensitivity of the target.

Low-energy laser weapons, which are lower than 1 kW, are basically used as anti-eye or anti-sensor systems. Eye damage can take various forms, depending on the wavelength used. Using a wavelength above 3 μm can damage the cornea in the human eye.⁵⁷ If sufficient power is used, such a burn can make the cornea opaque and lead to

⁵⁷ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 21-24.

very painful injuries. In their anti-sensor role, low-energy lasers aim at either knocking out enemy photoelectric sensors and optical equipment for a certain time or purely destroying them.⁵⁸ Attack on a sensor or optical equipment works well when the wavelength of the low-energy laser is within the operating wavelength range of these systems.

The purpose of medium-energy laser weapons is the permanent destruction of optical and optoelectronic devices of ground, near-ground and air targets. These devices are valuable system components, for example, in the fire control systems of helicopters and tanks or the sensor heads of drones and missiles. Destroying these devices at relevant distances, including out-of-band and out-of-field-of-view effects, will at least result in a precision loss or mission kill.⁵⁹

The main anticipated use of high-energy laser weapons is destruction of material structure for air defense to destroy incoming munitions or aircraft before they reach their targets. Although many of these laser weapons exist, only a few of them can reach high enough energy levels. These would be the chemical lasers, solid-state lasers, and free-electron lasers. Within the next section three military applications and key features for high-energy laser weapons are generally described. These are the ground-based laser (GBL), the airborne laser (ABL), and the space-based laser (SBL).

Laser classification according to energy level is given in Figure 9.

⁵⁸ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 25.

⁵⁹ Weise et al. 2004, 484.

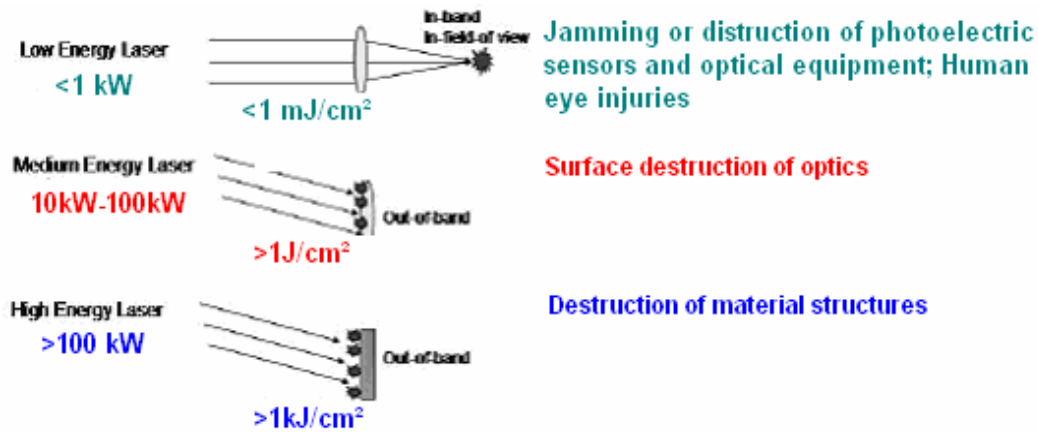


Figure 9. Energy Level Classification of Laser Weapons⁶⁰

1. Ground-Based Lasers

a. Tactical High-Energy Laser

The tactical high-energy laser (THEL) is a ground-based laser which uses a deuterium fluoride (DF) chemical laser and is designed for air-defense and the destruction of short-range rockets and artillery rounds at ranges of about ten kilometers. System development was initiated in 1996 and the first in-flight destruction of a live artillery rocket was achieved in June 2000.⁶¹

The tactical high-energy laser (THEL) system includes three principal subsystems:

- A command, control, communications, and intelligence (C3I) subsystem, which controls the fire control radar (FCR) as well as all laser subsystems (LS) and pointer-tracker subsystems (PTS). It manages the complete engagement, searching, the extended treat zone, detecting and classifying of aerial targets within its range, irradiating and destroying the designated targets, and providing kill assessment as well.⁶²
- A laser subsystem (LS), which uses a deuterium fluoride (DF) gas laser with good atmospheric propagation characteristics, generates the high-power laser beam for destruction of the target.

⁶⁰ After Weise et al. 2004, 484.

⁶¹ Horkovich 2006, 843-859.

⁶² Sforza and Zmuda 2003, 37.

- A pointer-tracker subsystem (PTS), which optically tracks the target with sufficient precision to direct the lethal laser beam on the desired aim point and keeps the beam there until the target is destroyed (Figure 10).

b. Mobile Tactical High-Energy Laser

The mobile tactical high-energy laser (MTHEL) is another ground-based laser weapon system which uses a deuterium fluoride (DF) chemical laser, similar to the THEL, but with capabilities that go well beyond those of the THEL.

The proposal to create a MTHEL system addresses one significant drawback of the THEL - mobility. Besides mobility, the MTHEL will extend the capability of the THEL by making the system lighter and smaller.

Once the development of the MTHEL is completed, the system could be employed against a range of air-breathing targets such as ground attack aircraft, helicopters, unmanned aerial vehicles (UAVs), short-range ballistic missiles, and cruise missiles.

Figure 10 shows the tactical high-energy laser (THEL) and mobile tactical high-energy laser (MTHEL) together.

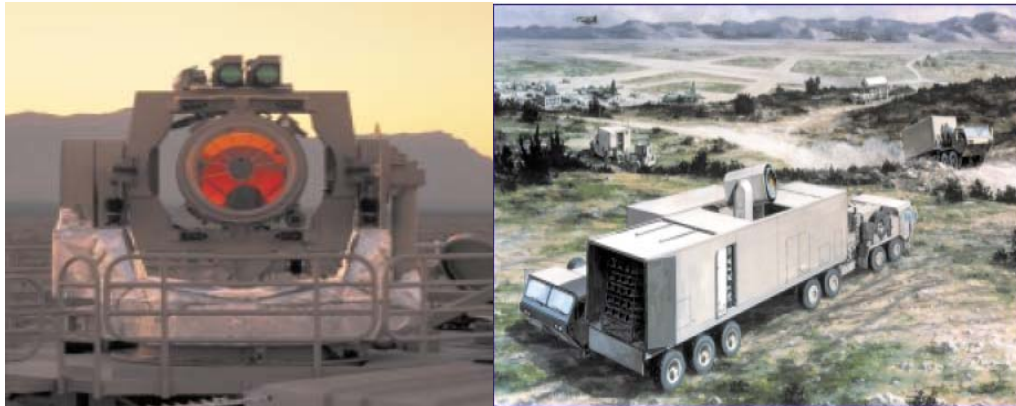


Figure 10. Ground-Based Laser Concept⁶³

⁶³ After Thompson and Goure 2003, 10.

2. Airborne Lasers

Currently, there are two airborne laser weapons under development: the airborne laser (ABL) for boost phase missile defense and a new program, namely the advanced tactical laser (ATL), for air-to-ground operations.

a. Airborne Laser (ABL)

The airborne laser (ABL) is a multi-megawatt (MW) chemical oxygen-iodine laser (COIL) weapon on a Boeing 747 platform. The ABL, cruising at 40,000 feet, engages and destroys ballistic missiles during the first phase of their flight at a 500-700 kilometers standoff range.

The boost phase is the first stage in a ballistic trajectory, when missiles present large and vulnerable targets that can be easily tracked. During the boost phase, infrared (IR) emission from the missile is so intense and almost impossible to hide. An attack during the boost phase can destroy a missile, carrying chemical or biological agents, over enemy territory before any smaller warheads are released.

The ABL is arguably the most expensive military hardware to ever be flown in an aircraft, with its 1.5-meter-diameter telescope mounted on the nose of the aircraft.⁶⁴ It has six onboard infrared sensors that provide 360 degrees of coverage to detect missile boost motor plumes.

The airborne laser (Figure 11) is an extremely complex system consisting of four main assemblies:

- The turret assembly, which locates and tracks targets and propagates the tracking illumination laser (TILL) beam.
- The beam control assembly, which acquires the target, aligns the laser, and compensates for atmospheric distortion with a beacon illuminator laser (BILL).
- The battle management and communications, command, control and intelligence subsystem, which provides engagement and fire control.

⁶⁴ National Defense University Washington DC Center For Technology And National Security Policy and Zimet 2002, 5.

- The laser assembly, which provides chemical oxygen iodine laser (COIL) power.^{65 66 67}

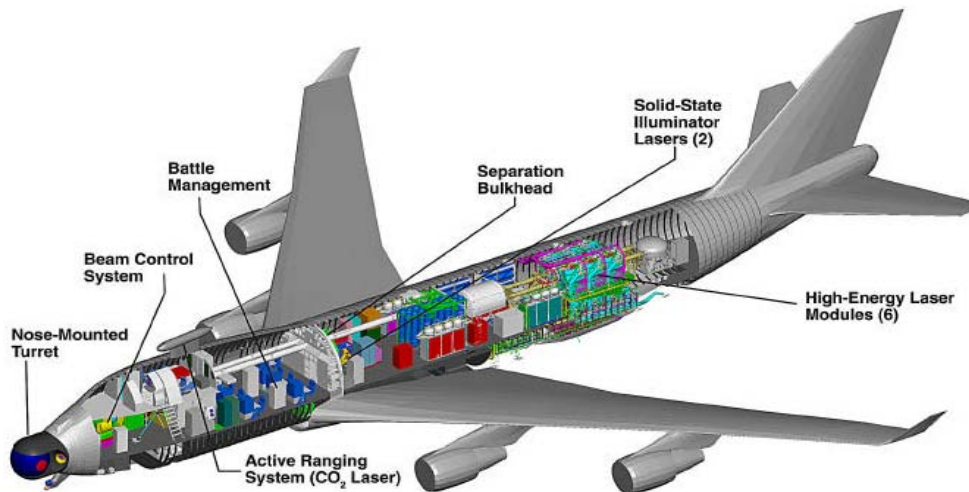


Figure 11. Airborne Laser (ABL)⁶⁸

Although its primary mission is missile defense, the ABL also has the potential to accomplish other missions such as counter-air, counter-space, and intelligence, surveillance and reconnaissance (ISR).

b. Advanced Tactical Laser (ATL)

The advanced tactical laser (ATL) is another concept for an airborne laser that uses a less powerful version of the chemical oxygen iodine laser (COIL), instead of missiles, to disable ground targets. This type of airborne laser has the advantage of being able to produce a surgical strike and lethal or non-lethal effects, particularly in an urban environment, at significant standoff distances.

⁶⁵ Defense Science Board Washington DC, Welch, and Latham 2001, 213.

⁶⁶ Kochems and Gudgel 2006, 8.

⁶⁷ Forden 1997, 40-49.

⁶⁸ From Scott 2003, 6.

The ATL (Figure 12) will use laser power from the tens to a few hundred kilowatts to disable target sets including vehicles, aircraft, munitions, rockets/mortars, optical and radar surveillance systems, communication infrastructure, and other military targets.

Although in the current demonstrations, several large platforms such as the C-130, AC-130, CV-22, and larger helicopters are being used to carry ATLs, fighter aircraft might be included in these platforms for solid-state advanced tactical lasers, even if their power source problems are overcome.



Figure 12. Advanced Tactical Laser Platforms^{69 70}

3. Space-Based Laser

The space-based laser (SBL) is another high-energy laser type that uses a hydrogen fluoride (HF) chemical laser to achieve an effective, global ballistic missile defense capability. The SBL is currently envisioned to be a constellation of orbital laser weapons capable of engaging and destroying several classes of missiles, launched from anywhere in the world, during the boost phase.⁷¹

⁶⁹ After Thompson and Goure 2003, 47.

⁷⁰ Army Aviation and Missile Command Redstone Arsenal AL Short-Range Air Defense (Shorad) Project Office (PO), Souder, and Langille 2004, 6.

⁷¹ Defense Science Board Washington DC, Welch, and Latham 2001, 213.

The SBL will also have the capability to destroy or disable other space-based systems such as surveillance satellites. Moreover, a different laser type that has an appropriate wavelength other than that of the hydrogen fluoride (HF) chemical laser could attack ground targets.

According to sources, the best space-based laser (Figure 13) concept would operate at an altitude of 1,300 km above the earth's surface with twenty different space-based platforms. This would provide a continuous worldwide defense ability to destroy hostile missiles launched anytime from anywhere on the globe.

Each space-based laser platform consists of four major subsystems:

- *A laser device*, which uses megawatt-class hydrogen fluoride (HF) chemical laser operating at 2.7 microns.
- *An optics and beam control system*, which has a 2.4- to 4.0-meter-diameter primary beam director and an integrated beam control system.
- *An acquisition, tracking, pointing and fire control (ATP/FC) system*, which includes a stabilized platform to maintain the beam on the target.
- *Associated space systems*, which provide the necessary electrical power, laser reactants, on-board data processing, and command and control.⁷²

Two other longer term options are considered to involve space-based laser systems.

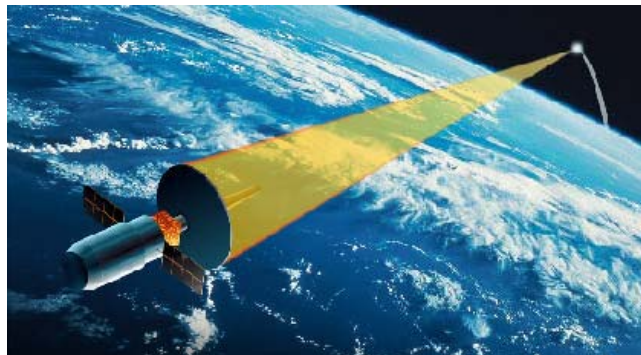


Figure 13. Space-based Laser⁷³

⁷² From Possel and Air University (U.S.). Center for Strategy and Technology 1998, 60.

The first uses space-based mirrors and places the laser on the ground. The distinct advantage of this architecture is that the high-energy laser is kept on the ground, which eliminates refueling and complex maintenance problems. Although it has an advantage, this option has disadvantages that include the requirement for higher energy levels to counter greater losses due to atmospheric transmission.

A second option is deployment of space-laser weapons with large orbital mirrors. The concept behind this architecture is to increase the altitude of platforms and insert bifocal mirrors into the same orbit as the laser weapons. One distinct advantage of this architecture is the possibility of reducing the weight and expense of the system. Instead of twenty laser platforms, the concept requires roughly ten platforms and ten orbiting mission mirrors.⁷⁴ This will decrease the number of laser platforms but will also require higher energy levels because of the higher orbital altitude.

D. LASER COUNTERMEASURES AND PROTECTIVE TECHNIQUES

Although there is no simple solution, from a technological point of view there are some means to protect against and counter laser weapons. Countermeasures will largely depend upon the duration of the target's exposure to the laser beam, weather conditions, intensity of the laser, effectiveness of the laser weapon, and its targeting accuracy, beam pointing and tracking stability.

It is evident that the most vulnerable target of low-energy and medium-energy laser weapons will be the optical and electro-optical systems, and the personnel behind the sights. A laser beam entering an electro-optical device such as night vision sights or a direct view optical system such as a telescope, as well as anyone looking through the system will suffer from its deposited energy. Any uncovered glass surface, namely eyeglasses, vision blocks, or binoculars, has the potential to attract or alert an anti-electro-optical weapon's target acquisition system.⁷⁵

⁷³ Army and General Staff Coll Fort Leavenworth KS School of Advanced Military Studies and Lincoln 2004, 15.

⁷⁴ Possel and Air University (U.S.). Center for Strategy and Technology 1998, 21.

⁷⁵ Ghosh 2001.

In order to avoid anti-electro-optical laser weapons the obvious protection will be the use of optical filters, individual eye protection, and detectors that provide a certain amount of hardening and blocking against the laser beam. Since only the sensitive parts of the electro-optical devices will be destroyed or blinded, indirect view might also be another protection technique against laser weapons. For example, using thermal imagers, image intensifiers or TV cameras for observation might protect the observers.⁷⁶

Using reflective devices and insulating targets with inexpensive materials can be used to decouple the beam from the target surface, but their use may result in increased counter-detection susceptibility.

Tubular extensions over optical lenses and covering part of them with tape or some other type of material will lessen their chances of being detected and reduce their vulnerability.⁷⁷

Reducing the number of personnel in observation and minimizing the exposure of glass surfaces in the direction of laser weapons by positioning vehicles and weapons gives tactical protection over the low-energy and medium-energy laser weapons.⁷⁸

Another way to provide tactical protection is mimicking the atmospheric effects. Laser weapons will be effective only if they have a line-of-sight view to their targets. However, rain, smoke, fog, snow and dust are very effective as a countermeasure.

Rotating static positional targets and concealing the target damage signature will be the easiest tactical protection method against the low-energy and medium-energy lasers, whose kill mechanism depends on holding the beam on a vulnerable portion of the target for a period of time.

A general countermeasure to high-energy lasers would be the hardening of the target. High-energy laser light causes damage only if the target absorbs its energy. If the reflectivity of the surfaces were sufficiently great, the possibility of damage to them

⁷⁶ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 30.

⁷⁷ Ghosh 2001.

⁷⁸ Bayer 1986, 46.

would be reduced. Here, rotation will also be effective and will spread the laser energy over a larger area to reduce the impact of the beam.

Last but not least, the most effective countermeasure against laser weapons is attacking them with weapons before they engage their targets. Table 5 summarizes the material and tactical protective techniques against laser weapons.

Laser Countermeasures and Protective Techniques	Material	Tactical
	Covering optical lenses with tape	Conceal target damage signature
	Filters, detectors, and protectors	Covered or shielded unused glass surfaces
	Indirect viewing	Hit them before they hit you
	Reflective and harden materials	Mimicking atmospheric effects
	Tubular extensions over optical lenses	Minimize the number of personnel
	Rotate static openings	

Table 5. Laser Countermeasures Summary

IV. HIGH-POWER MICROWAVE WEAPONS

In a future war where all sides depend heavily on electronic systems, weaponry and command and control, a weapon that disrupts and damages these systems will be extremely valuable. If it can perform this function at the speed of light, with minimal prior target information and with minimum collateral damage, it will be especially useful.⁷⁹

A. PHYSICAL PRINCIPLES OF HIGH-POWER MICROWAVES

As weapon systems become increasingly dependent on electronic components, they also become more susceptible to microwave radiation. Producing output power into the gigawatt range has stimulated interest in using high-power microwave weapons in military applications in both offensive and defensive roles to disrupt or destroy enemy electronic systems.

1. Structure and Basic Considerations

High-power microwaves (HPM) are another type of directed-energy weapon, having a much longer wavelength and much lower frequency than the laser. Although the term microwave technically only applies to the highest-frequency radio waves, namely those operating in the gigahertz range, it has become commonplace to refer to all directed-energy weapons operating at radio frequencies as high-power microwaves. Rather than operating in the infrared, visual, or ultra-violet spectra, high-power microwave weapons generate and deliver electromagnetic waves in the microwave frequency band from approximately 100 MHz to 100 GHz, corresponding to wavelengths from 3 m to 3 mm. High-power means that the microwave source is able to generate a peak power of more than 100 MW.

A typical high-power microwave weapon has the following three main components as shown in Figure 14:

⁷⁹ Bolkcom and Tatman 1997.

- *A pulse power source*, which generates highly amplified electronic pulses that drive the high-power microwave source.
- *A high-power microwave source*, which is the heart of the weapon and converts kinetic or potential energy in the beam to electromagnetic energy, in the form of microwaves, to be delivered to the target.
- *An antenna*, which directs the microwaves toward a target and acts as the mechanical interface between the atmosphere and the microwave source.^{80 81}

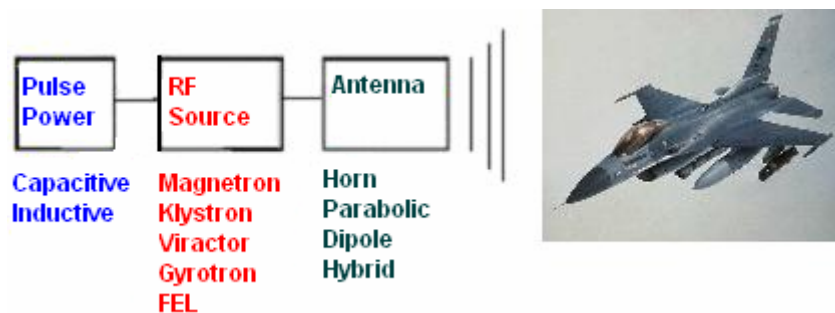


Figure 14. Basic Set-up of a HPM System ⁸²

Besides these three components high-power microwave weapons have tracking, aiming and control systems.

High-power microwave weapons are typically sub-categorized as either narrowband or ultra-wideband systems. Narrowband (NB) weapons produce a single frequency or closely clustered frequencies with the bandwidth being only a few percent of the center frequency at very high power. Therefore, when using a narrowband source, knowledge of the frequency dependent target, meaning the absorption as a function of frequency and aspect angle, is an advantage. This knowledge can be achieved in principle by scanning the target with a tunable low-energy source and receiving and evaluating the reflected signals for missing frequencies (high absorption at the target). However, it must

⁸⁰ National Air Intelligence Center Wright-Patterson AFB OH, Li, and Wang 1996, 16.

⁸¹ Sforza and Zmuda 2003, 17.

⁸² After Scannell 2003, 6.

be recognized that all high-energy narrowband sources are not easily, or even not at all, tunable in a bandwidth worth mentioning.⁸³

Ultra-wideband (UWB) weapons radiate over a broad frequency range, but deliver less energy at any specific frequencies. Ultra-wideband weapons are intended for use against a wide range of different systems, rather than defeat of a narrow-focused and well-defined target or class of targets.

Narrowband high-power microwave systems have better transmission characteristics and fewer problems with fratricide than ultra-wideband systems. Besides, narrowband systems require prior knowledge of the threat so as to identify the specific frequency of interest and are more susceptible to countermeasures such as hardening.

Ultra-wideband high-power microwave weapons provide a broad capability range even with little or no knowledge of the target. Since the destructiveness of ultra-wideband high-power microwave weapons depends on their distance from the target, they have shorter effective ranges than narrowband weapons which usually have higher radiated power.

2. High-Power Microwave Sources

As the heart of the high-power microwave weapon, high-power microwave sources have been under investigation for several years, and many varieties of microwave sources exist. High-power microwave sources include the traditional magnetron and klystron as well as newer devices such as the virtual-cathode oscillator (vircator), gyrotron and free-electron laser.

In contrast to a magnetron, the physical structure of the klystron permits higher power and frequencies. While they could deliver the requisite power levels, they are problematic with regard to size, mass, and power consumption. Another negative feature is that they have a limited tuning ability.⁸⁴

⁸³ Weise et al. 2004, 487.

⁸⁴ Advisory Group For Aerospace Research and Development Neuilly-Sur-Seine (FRANCE) 1997, 52.

Vircators generate microwave energy at centimeter wavelengths and are candidates for future high-power microwave weapons. The vircator is of particular interest because it is a one-shot device capable of producing a very powerful single pulse of radiation, yet it is mechanically simple, small and robust, and can operate over a relatively broad band of microwave frequencies.⁸⁵

Gyrotrons are another new type of microwave source that operate at millimeter wavelengths, and are capable of continuous wave operations at very high power levels. The disadvantages of gyrotron devices are their size, weight and very narrow bandwidth.⁸⁶

B. OPERATIONAL CAPABILITIES

High-power microwave weapons provide new means and interesting operational characteristics for both defensive and offensive operations. First, a HPM weapon is a wide-area weapon that can affect multiple targets with minimal prior data on threat characteristics. It could be used while focused or in a scan mode to cover a region of vast extent. HPM weapons illuminate every target within their beams' path, near or far. Their area effect depends on several factors, such as frequency generated, distance from target area, the characteristics of the antenna, and susceptibility of the targets.

Second, they are tunable weapons that allow users to vary the effects imposed on the different targets, such as electronic equipment and people. They do not provide significant collateral damage like chemical and biological weapons do. They could possibly be employed against targets in urban environments or where collateral damage and casualty concerns constrain the use of explosive or kinetic weapons. They do not cause physical or structural damage, yet they still permit strikes against a range of high-value targets such as military and civil communications systems, ammunition and fuel depots, transportation systems or even critical industrial facilities.

⁸⁵ Monash University Clayton (Australia) and Kopp 1996, 31.

⁸⁶ Taylor and Giri 1994, 28.

Third, they have all-weather attack capability. Microwave beams, just like radio, television and radar signals, can propagate in clouds, dust, snow, rain and most other atmospheric conditions.

Fourth, they are three-dimensional weapons. HPM weapons might be particularly useful against buried targets or those that are located in populated areas. They not only can cause injury, kill surgical targets and do great damage or performance degradation to electronic equipment on the ground, but also can penetrate buried and protected targets.⁸⁷

Fifth, HPM weapons can be effective against electronics even when those systems are turned off. However, this might be limited to just damage effect and can be achieved only if a weapon system produces sufficient fluence on the target. The very single effective defense is to isolate the target from the means of conducting energy, which might produce a mission kill.⁸⁸

Sixth, when compared to other kinetic or biological weapon systems. HPM weapons have reduced life cycle costs and provide a deep magazine. Unlike conventional systems, microwave weapons require little logistical support, backup missiles or ammunition. Their bullets are simply electrical energy derived from their power sources.

Lastly, they are multi-platform weapons that can be carried by unmanned air vehicles (UAV), land vehicles, aircraft, tactical fighters, helicopters, bombs or missiles, ships, and even by manned or unmanned future combat system (FCS) platforms.

1. How High-Power Microwave Weapons Affect Their Targets

High-power microwave energy can affect anything that responds to electromagnetically induced voltages and currents, to include electronics, materials and personnel. Two mechanisms are at work within objects caught in a high-power microwave beam: molecular heating and electrical stimulation (Figure 15).⁸⁹

⁸⁷ Guoqi Ni, Benqing Gao, and Junwei Lu 2005, 4.

⁸⁸ Thompson and Goure 2003, 25.

⁸⁹ Air War Coll Maxwell AFB AL and Brunderman 1999, 11.

Once microwave energy reaches a target, a sequence of penetration and propagation processes will take place from the target's outer surface into its interior. Molecular heating is the result of narrowband high-power microwave weapons on the target's outer surface. The molecules of the target rub together due to the power of the microwave energy. The power required to gain this effect is quite large and a significant dwell time on intended target is necessary.

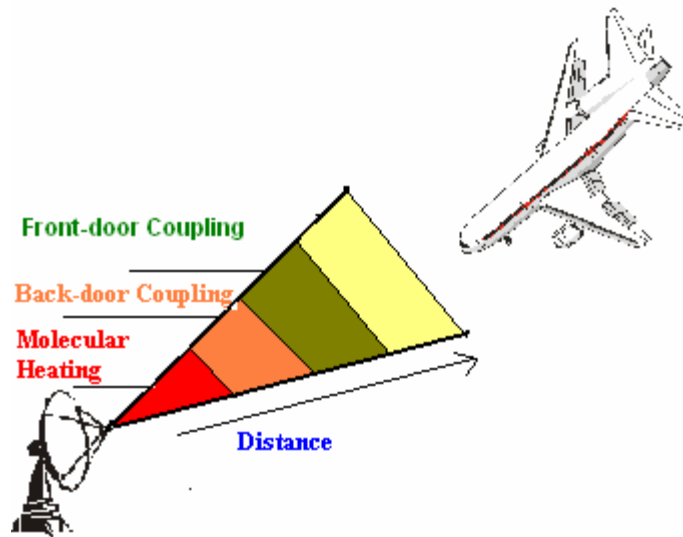


Figure 15. Range vs. Effects ⁹⁰

The other efficient mechanism takes place when the microwave energy ultimately arrives at the target's electronics. Microwave weapon systems have the ability to produce graduated effects in the target electronics, depending upon the amount of energy that is coupled to the target. Coupling begins with an exterior response on shielded systems like aircraft, tanks and other targets. Later, the energy that is received can be subsequently transmitted deeper into the electronics through the circuitry pathways that exist within the

⁹⁰ After Naval Air Warfare Center Aircraft Div Patuxent River MD and Frazier 2000, 18.

target itself.⁹¹ The power level and dwell time required for electrical stimulation are much smaller than for molecular heating, which allows longer engagement range (Figure 15).

Depending on the coupling, high-power microwave effects can change from degraded system interaction to more serious destructive accomplishments. For electrical stimulation or penetration into the target, high-power microwave weapons use two different coupling mechanisms.

a. *Front-Door Coupling*

Front-door coupling denotes in-band penetration through the target with its own antenna, which is designed to receive microwaves such as communication antennas, radar antennas or altimeters. If unprotected, these coupling paths provide an easy entrance at in-band frequencies. In-band damage or performance degrading requires that the attacking microwaves be of the same frequency as those the target is tuned to receive. Out-band signals may also couple with front-door openings and overwhelm the target, but are weaker as they do not couple as efficiently.

The disadvantage of in-band damage or performance degrading is the need to know the target's operating frequency in advance, or to obtain that information in real time and adjust the weapon's output appropriately. A common countermeasure to in-band attack is frequency hopping, which means changing the frequency with each pulse. The counter to this countermeasure is to attack over a broad band of frequencies, but this carries with it the disadvantage of spreading the weapon's available energy over a broad band.⁹²

b. *Back-Door Coupling*

Back-door coupling is a more complex mechanism and refers to any radiation coupling that follows a path other than an antenna, such as windows, slots,

⁹¹ Air University Press Maxwell AFB AL and Walling 2000, 4.

⁹² Nielsen and National Defense University Press 1994, 249.

seams, improperly shielded wires, cracks or gaps. Any conductive material can provide a path for energy to reach key electronic components. Back-door paths require higher energy levels before damage or performance degrading is likely to occur, but they are typically much more difficult to diagnose or eliminate.

2. Lethality of High-Power Microwave Weapons

High-power microwave weapons cause four levels (upset, lock-up, latch-up, and burnout) of destructive effect in electronic devices depending on:

- Distance to the target
- Vulnerability of the target
- Weapon frequency
- Generated power level and power density on the target
- Bandwidth
- Burst rate and pulse duration
- Dwell time on the target
- Coupling mode or entry points

Four potential effects of high-power microwave weapons on targets can be categorized into a hierarchy of lethality, which require increasing microwave emission on the target.

a. Upset

Upset means particular interaction as observed between a weapon and the operating state of the target system at the time, as the system state changes, upsets could subside. Once the signal is removed, the affected system can be easily restored to its previous condition. Interference caused by jamming equipment or lightning are examples of this type of deny effect.

b. Lock-up

Lock-up produces a temporary alteration similar to upset, but electrical reset or shut off and restart is necessary to regain functionality after the radiation is

removed. Degrading is an example which requires the intervention by an external operator or special safeguard procedures to reload the target system.

c. Latch-up

Latch-up defines an extreme form of lock-up in which circuits of the target are permanently destroyed or electrical power is cut off, which spoils the target's mission. No responding semiconductor devices to an input or transistors failing on a circuit board due to overloads from radiation are two latch-up examples.

d. Burnout

Burnout occurs when the high-power microwave energy causes melting in capacitors, resistors or conductors. Burnout mostly occurs in the junction region where multiple wires or the base collector or emitter of a transistor come together, and often involves electrical arcing. Consequently, the heating is localized to the junction region. A lightning strike's effect on electronic devices is a burnout example.

C. HIGH-POWER MICROWAVE WEAPONS AND ELECTRONIC WARFARE

The term electronic warfare (EW) refers to any military action involving the use of electromagnetic (EM) and directed energy to control the electromagnetic spectrum or to attack the enemy. There are three major subdivisions of EW: electronic attack (EA), electronic protection (EP), and electronic warfare support (ES).

Directed energy and directed-energy weapons are primarily involved in EA. This division of electronic warfare involves the use of electromagnetic energy, directed energy, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of denying, degrading, neutralizing, or destroying enemy combat capability and is considered a form of fire. EA includes:

- Actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum, such as jamming and electromagnetic deception

- Employment of weapons that use either electromagnetic or directed energy as their primary destructive mechanism⁹³

Therefore, directed-energy weapons and ultimately high-power microwaves are integral to electronic warfare.

Although both traditional electronic warfare systems and microwave weapons rely on the frequency spectrum, pulsed energy, waveform and peak power to work against enemy electronics, high-power microwave weapons are distinct from traditional electronic warfare systems on several counts.

The first and most obvious point is that high-power microwave weapons do not rely on extensive prior knowledge of the target system. In order to jam or spoof, electronic warfare systems have to be at the target's frequency and modulation, which is countered by using filters or increasing the frequency bandwidth of the system.

A second, related feature is that electronic warfare systems will affect target systems only when they are operating/transmitting-receiving. However, high-power microwave weapons can affect enemy systems even when they are turned off.

A third important aspect of high-power microwaves is that their effects continue after exposure has ended. Unlike conventional electronic warfare systems, which have just deny and disturb capacity, HPMS can leave persisting and lasting effects on enemy targets through damage or performance degrading and destruction of electronic circuits, components, and subsystems.⁹⁴

A fourth key characteristic of high-power microwave weapons is that instead of just having front-door coupling features, microwave weapons also damage or degrade their targets' performance through backdoors, where there is no perfect way to defend (Figure 16). Due to high-power microwave weapons' stealthy characteristics, there is no easy way to determine the back door openings available to microwave weapons. Damage is done without victim knowledge. For this reason the target systems must be hardened in

⁹³ Joint Chiefs of Staff Washington DC 2005, 179.

⁹⁴ Air University Press Maxwell AFB AL and Walling 2000, 2.

their entirety, not just individual components or circuits. This makes countermeasures against high-power microwaves difficult.

	Front Door Coupling	Back Door Coupling
In-Band	EW Effective HPM Effective	HPM Effective
Out-of-Band	HPM Effective	HPM Effective

Figure 16. EW Systems and HPM Systems Coupling Methods ⁹⁵

Table 6 shows the unique characteristics of high-power microwave weapons compared to classic electronic warfare systems.

HPM Weapons are Different from Traditional EW Systems	HPM Weapons	Classic EW Systems
	Do not rely on exact knowledge	Target-specific knowledge required
	Affect targets even turned off	Affect targets when operating
	Effects continue after exposure	Effects last as long as exposure
	Back-door coupling (In-band or Out-of-band)	Front-door coupling (In-band)
	Difficult countermeasure	Easy countermeasure

Table 6. Differences Between EW Systems and HPM Weapons

⁹⁵ After Naval Air Warfare Center Aircraft Div Patuxent River MD and Frazier 2000, 18.

D. HIGH-POWER MICROWAVE APPLICATIONS AND TARGETS

To subdue the enemy without fighting is the acme of skill.

Sun Tzu, *The Art of War*

High-power microwave weapons are the most promising type of direct-energy weapons for military and law enforcement operations due to the increasing application of electronics. Generally, as modern devices become more electrically sophisticated, the more vulnerable they become against high-power microwaves. As described earlier, the rate and degree to which microwave weapons affect targets depends upon numerous factors of both the weapon itself and the design of the target.

High-power microwave weapons provide a range of strategic, operational, and tactical capabilities in both offensive and defensive areas.

Among the most likely near-term applications of high-power microwaves are as an adjunct to precision-strike weapons. High-power microwave weapons could address the problem posed by underground or deeply buried targets. In addition, a high-power microwave weapon could be employed against targets in urban environments or where collateral damage and casualty concerns constrain the use of explosive or kinetic weapons.⁹⁶

Air defense systems are extremely intensive users of electronics, to include tracking radars, targeting radars, communications, and missile guidance, control and intercept functions. By their nature, they are highly vulnerable to microwave attacks. High-power microwave weapons could destroy the entire enemy defense system and could be used for the suppression of enemy air defenses (SEAD).

Similarly, high-power microwave weapons could be used to damage and degrade performance electronic systems in the enemy's front-line equipment. Potential targets would include the enemy's command and control systems, radio and satellite

communications, artillery targeting capability, and the guidance and control functions on guided munitions. This will give close air support for the troops on the ground (Figure 17).⁹⁷

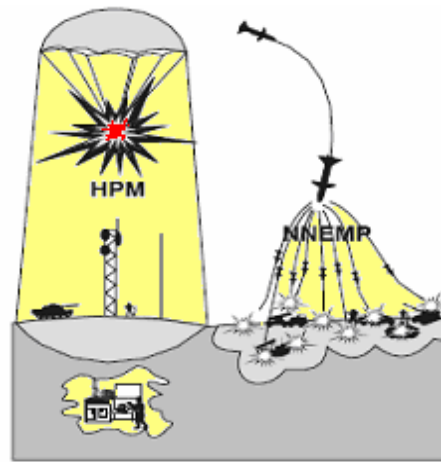


Figure 17. HPM Weapons Close Air Support⁹⁸

One possible defensive application of microwave weapons is against missiles. Surface-to-air missiles, air-to-air missiles, anti-aircraft missiles, cruise missiles and many other types are significant threats to large and small aircraft, ships and armored vehicles. However, these missiles are guided by a variety of sensor systems, such as infrared, electro-optic, laser-guided or a combination. Even if a microwave weapon could operate within the timing of the missile navigation or guidance systems or in the command and control elements, by disabling the guidance and control functions of the approaching missile, a high-power microwave weapon might be an effective means of protection.

High-power microwave weapons could also be used to attack critical enemy military and civil infrastructures such as telecommunication systems, power grids, transportation systems, radio and television stations, civil emergency services, finance and banking systems, oil and gas control and refining stations, and security systems. This

⁹⁶ Thompson and Goure 2003, 26.

⁹⁷ Air Univ Press Maxwell AFB AL and Walling 2000, 18.

⁹⁸ After Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 69.

might cause confusion for the enemy before tactical assaults by other (more conventional) means. Contrary to this, high-power microwave weapons could be used to defend critical national infrastructures, high-value targets, and air defense systems.

High-power microwave weapons will prove to be a valuable tool in law enforcement as non-lethal weapons. They can be used against hostile crowds to disable or stop criminal land, sea, and air vehicles without hazard to the public associated with firearms.

Table 7 illustrates a number of possible high-power microwave applications.

Typical HPM Weapon Applications and Targets	Potential HPM Targets	Potential HPM Applications
	Acquisition and tracking radars	Air interdiction of C4I
	Avionic systems	Aircraft self-protection
	Command, control, communications, computing and intelligence (C4I) systems	Close air support
	Electro-explosive devices	Counter surface-to-air and air-to-air missiles
	EW equipment	Degrade enemy air control
	Missile guidance	Non-lethal weapon
	Night vision devices	Protection of critical infrastructure
	Sensor systems	Suppression of enemy air defenses (SEAD)

Table 7. Potential HPM Weapon Applications and Targets

For the conduct of future warfare, it is vitally important to reduce the size and weight of high-power microwave weapons. This will enhance mobility and raise the

efficiency of high-power microwave weapons. Although long-range space defense and other similar applications might not be feasible within a short time, improvements in the power levels are continuing.

E. DEFENSE AGAINST HIGH-POWER MICROWAVE WEAPONS

The most effective defense against high-power microwave weapons is to prevent their operations by destroying their operating platforms. This may not always be possible, and therefore systems that can be expected to suffer from high-power microwave weapons must be hardened.

The most reliable robust strategy for protection against high-power microwave weapons is to wholly contain the vulnerable equipment in an electrically conductive metal shielding or enclosure. This closed barrier surface, termed a Faraday cage, excludes the effects of all sources outside the shield and prevents the electromagnetic field from gaining access to protected equipment.

Complete and uncompromised topological shielding is a difficult protective technique to implement and requires containment of either full platforms or facilities. Even if a system was perfectly shielded, such a system would still need to communicate with and be fed power from the outside. These openings could provide vulnerability to high-power microwave entry.

Another countermeasure is to use a layered defense with filters, where the damaging radiation or voltages must penetrate several segments. In order to provide in-band filtering, systems use the narrowest feasible tunable filters to keep out all possible in-band energy. For out-band filtering, systems use low-pass and high attenuation filters at radio frequency interfaces below the high-power microwave spectrum.

The use of surge-protective devices is another protective technique against high-power microwave weapons and an alternative to using filters. These are nonlinear devices that limit surge voltage to safe levels. Although surge-protective devices are commonly

used, there are a number of significant problems with their application. Device failure detection and defective identification are two major problems with these systems.⁹⁹

Fiber optic cables, which contain no metal as a strain relief or protective jacket, can also reduce the effects of high-power microwave weapons. However, either end of the optical connections must also be hardened.

Using one system at a time during the threat period is a tactical protective measure against high-power microwave weapons. Unused devices should be disconnected from power and antennas and kept in the Faraday cages.¹⁰⁰

Another strategy against a high-power microwave weapons attack is multi-layer shielding to eliminate their line-of-sight propagation. In-depth defense with multiple shields with staggered joints minimize penetration probability.

Likewise to these countermeasures against high-power microwave weapons, system maintenance, which ensures that hardening fixes retain the necessary level, is another key issue to keep vulnerable systems operating properly.

Table 8 lists current possible high-power microwave protective techniques.

- Shielding and filtering
- Extreme care in eliminating very small openings
- Gasketing
- Flexible metal jackets on cables
- Multi-layer shielding
- Welded structures
- Non-metallic cables (fiber optics)
- Minimization of metal fixtures and fastenings in non-metallic structures

⁹⁹ Taylor and Giri 1994, 192.

¹⁰⁰ Steward 2006, 213.

<ul style="list-style-type: none"> • Narrow beam antennas with minimum side lobes • Laser communications • Internal optical communications • Conductive foil over joints • Interval system usage

Table 8. High-power Microwave Protective Techniques ^{101 102}

Although high-power microwave weapons have much destructive potential, the hardening of equipment is technically feasible to some extent. Instead of partial protection, hardening of equipment must be carried out at system levels and in a comprehensive manner. Most importantly, experience and testing shows that hardening new systems by design is significantly easier than attempting to harden existing systems.¹⁰³ Also, experiences learned about the protection of systems from hostile transients from the EMI/EMC world might be directly applied to the HPM hardening problem as well.

¹⁰¹ After Keuren and Knighten 1995, 484.

¹⁰² After Wilkenfeld, Knighten, and Keuren 1991, 20.

¹⁰³ Monash University Clayton (Australia) and Kopp 1996, 17.

THIS PAGE INTENTIONALLY LEFT BLANK

V. COMPARISON OF DIRECTED ENERGY WEAPONS

The theories behind the various types of directed-energy weapons are very similar, involving what is in essence slight variations of electromagnetic radiation. While lasers generate tightly focused beams of monochromatic (single frequency) photon energy in the visible and infrared region of the electromagnetic spectrum, high-power microwave devices generate much less focused beams of energy in the radio frequency range of the electromagnetic spectrum.¹⁰⁴

The difference between the two is that they have different wavelengths so that they take advantage of a different portion of the electromagnetic spectrum. However, electromagnetic waves are characterized by how fast they spread out (diffraction), how far they propagate (range), how they interact with various types of matter, how they propagate through the atmosphere, and how they are created. These characteristics all arise from variations in the wavelength and photon energy.¹⁰⁵

High-power microwave wavelengths are longer than that of lasers. As a feature of the atmosphere, diffraction or light spreading increases when the wavelengths increase. This spreading decreases the amount of energy placed on a target. Thus, high-power microwave weapons can project less energy into a large area, for a fixed range, than laser weapons.

Shorter wavelength light is less affected by diffraction but can be more strongly affected by device optical imperfections, turbulence, jittering and other atmospheric effects. Since laser wavelengths are shorter than high-power microwave wavelengths and about the same size as atmospheric gas molecules, they scatter in the atmosphere more than microwaves do. However, a smaller wavelength increases the energy, decreases the diffraction of laser weapons, and makes lasers more effective over longer distances. Laser energy may directly interact with the outer material of the target, which provides a potential hard-kill mechanism.

¹⁰⁴ Geis and Air University (U.S.). Center for Strategy and Technology 2003, 8.

¹⁰⁵ Beason 2005.

A. ADVANTAGES AND DISADVANTAGES OF LASER WEAPONS

One of the major advantages of laser weapons is their precise targeting and discrimination, which reduces the miss casualties and fratricide potential associated with high-power microwave weapons. However, this precision requires complex tracking and pointing systems that are susceptible to losses due to vibration and jittering. This precision also limits the engagement to one target at a time.

Although damage assessment for low-energy and medium-energy laser weapons is difficult for the gunner, kill assessment and immediate feedback is much easier for high-energy laser weapons than high-power microwave weapons.

Another advantage of laser weapon systems is the straight line of sight along which the energy is delivered. It is not necessary to calculate a ballistic trajectory, as is the case with normal munitions. Consequently, laser weapons (especially low-energy laser weapons) do not require very costly and complex fire control systems to calculate their trajectories.¹⁰⁶

Different from other weapon systems, laser weapons are very effective against maneuvering and crossing targets. Even the fastest target will present minimal problems to the laser beam director in holding the beam on the target. However, a target pulling such Gs will be much more susceptible to fail after being destructed by the laser weapon. A crossing target presents its profile rather than just its nose to the high-energy laser weapon, which increases the target's vulnerability to a guidance or propellant kill.¹⁰⁷

Directed-energy weapon wavelengths have to be roughly the same size of the target to cause any damage or performance degradation. Laser weapons are about the same size as solid material molecules. Thus, laser weapons can deposit their energy through most material structures whereas high-power microwave weapons pass through most materials and are not much of a threat.¹⁰⁸

¹⁰⁶ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 166.

¹⁰⁷ National Defense University Washington DC Center For Technology And National Security Policy and Zimet 2002, 9.

¹⁰⁸ Beason 2005, 186.

Although fratricide is not considered a problem, target suitability is one of the disadvantages of laser weapons. Laser weapons are mostly effective against thin-skinned targets or those that can be damaged with a small spot beam area. Their effects are minimal on hardened and armored targets. The lethality and effective range are directly related to laser beam quality and laser power as explained in Chapter III. Their current low megawatt power is not sufficient enough to affect hardened targets. Figure 18 shows the required laser power levels for sample targets.^{109 110}

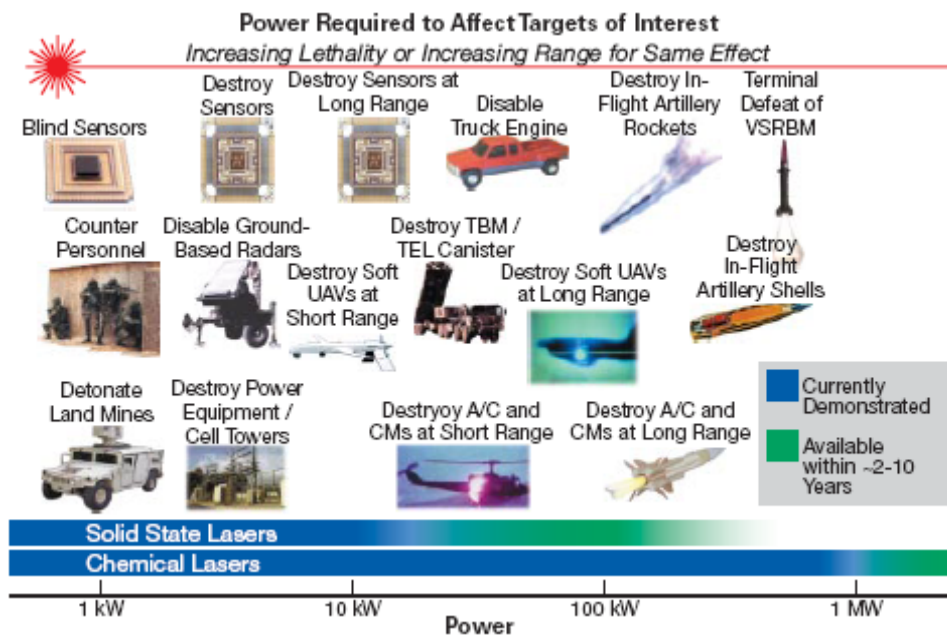


Figure 18. Required Laser Power Levels for Sample Targets¹¹¹

One of the main difficulties with high-energy lasers is that they are unable to operate through inclement weather. They are affected by conditions within the atmosphere, whether naturally occurring or manufactured. A modern laser system such as the airborne laser weapon (ABL) employs adaptive optics to compensate for the problem of beam attenuation caused by atmospheric turbulence. In addition, the airborne laser

¹⁰⁹ Campbell 2000.

¹¹⁰ Thompson and Goure 2003, 21.

¹¹¹ From Richard J. Dunn, III 2006, 7.

addresses the problem of weather and obscurants by engaging targets above the cloud level (forty thousand feet or twelve kilometers above the earth). However, fog, smoke, clouds and other obscurants will be a problem for near-Earth laser weapons, such as the tactical high-energy laser (THEL) or mobile tactical high-energy laser weapon (MTHEL).¹¹² Simply stated, lasers will probably never be complete all-weather weapons.

Another important weakness of laser weapons is that they are line-of-sight weapons, which means they have no indirect-fire mode and cannot shoot beyond the system's visual horizon.¹¹³ In current technical conditions, an obstruction that provides cover or blocks line-of-sight vision might hinder the effectiveness of laser weapons. This disadvantage could be used as an easy countermeasure against laser weapons.

The other great disadvantage of visible laser beams, as a weapon, is the source pinpointing which reveals location of the laser platform. Laser beams can also be detected and located by laser warning receivers.

Hardening techniques as a countermeasure against laser weapons are not as complicated or as hard to accomplish as is a defense against high-power microwave weapons. Since their lethality starts from the outside and goes to the inside, simple shielding or modification of vulnerable targets might be effective against laser weapons. In addition, some tactical countermeasures work well against laser weapons as explained in Chapter III.

Cost is probably the biggest disadvantages to some types of high-energy laser weapons such as the space-based laser. For example, the space-based laser costs almost eighty billion dollars.¹¹⁴

¹¹² Thompson and Goure 2003.

¹¹³ Kochems and Gudgel 2006, 8.

¹¹⁴ Possel and Air University (U.S.). Center for Strategy and Technology 1998, 60.

B. ADVANTAGES AND DISADVANTAGES OF HIGH-POWER MICROWAVE WEAPONS

Area coverage is one of the critical advantages of high-power microwave weapons. Unlike a laser weapon, which can engage one target at a time, a high-power microwave weapon can simultaneously affect every target within the beam's pathway with minimal prior target information.

Another advantage of microwave energy is its all-weather attack capacity or insensitivity to weather. Compared to laser weapons, which are greatly affected by atmospheric conditions, microwave weapons are mostly unaffected by clouds, rain, snow, dust and most other atmospheric obstacles.

Opposite to laser target suitability and line-of-sight attack capability, many targets are very sensitive to high-power microwave weapons even if they are completely covered or hidden behind walls. As most of the modern military targets are heavily dependent on a wide variety of sensitive electronic components, they are becoming more vulnerable to microwave weapons.

Countermeasures and defense against high-power microwave systems is very expensive and not well understood. Modernization of expected weak targets against high-power microwave weapons might not work as planned, and in addition might place those systems into jeopardy with minor openings that are not shielded completely. Producing new systems totally hardened against high-power microwave systems will have a limited life cycle, which also needs to be renewed periodically. This will make such protection expensive.

Microwaves have been used for communication and radar systems since the 1940s. As a result, the technology for high-power microwaves is more advanced than for laser weapons.¹¹⁵

Minimum collateral damage and performance degradation is another key advantage of high-power microwave systems. High-power microwave weapons are

¹¹⁵ Nielsen and National Defense University Press 1994, 218.

ideally suited for low-intensity conflicts, politically sensitive environments and non-lethal applications since they attack the electronics of adversary systems rather than munitions or personnel using them, and they go for a function kill of the target rather than for damaging its structure or harming its crew.^{116 117}

High-power microwave weapons require less accurate targeting, so that they have a simplified pointing and targeting system. Instead of being precisely aimed and pointed, they need only be directed generally toward the targets. However, this causes less destructive energy on a specific target or target area than laser weapons.

In addition, diffraction or spreading out of the high-power microwave beams is much greater than for laser light. This enhances coupling techniques to larger objects and distributed entryways of high-power microwaves over straight-line propagated laser weapons.

The first and most obvious drawback of high-power microwave weapons is fratricide. Since high-power microwave weapons are not discriminating weapons, they will affect anything in their beam's radiation path on the ground or in the air. It is likely that unshielded or unprotected friendly systems would be as vulnerable as target systems. In order to minimize this disadvantage, as written in the previous chapter, critical friendly systems should be hardened during their design phase.

Another potential disadvantage to the military application of high-power microwave weapons is the ability to make a damage or performance degrading assessment. Not all electronic systems will respond the same way to the deposition of an equal amount of energy. In addition, unlike the obvious damage caused by high-energy laser weapons, microwave weapons affect the electronics inside the target systems and this may not prove lethal, or may be more difficult to observe.¹¹⁸

Limited range and power is another important multi-dimensional problem and disadvantage of high-power microwave weapons. Due to the atmospheric breakdown,

¹¹⁶ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 69.

¹¹⁷ Scannell 2003, 2.

¹¹⁸ Thompson and Goure 2003, 32.

which absorbs and limits the energy directed to the targets, high-power microwave weapon systems need more power to overcome this limitation.¹¹⁹ Nevertheless, this makes the microwave weapon system platforms bigger and provides a large visual signature due to their size. At some point, current technologies are not mature enough to produce such high-average power sources. Furthermore, increasing the power levels and at the same time reducing the size of microwave weapon systems is technically challenging, and does not seem feasible for the next few years.¹²⁰

Another important weakness of high-power microwave weapons is that they emit a very distinctive electronic signature that might be detected from great distances. Thus, high-powered electromagnetic radiation emitted by the microwave weapons makes them susceptible to attacks by anti-radiation missiles, which use the radiation from the source systems for guidance.¹²¹

Table 9 and Table 10 show the advantages and disadvantages of laser weapons and high-power microwaves.

¹¹⁹ Atmospheric breakdown occurs at very high power levels when microwave energy creates plasma in the air that prevents the microwaves from propagation.

¹²⁰ Sweetman 2006.

¹²¹ National Air Intelligence Center Wright-Patterson AFB Oh and Zhihao 1996, 5)

Comparison of Laser and High-power Microwave Weapons Advantages	Laser Weapon Advantages	HPM Weapon Advantages
	Effective against maneuvering and fast targets	All-weather attack (Insensitivity to weather)
	Effective against material	Area coverage of multiple targets
	Long range engagement	Enhance target entryways
	Precise targeting	Harder to defense against
	Visual damage assessment	Many possible targets
		Minimum collateral damage
		Old and advanced technology
		Simplified pointing and tracking
	Attack at the speed of light	
Graduated effect capability (non-lethal to lethal)		
Low cost per shot		
Minimum collateral damage		
Unaffected by gravity or atmospheric drag		
Unlimited magazine		

Table 9. Comparison of Laser and HPM Weapon Systems Advantages

Comparison of Laser and High-power Microwave Weapons Disadvantages	Laser Weapon Disadvantages	HPM Weapon Disadvantages
	Atmospheric and weather dependence	Atmospheric breakdown
	Easier material and tactical countermeasures	Difficult damage assessment
	Engage one target at a time	Distinctive electronic signature
	Expensive concepts (SBL)	Fratricide
	Line-of-sight vision	Large visual signature
	Source pinpointing	Technical challenges
	Susceptible against vibration and jittering	
	Target suitability	
	Protection of friendly systems	
Relatively new technologies		

Table 10. Comparison of Laser and HPM Weapon Systems Disadvantages

There is not a weapon that exists without limitations and constraints due to environmental or tactical conditions. Like any weapon system in the real world, directed-energy weapons have constraints and disadvantages.

Despite their differences, directed-energy weapons

- Are unaffected by gravity,
- Are capable of graduated effects,
- Cause minimal collateral damage,
- Have deep magazines,

- Low cost per shot,
- Moreover, they most importantly attack at the speed of light.¹²²

They are complementary to each other and because of this, they have distinct advantages over other weapon systems and are ready for the next war or conflict.

¹²² Beason 2005, 58.

VI. PRESENT AND NEAR FUTURE DIRECTED-ENERGY WEAPONS

A. E-BOMBS

Electromagnetic bombs or E-bombs, described as the “nuclear weapons of the information age”, are devices specifically designed to destroy a wide range of electronic equipment over their footprints.¹²³ E-bombs produce high voltage standing waves on wiring and cables or cause secondary radiation of an intense electromagnetic blast at the gigahertz level which is strong enough to melt electrical circuitry.

The basic principle of an E-bomb entails the use of an explosive magnetic flux compression generator. Essentially, a magnetic armature is driven by explosives through a coil, energized by a bank of capacitors, and the resulting energy is directed through an antenna.¹²⁴ Figure 19 shows the hypothetical design for an E-bomb warhead in which a two-stage flux compression generator provides gigawatts of power to the virtual cathode oscillator (vircator), which produces the high-power microwaves.¹²⁵

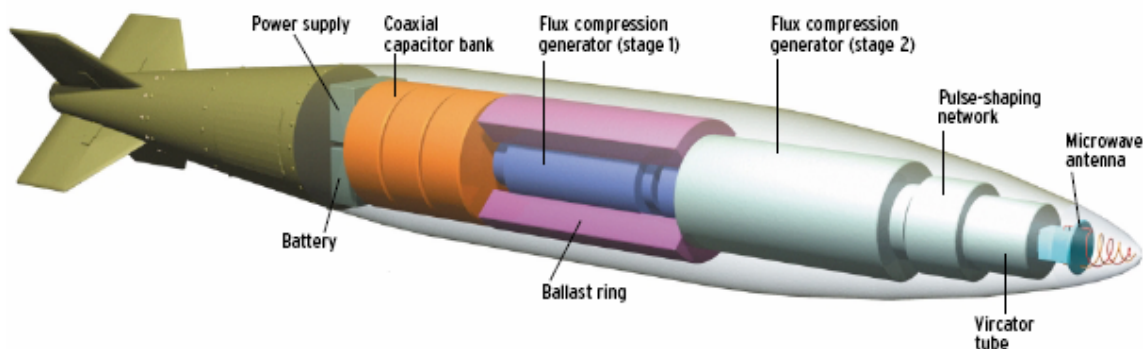


Figure 19. E-bomb Warhead¹²⁶

¹²³ Kopp 1996.

¹²⁴ Sweetman 2006.

¹²⁵ Abrams 2003, 29.

¹²⁶ From Ibid.

Electromagnetic bombs could be delivered by a cruise missile, unmanned air vehicle (UAV) or conventional aircraft as an aerial bomb. Improving the lethality of an electromagnetic bomb might be achieved through several means:

- Increasing bomb output energy
- Maximizing the duration of operation
- Minimizing losses incurred inside the bomb
- Achieving the best possible coupling efficiency
- Initiating the weapon at lower altitude¹²⁷ (Figure 20)

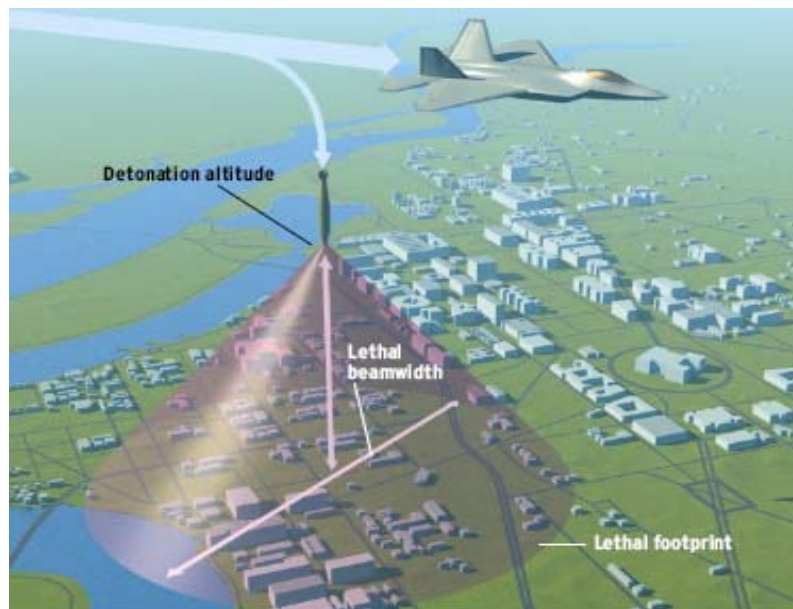


Figure 20. Lethal Footprint of an E-bomb¹²⁸

Countries known to have studied E-bombs are the United States, Germany, Russia, France and the United Kingdom.¹²⁹

¹²⁷ Kopp 1996.

¹²⁸ From Abrams 2003, 29.

¹²⁹ Sweetman 2006.

B. ACTIVE DENIAL SYSTEM (USA)

The Active Denial System (ADS), which is known as the pain ray, is a non-lethal directed-energy weapon used against human targets. It uses the millimeter-wave region of the electromagnetic spectrum, which penetrates shallowly into a conducting surface like human skin. The ADS uses a 95 GHz radar beam that penetrates 0.4 to 0.5 mm into human skin.¹³⁰

ADS produces a heat sensation that within seconds becomes intolerable and forces the targeted individual to instinctively flee. The sensation immediately ceases when the individual moves out of the beam or when the operator turns off the system.¹³¹ Since the produced pulses are very short and targeted humans react instinctively, ADS does not cause permanent injury.

ADS (Figure 21) could be used for protection of defense resources, peacekeeping, humanitarian missions and other situations in which the use of lethal force is undesirable. The system is described as having a range of 700 yards.¹³²



Figure 21. Vehicle-mounted Active Denial System (V-MADS)¹³³

¹³⁰ Scannell 2003, 8.

¹³¹ Anonymous 2006.

¹³² Anonymous 2007.

¹³³ From Anonymous 2006.

C. ZEUS (USA)

Zeus is a high-energy laser system that is capable of neutralizing surface-laid mines and unexploded ordnance (UXO) such as artillery rounds, mortar rounds, rifle grenades, and large general-purpose bombs (Figure 22).¹³⁴ The system, which was integrated on a high-mobility multi-purpose wheeled vehicle (HMMWV), was developed by the United States Army Space and Missile Defense Command.

The Zeus system uses high-energy laser to warm the outer surface of the target to neutralize it at ranges up to 250 to 300 meters. The system is able to engage only the targets which are in a clear line of sight, not buried threats. Its dwell time depends on the thickness of the target outer surface. Unlike other mine-clearance systems, the Zeus system causes only low-level detonations, which mitigates flying fragments and damage to roads and supply routes needed by friendly forces.¹³⁵



Figure 22. Zeus System¹³⁶

¹³⁴ Defense Science Board Washington DC 2001, 83.

¹³⁵ Sirak 2002.

¹³⁶ From Defense Science Board Washington DC 2001, 83.

Zeus is controlled by a driver and laser operator, and has the ability to search an area and store all targeting coordinates onto a global positioning system-aided map before destroying the mines.¹³⁷ The Zeus system consists of seven subsystems as illustrated in Figure 23:

- Fire control subsystem
- Laser device subsystem (LDS)
- Laser power subsystem (LPS)
- Prime power subsystem
- Beam control system (BCS)
- Waste heat subsystem
- Armored vehicle subsystem¹³⁸

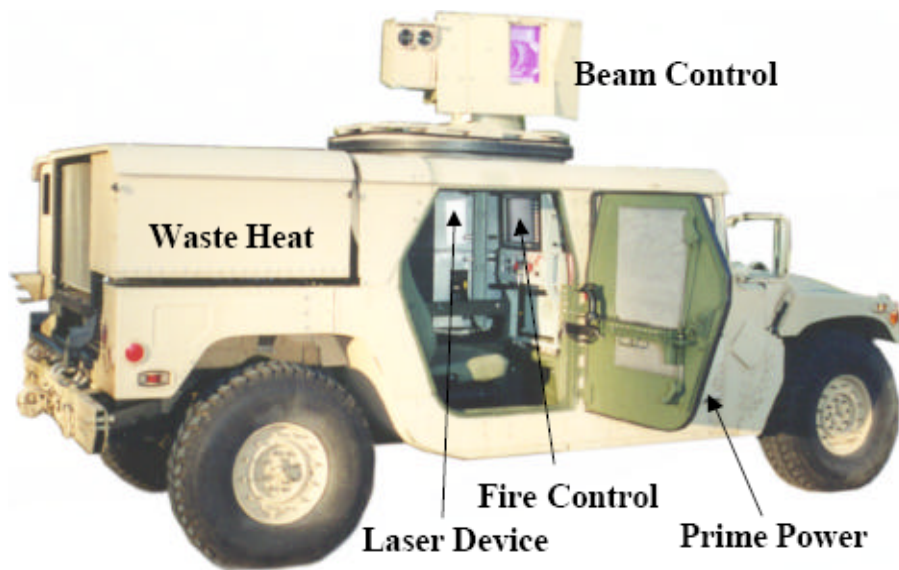


Figure 23. Zeus Subsystems¹³⁹

¹³⁷ Sirak 2002.

¹³⁸ Defense Science Board Washington DC 2001, 84.

¹³⁹ From Ibid, 85.

D. VIGILANT EAGLE (USA)

Vigilant Eagle is a ground based high-power microwave weapon system which functions like modern radar systems to protect arriving and departing aircraft from an airport. It is an alternative or complement to installing infrared countermeasures on the aircraft themselves as a defense against shoulder-fired missiles or man-portable air defense systems (MANPADS) during the landing and takeoff phases of flight.

Vigilant Eagle works with four or five overlapping missile warning systems (MWS), which consist of infrared detectors mounted on cell phone towers, buildings and other common structures around an airport as camouflage. These distributed infrared sensors identify and track a missile and pass the triangulated data to a Command and Control (C2) segment. Once the target data is nominated by C2, commands are sent to the high power array transmitter (HAT) to focus a disruptive beam on the missile to disrupt the missile circuits and divert it away from the target aircraft (Figure 24).^{140 141} The power level, frequency and waveform of the Vigilant Eagle system have been selected so as not to interfere with aircraft systems in the event that the high-power amplifier transmitter (HAT) illuminates a friendly aircraft.¹⁴²

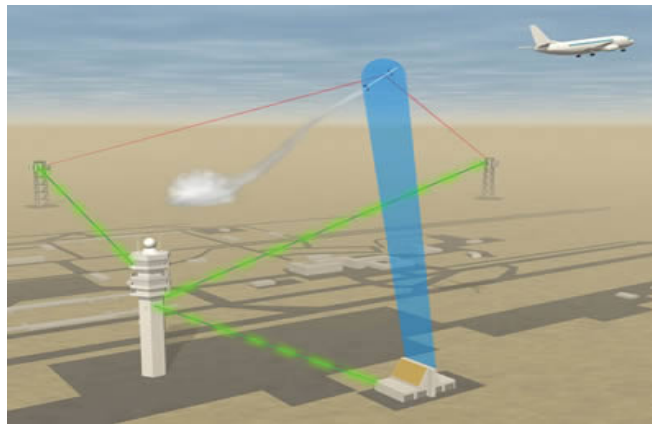


Figure 24. Vigilant Eagle System¹⁴³

¹⁴⁰ Fulghum 2005, 2.

¹⁴¹ Vollin, Jeff 2006, 4.

¹⁴² Sweetman 2006.

¹⁴³ From Fulghum 2005.

E. STINGRAY (USA)

The Stingray is a tactical laser system integrated into Bradley Fighting Vehicles and designed to detect and defeat threats with direct fire control systems (Figure 25).¹⁴⁴ The Stingray uses low-energy laser weapons to detect and counter multiple enemy electro-optic systems and fire-control equipment before the weapons can be fired.¹⁴⁵ The system sends and then picks up reflected laser light - which is called the cat-eye effect - from the enemy optical equipment and sensors in order to lock onto target systems.



Figure 25. AN/VLQ-7 Stingray¹⁴⁶

The Stingray can operate in automatic, semiautomatic, or manual modes depending on the control measures required to protect friendly forces. To obtain the maximum effect on enemy systems:

- The automatic mode is used when there is no danger to friendly forces and when there are large number of enemy systems
- The semiautomatic mode is used when more restrictive control measures are required

¹⁴⁴ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 31.

¹⁴⁵ Campbell 2000.

¹⁴⁶ From Anonymous 2000.

- The manual mode is used for security reasons when tight control of the system is required because of command restrictions or restrictions on laser operations.¹⁴⁷

F. SABER 203 (USA)

The Saber 203 is a type of laser weapon that was designed to impair the vision of enemy soldiers when fired from a standard 40-mm M-203 grenade launcher attached to the M-16 rifle.¹⁴⁸ This weapon system uses a semiconductor laser and its effective range is around 300 meters (Figure 26).



Figure 26. Saber 203¹⁴⁹

The Saber 203 system has the following two parts:

- A metal capsule, which is about the size and shape of a 40 millimeter grenade that houses the laser emitter and will load into the launcher as if it is an actual grenade.
- A battery pack, which is snapped on to the weapon's underside and a button on the battery pack fires the laser in a continuous or pulsed beam to illuminate a target.¹⁵⁰

¹⁴⁷ Anonymous 2000.

¹⁴⁸ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 31.

¹⁴⁹ From Anonymous 2006.

¹⁵⁰ Ibid.

The Saber 203 can be used to temporarily impair the vision of enemy soldiers or to alert or realize that they have been targeted.

G. ZM-87 PORTABLE LASER (CHINA)

ZM-87 is a portable laser weapon designed to damage electro-optical sensors such as laser rangefinders, video cameras and missile seeker heads at ranges up to 10 km.¹⁵¹ The weapon affects its targets by transmitting 15 MW laser pulses at two different wavelengths simultaneously with a 5 Hz repetition rate. It weighs less than 35 kilograms (Figure 27).¹⁵²

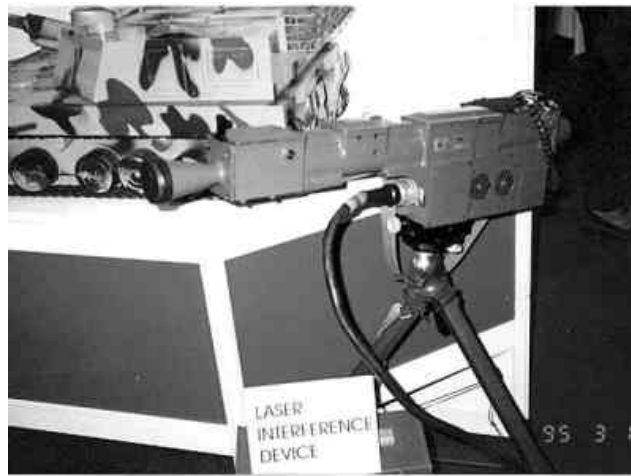


Figure 27. ZM-87 Portable Laser¹⁵³

H. BRILLIANT (CANADA)

Beam Rider Laser Localization Imaging and Neutralization Tracker (BRILLIANT) is a directed laser countermeasure weapon which is effective against laser guided weapon systems. Basically, BRILLIANT (Figure 28) consists of five units:

- A laser detection unit, which is covering 360 degrees and feeds the code breaker

¹⁵¹ Anonymous 2007.

¹⁵² Anonymous 1995.

¹⁵³ From Ibid.

- A code breaker, which analyses the inputs from the detection unit and triggers the gate of a video camera
- An imaging and localization device, which drives the video tracker
- A video tracker, which allows centering of the target in the camera field of view and provides precise localization of the threat
- A directed counter measure laser, with an eye-safe green laser mounted on top of the camera¹⁵⁴



Figure 28. BRILLIANT System¹⁵⁵

I. PERSONNEL HALTING AND SIMULATION RESPONSE (USA)

The Personnel Halting and Stimulation Response (PHaSR) is a first of its kind rifle-sized laser weapon system that can be operated by a single shooter. The PHaSR system uses laser light to illuminate or dazzle aggressors that temporarily impairs the vision of hostile individuals.¹⁵⁶

¹⁵⁴ Defence Research and Development Canada Ottawa (Ontario) et al. 2004, 32.

¹⁵⁵ From Ibid, 33.

¹⁵⁶ Anonymous 2006.

The PHaSR is about the same size and weight of a fully-loaded M60 machine gun, 9 kg, but shoots a low-powered beam of laser light rather than bullets. By incorporating the laser rangefinder, PHaSR can target an individual, determine his or her distance from the person holding the PHaSR, and then automatically adjust the laser power level. Possible applications of the PHaSR include non-lethal fire for controlling crowds and protecting areas such as checkpoints.¹⁵⁷



Figure 29. The Personnel Halting and Stimulation Response (PHaSR)¹⁵⁸

¹⁵⁷ Sirak 2005.

¹⁵⁸ From Anonymous 2006.

THIS PAGE INTENTIONALLY LEFT BLANK

VII. THE IMPLICATIONS OF DIRECTED-ENERGY WEAPONS FOR THE TURKISH ARMED FORCES

Peace at home, peace in the world.

Mustafa Kemal Atatürk
The founder and the first president of the Turkish Republic

Directed-energy weapons offer the potential for the most dramatic transformation of modern militaries since the advent of electronics and possibly even gunpowder. The deployment of these kinds of unique weapon systems with extremely long ranges, speed-of-light engagement, deep magazines, area coverage, surgical strike ability, and minimum collateral damage would naturally revolutionize the way military forces are equipped, organized, supplied and operated.¹⁵⁹

It is obvious that technology may allow nations to gain a decisive advantage over their enemies and protect their forces on the battlefield. Military operations will be different and revolutionary in a directed-energy environment. Under this reality, directed-energy weapons will clearly be a force multiplier and provide revolutionary combat capabilities to the Turkish Armed Forces. Due to this reason, the Turkish Armed Forces should prepare itself to deal with this circumstance.

As written in the previous chapters, several nations have started to make investments to develop and field directed-energy weapons, and countries who underestimate the features of these weapon systems will be susceptible against these nations in the event of unwanted conflicts. Directed-energy weapons clearly offer some novel and potentially very important offensive and defensive missions and concepts and may become more than a force multiplier for the Turkish Armed Forces.

¹⁵⁹ Thompson and Goure 2003, 33.

A. WHY SHOULD THE TURKISH ARMED FORCES INTEGRATE DEW

The Turkish Armed Forces' missions and responsibilities are clearly stated in the Turkish Constitution and determined by law. In this context, the small but flexible units, having sufficient capability equipped with technological weapons and systems, comprising sufficient command-control assets, precise and developed ammunition, covering early warning assets and also able to conduct operation in any weather condition, are very desirable and take priority in the new approach.¹⁶⁰

1. Support All Levels of War

The challenge to the Turkish Armed Forces is to define a vision and a doctrine of directed-energy weapons and determine how it can best integrate and implement DEW systems into current war levels. The benefits of this integration might lead to more effective offensive and defensive strategies for the Turkish Armed Forces. Directed-energy weapons are capable of creating effects across tactical, operational, and strategic, levels of war.

- **Tactical level of war:** The level of war at which battles and engagements are planned and executed to accomplish military objectives assigned to tactical units or task forces. Activities at this level focus on the ordered arrangement and maneuver of combat elements in relation to each other and to the enemy to achieve combat objectives (Joint Publication 1-02, 161).
- **Operational level of war:** The level of war at which campaigns and major operations are planned, conducted, and sustained to accomplish strategic objectives within theaters or other operational areas. Activities at this level link tactics and strategy by establishing operational objectives needed to accomplish the strategic objectives, sequencing events to achieve the operational objectives, initiating actions, and applying resources to bring about and sustain these events. These activities imply a broader dimension of time or space than do tactics; they ensure the logistic and administrative support of tactical forces and provide the means by which tactical successes are exploited to achieve strategic objectives (Joint Publication 1-02, 161).
- **Strategic level of war:** The level of war at which a nation, often as a member of a group of nations, determines national or multinational

¹⁶⁰ Turkish General Staff 2007.

(alliance or coalition) security objectives and guidance, and develops and uses national resources to accomplish these objectives. Activities at this level establish national and multinational military objectives, sequence initiatives, define limits and assess risks for the use of military and other instruments of national power; develop global plans or theater war plans to achieve these objectives; and provide military forces and other capabilities in accordance with strategic plans (Joint Publication 1-02, 161).

Directed-energy weapons will be the newest technology and weapon systems in the twenty-first century. Tactically, directed-energy weapons that deliver lethal force against a target instantaneously will provide new killing mechanisms for the Turkish Armed Forces. Since the range and magazine of directed-energy weapons are greater than kinetic energy weapons, these weapons will enhance the combat capability of small and flexible tactical Turkish units. As a result, tactical troops equipped with directed-energy weapons, such as low-energy and medium-energy laser weapons, mobile tactical high-energy laser (MTHEL) weapons and compact high-power microwave weapons loaded on unmanned combat air vehicles (UCAV), are likely to be more capable than the troops equipped with traditional weapons systems.

The operational level focuses on a large piece of the battlefield and connects the other two levels of war. Any weapon affecting operational doctrine and operational command and control systems will be effective at this level. Airborne laser (ABL) weapons, tactical high-energy laser (THEL) weapons and high-power microwave bombs (E-bombs) may be useful at this level of war.

At a strategic level of war, increased interaction between Turkish troops and friendly troops, or even hostile civilian populations especially in urban warfare, will play important roles. Active Denial non-lethal directed-energy weapons could help Turkish Tasked Forces undertaking peacekeeping missions and joint operations with its allies. This will minimize the need to rely on lethal weapons for crowd control and fratricide against allied forces. In addition, high-power microwave bombs (E-bombs), which produce negligible collateral damage when compared with conventional explosive munitions, allow the administration of effective strategic strike operations against buried targets or targets that are located in civilian populated areas.

2. Homeland Defense

Use of directed-energy weapons might alter current and future defense concepts of the Turkish Armed Forces. Stationary and mobile directed-energy weapons, which deliver their lethality at the speed of light, might also decrease defensive reaction time against fast moving and maneuvering multiple targets such as artillery, fighter aircraft, and long-range ballistic missiles that threaten the Turkish borders.

Because of Turkey's geostrategic position, the Turkish Armed Forces might need weapon systems that react fast and engage rapidly against multiple targets. With their deep magazine, directed-energy weapons might give both area coverage and precise accuracy to prevent hostile attacks on the Turkish borders for homeland defense. This will enable the Turkish Armed Forces to develop highly effective offensive capabilities to protect its warfighters on the ground, in the air, and at sea.

3. Effective Domestic Security

Directed-energy weapons provide instantaneous target engagement and discriminatory firepower with high accuracy even when used in urban environments. Using this new technology is critical to defense of national domestic entities.

Since directed-energy weapons demonstrate tremendous potential against rockets and missile threats, the Turkish Armed Forces can use them against these threats. These electromagnetic swords might be considered to provide an adequate, credible security zone around domestic targets such as Turkey's critical infrastructures (government buildings, major transportation nodes, telecommunication facilities, power plants) and important military bases. In addition to their precision and instantaneous reaction capability, such defense systems might also be cost efficient and safe.

4. Low Operational Cost

Some types of directed-energy weapons might be able to intercept targets at lower cost than conventional munitions in current use by the Turkish Armed Forces. Although directed-energy weapons require major investments to build and develop, costs after

these stages might be minimal because these weapons systems expend only energy. For example, in the case of a defense against short-range and long-range missiles, shots from directed-energy weapons might cost around \$8,000, whereas kinetic energy missiles cost hundreds of thousands of dollars or even millions of dollars, depending on their types. Moreover, unlike currently used conventional weapon systems, directed-energy weapons might simplify logistics. Since fuel is their only expendable to produce energy and they do not require a large logistical tail, they might save money and time for the Turkish Armed Forces as well. Table 11 provides examples of some typical missile costs.

Missile Costs	System	Nomenclature	FISCAL YEAR 2007 Unit Cost (\$M)
	AMRAAM	AIM-120-A-C	0.643
	ATACMS	MGM-140B	1.407
	BDM	XM-141	0.009
	ESSM	RIM-162A	0.922
	GMLRS		0.216
	HELLFIRE II	AGM-114K	0.096
	JASSM	AGM-158A	0.8
	JAVELIN		0.145
	JDAM	GBU-31/32	0.022
	PAC-3		4.529
	RAM	RIM-116A	0.632
	SDB	GBU-39/B	0.074
	SIDEWINNER	AIM-9X	0.231
	SLAMRAAM		1.467
	TACTICAL TOMAHAWK	RGM-109E	1.013
WCMD		0.139	

Table 11. Missile Costs¹⁶¹

¹⁶¹ From Nicholas and Rossi 2006.

5. Superior Information Warfare

Modern warfare totally depends on communication and information operations. Directed-energy weapons might give the Turkish Armed Forces the capability to limit its enemy's ability to control and command their military forces. In this context, high-power microwave weapons might be extremely effective against enemy communication and electronic systems (Figure 30).

Turkish Armed Forces could use directed-energy weapons to attack and disable enemy ground and air control systems, communication facilities, radars, and ground defense systems. Furthermore, directed-energy weapons can be used to attack enemy commercial radio and television stations to limit their information network capabilities.

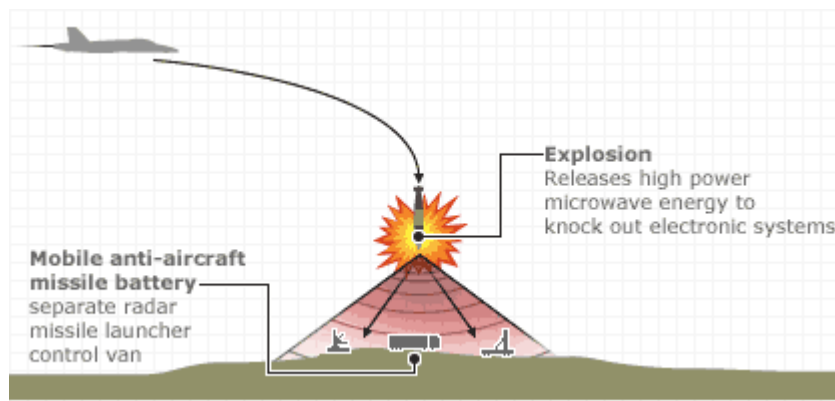


Figure 30. Damage and Destroy Enemy Information Systems¹⁶²

6. Non-lethal Warfare

- **Non-lethal weapons:** Weapons that are explicitly designed and primarily employed so as to incapacitate personnel or material, while minimizing fatalities, permanent injury to personnel, and undesired damage to property and the environment. Unlike conventional lethal weapons that destroy their targets through blasts, penetration, and fragmentation, non-lethal weapons employ means other than gross physical destruction to prevent the target from functioning (Joint Publication 1-02, 161).

¹⁶² From Anonymous 2003.

Directed-energy weapons might enable entirely new concepts of operation for “non-lethal warfare” for the Turkish Armed Forces. This new way of war does not cause physical destruction while striking against high-value enemy targets (communication systems, critical industries) and critical military targets, which may be located in populated areas, urban centers or even buried locations. Directed-energy weapons can strike such targets with little to no collateral damage when conventional weapons would not be feasible due to the risk to the public.

Since the Turkish Armed Forces has always attached great importance to peacekeeping missions and serving the needs of maintaining peace throughout the world, interaction between friendly troops, civilian groups and Turkish soldiers are ever increasing. Equipping Turkish peacekeeping forces with effective non-lethal weapons might be beneficial in urban environments, especially in peacekeeping activities, to minimize damage to property and personal injury.

Similarly, Turkish law enforcement units and the Coast Guard can use this capacity of non-lethal directed-energy weapons as a countermeasure against criminal equipment and materials. These law enforcement troops can utilize non-lethal directed-energy weapons to disable and stop the criminal land, sea and air vehicles as well as criminal human targets without the hazards to the public associated with small firearms. Due to their non-lethal to lethal graduated effect properties, directed-energy weapons might provide a valuable tool in law enforcement for Turkey.

In summary, because of their unique advantages, directed-energy weapons might offer the Turkish Armed Forces the capability to maintain an asymmetric technological advantage over its adversaries during the twenty-first century.

B. HOW DIRECTED-ENERGY WEAPONS BENEFIT TURKISH LAND FORCES

Directed-energy weapons might be able to change the existing capabilities of the Turkish Land Forces and extends these capabilities both defensively and offensively. A Turkish Armed Force equipped with unique directed-energy weapons might offer a new way of war beyond those nations equipped with modern kinetic energy weapons.

Communications and command systems are key elements in land warfare, and their essence is to permit forces to gain situational awareness. Due to this key element, C⁴ISR systems and units are one of the first targets attacked so as to limit the enemy military forces' operations. The Turkish Armed Forces could use effective directed-energy weapons to attack an enemy's C⁴ISR systems and defeat one element of the enemy's center of gravity. A useful strategy with directed-energy weapons might be an initial attack with high-power microwave payloads to create a maximum dislocation and disruption of enemy C⁴ISR systems and then a follow-up attack with precise laser weapons and traditional conventional munitions.

Integrating directed-energy weapons into the current land warfare doctrine might also increase the precision and volume of the Turkish Land Forces' fire in complex environments. Furthermore, directed-energy weapons used by the Turkish Army might provide a non-lethal kill of a wide range of targets with non-destructive strikes. As seen from the latest land warfare underway worldwide, the probability of fighting in urban areas is increasing. Since civilian involvement and collateral damage is also increasing, conventional weapons might be hard to use in this environment. Against this complexity of fighting in urban areas, different structures of precise and tunable directed-energy weapons might be a new force multiplier that broadens the range of military options for the Turkish Land Forces.

Increased lethality at sufficient ranges and area coverage (or rapid targeting) are other important factors that might affect land warfare in this century. Directed-energy weapons, which give adjustable lethal power and can strike their targets with almost no time delay, might give this lethality to the Turkish Land Forces. Area coverage of high-power microwaves or rapid targeting of laser weapons is also an effective application of directed-energy weapons to meet the Turkish Land Forces' requirement for an active air defense against rockets, artillery and mortars (RAM), which are extremely fast and have a short time of flight. Figure 31 visualizes the defense against rockets, artillery and mortars (RAM) via the use of directed-energy weapons.



Figure 31. Defense against RAM¹⁶³

Stealthiness of high-power microwave weapons might provide physiological and technological superiority to the Turkish Land Forces. During low-intensity conflicts or even in major conflicts, defeating the enemy's will to fight without allowing an adversary to know he is under attack would be an advantage for the Turkish Army.

Directed-energy-equipped helicopters or unmanned combat air vehicles (UCAV) could provide close air support for the Turkish Army. In this capacity, high-power microwave-equipped air platforms might target critical command, control, and communication (C3) capabilities, sensors and weapon guidance systems.

Reasonable applications of directed-energy weapons for the Turkish Land Forces are given in Table 12.

¹⁶³ From Anonymous 2006.

- Attack against pop-up targets (tanks, helicopters, UAVs, aircraft)
- Anti-personnel
- Close air support for ground forces
- Controlling riots or hostile civilian crowds
- Counter rockets, artillery and mortars (RAM)
- Counter command, control, communications, computers, intelligence, surveillance, and reconnaissance (C⁴ISR) missions
- Air defense of important military bases and high value targets
- Mine detection and detonation
- Protection of armored vehicles

Table 12. Land Applications of DE Weapons

The Turkish Army will remain a vital component in the Turkish national strategy and when complimented with directed-energy weapons, equipped Turkish Land Forces would maintain a decisive advantage over forces of other nations who neglect the importance of these twenty-first century weapon systems.

C. HOW DIRECTED-ENERGY WEAPONS BENEFIT TURKISH NAVAL FORCES

Since Turkey is surrounded on three sides by water, seapower will always be critical to the success of its national security. Modernization and being equipped with directed-energy weapons might change the Turkish Naval Forces' ability to execute its missions.

Today, some of the possible threats that naval forces might encounter in either the deep water or the littoral battle space are:

- Aircraft attack
- Ship-based or land-based helicopters

- Ship-based or land-based UAVs
- Ship-launched or submarine-launched anti-ship missiles (ASM)
- Surface ship gunfire
- Torpedoes
- Mines¹⁶⁴

Due to their sophisticated attack capacity, the greatest threat to the Turkish Naval Forces is probably anti-ship missiles (ASMs). Additionally, mines and torpedo threats are relatively inexpensive weapons against expensive naval platforms. These threats are followed by low-observable stealth aircraft and ships. In addition to these threats, the most susceptible segments of the naval order of battle are high-technology communication, sensor, and navigation systems.

Ships are large relatively slow-moving platforms, making them easy targets against missile threats. Although missiles are very effective against sea targets, they require extremely fast control systems to avoid flying into the water even in relatively benign weather. Thus, even a minor disturbance of the missile's radar altimeter or guidance software could be sufficient to create a "hard-kill" if the missile hits the surface of the sea.¹⁶⁵ Area coverage, precise targeting, and rapid engagement with different targets are properties of directed-energy weapons that might address this missile threat for the Turkish Navy. Against the increased speed and maneuvering capabilities of these missiles, the Turkish Navy can benefit from the speed advantage of directed-energy weapons to minimize the risk of missile attacks. Figure 32 visualizes the ship defense against anti-ship missiles (ASM).

¹⁶⁴ (Royal Institution of Naval Architects, 2004.

¹⁶⁵ Air University Press Maxwell AFB AL and McCarthy 2000, 31.



Figure 32. Ship Defense Against ASMs ¹⁶⁶

Furthermore, directed-energy weapons might provide enhanced protection against low-speed slow flying air vehicles for the Turkish Navy. Effective defense with directed-energy weapons against the sensor and complicated avionic systems of these air targets might disrupt and degrade their digital flight control, target acquisition, target tracking, command and control, and weapon systems, and therefore protect valuable literal assets of the Turkish Navy.

In addition to defense against slow targets, the Turkish Navy might use directed-energy weapons against pop-up targets such as small speedboats, patrol boats or helicopters. Rapid response and precise targeting of directed-energy weapons might also be effective against these fast maneuvering and suddenly appearing targets.

There is a theoretical possibility that a laser director-tracker could be used to detect and destroy submarine periscope sensors.¹⁶⁷ Although this concept is not practical with current technologies, in later years Turkish Naval Forces might use directed-energy weapons against enemy submarine threats.

¹⁶⁶ From Kalfoutzos 2002.

¹⁶⁷ Air University Press Maxwell AFB AL and McCarthy 2000, 38.

Turkish Naval Forces might utilize directed-energy weapons against enemy surveillance, communication and fleet navigation systems. As written before, these highly complicated electro-optic systems are very susceptible to high-power microwave attacks. The Turkish Navy might use directed-energy weapons to destroy and disrupt these electronic systems.

Another unique advantage that directed-energy weapons might provide to the Turkish Navy is the bottomless magazine. Not only are sea platforms large enough to install directed-energy weapons, but they also have no power limitation to support directed-energy weapons. This feature might eliminate the need to reload and reduce the logistic tail of the Turkish Naval Forces.

There are several ways that the Turkish Naval Forces might use direct-energy weapons to defend its fleet as written below in Table 13.

<ul style="list-style-type: none">• Fleet defense against missile threats• Counter to low- and slow-flying air vehicles• Counter to pop-up targets• Attack submarines• Attack enemy surveillance, communication, navigation and weapon systems
--

Table 13. Naval Applications of DE Weapons

In regards to the maritime environment, directed-energy weapon types might have some limitations, such as the short range of high-power microwaves and weather sensitivity of laser weapons. However, directed-energy weapons provide extraordinary advantages to the Turkish Naval Forces as long as their inherit limitations are well understood. A combination of both directed-energy weapons and conventional weapons might enhance the war fighting capability of the Turkish Navy.

D. HOW DIRECTED-ENERGY WEAPONS BENEFITS THE TURKISH AIR FORCE

Applications of the directed-energy weapons might have major impacts on the Turkish Air Force. These impacts might be profound in both the air-to-air battle and the air-to-ground battle.

Self-protection of Turkish aircraft against their deadliest significant threat, surface-to-air and air-to-air missiles, might be the most important employment of directed-energy weapons for the Turkish Air Force. As written in previous chapters, missile systems use different types of sensitive sensors that include infrared, radio frequency, laser or a combination for guidance. The Turkish Air Force might use directed-energy weapons to defend against these threats and disable the guidance and control functions of approaching missiles (Figure 33).

At present, the limiting factor in air-to-air engagements is the number of missiles an aircraft can carry.¹⁶⁸ Instead of having a limited payload, directed-energy weapon-equipped Turkish fighter aircraft might be effective against numerous thin-skinned air targets. DEW-equipped fighter aircraft might be used against the electronic equipment of hard ground targets such as tanks and armored personnel carriers.



Figure 33. Self-protection of Fighter Aircraft¹⁶⁹

¹⁶⁸ Thompson and Goure 2003, 31.

¹⁶⁹ From Anonymous 2005.

This advanced air-to-ground ability of the Turkish Air Force might be particularly valuable for close-air support and offensive counter-air missions that involve attacks on an enemy's fuel supplies, ammunition storage areas and aircraft on the ground.¹⁷⁰ In addition, the Turkish Air Force might use directed-energy-equipped aircraft against enemy C⁴ISR systems to interdict these assets.

Air defenses are extremely intensive users of electronics for ISR, command, control and communications and targeting. Due to this feature, they are highly vulnerable to even minor electronic attacks. To ensure air supremacy, the Turkish Air Force might use directed-energy weapons in the suppression of enemy air defense systems, to include tracking radars, targeting radars, communications and missile guidance, control and intercept functions that are necessary for locating, tracking, targeting, and attacking friendly aircraft.¹⁷¹

Furthermore, the low cost per-shot feature of directed-energy weapons might be an advantage for the training of Turkish pilots. Unlike expensive aircraft munitions, directed-energy weapons would take their source power from the aircraft's electronic supply. According to their training concept, Turkish fighters might utilize this feature of directed-energy weapons on their fighter lead-in training.

Defensive and offensive capabilities of directed-energy weapons for the Turkish Air Force are listed below in Table 14.

¹⁷⁰ Thompson and Goure 2003, 28.

¹⁷¹ Air Univ Press Maxwell AFB AL and Walling 2000, 16.

- Aircraft self-protection
- Air-to-air and air-to-ground attack
- Close air-support
- Air interdiction of C⁴ISR systems
- Suppression of enemy air defense
- Low cost for pilot training

Table 14. Air Applications of DE Weapons

As presented in Chapter II, many nations are making the investment to develop and produce directed-energy weapons. While directed-energy weapons are not yet mature, they are posing increasing capabilities for strategic, operational and tactical levels of war. Therefore, it is time to make a commitment if the Turkish Armed Forces are to take advantage of this revolution in weaponry. It is time to place increased emphasis on the research and development of the value added by these emerging revolutionary weapon systems.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Victory is for those who can say "Victory is mine". Success is for those who can begin saying "I will succeed" and say "I have succeeded" in the end.

Mustafa Kemal Atatürk

The founder and the first president of the Turkish Republic

After remarkable advancements in the past few decades, the revolutionary concept of directed-energy weapons has matured in many areas to the point that they are ready to be implemented by a country's military services as the twenty-first century's most challenging weapon systems, either in offensive or defensive applications. These revolutionary weapon systems offer asymmetric military advantages over adversaries that fail to take into consideration the application of future directed-energy weapons.

As explained in this thesis, directed-energy weapons, both high power-microwave weapons and laser weapons, are complementary to each other and have distinct advantages over traditional kinetic and chemical energy weapons. These inherent advantages include the ability to travel at the speed of light, delivery precision and discrimination of power, deep magazine capacity, low cost per shot, rapid and multiple target engagement, and non-lethal operations capability.

Engineering research continues to overcome various challenges to bring these weapons to the battlefield. These challenges include the need to reduce the cost, decrease the size and increase the power of directed-energy weapons, such as the high-energy laser. However, it is likely that directed-energy systems will continue to be developed for military applications, and in the near future nations will implement these weapon systems in compact sizes and will integrate them into small combat platforms or even man-portable systems.

The Turkish Armed Forces is likely to remain committed to the development and deployment of technologically advanced and modernized armed forces to be ready to face the uncertainties of future combat. In this context, the unique features of directed-energy

weapons will clearly be a force multiplier and provide opportunities to improve the Turkish Armed Forces' operational capabilities in a variety of mission areas. The advantages of directed-energy weapons, as explained in this thesis, might become exceptionally important as the Turkish Armed Forces moves to smaller and more professional combat units. On the other hand, failure to develop and understand directed-energy weapon systems might threaten the Turkish Armed Forces with an unknown battlefield and weaken its military power and war-fighting ability.

Furthermore, the Turkish Armed Forces might need to look into technological countermeasures against the effects of directed-energy weapons on the battlefield before facing an adversary equipped with these weapon systems.

This thesis concludes with several recommendations for the Turkish Armed Forces as it considers the possibility of integration of directed-energy weapons into its military force structure.

- Technological superiority gained by these weapons might give the Turkish Armed Forces new capabilities to cope with threats in its geostrategic position. This superiority might be attained by investing and focusing on directed-energy weapons.
- Drawing from recent peacekeeping missions and experiences, interaction between friendly troops, civilian groups and Turkish soldiers are increasing. Equipping Turkish peacekeeping forces with effective non-lethal directed-energy weapons might be beneficial in urban environments to minimize property and personnel injury to non-combatants and friendly forces.
- Against highly technologically armed forces that heavily depend upon information and equipped with stealth aircraft and sophisticated missile systems, Turkish Armed Forces could use the asymmetric advantages of directed-energy weapons to gain and maintain control of the battlefield.
- With proper cost-effective investments, participation of the national universities and national scientific research institutes, Turkey could establish a joint directed-energy organization to research directed-energy weapons. This organization might have overall responsibility for the engineering and manufacturing stages of these weapons, which would help to accelerate the advancements in directed-energy technology. In addition, this unit might collaborate with other friendly nations' military and civilian departments, which are conducting technological investigations related to directed-energy weapons, so as to share and transfer laser and microwave technologies.

- In regards to the types of laser technology, airborne and space-based HEL are inherently expensive and require too much investment at present to achieve significant development. In addition, they require large platforms and consume large amounts of power. Their key elements, such as cooling, target acquisition, aiming and tracking, and fire control systems, are expensive to manufacture and cumbersome to maintain. For these reasons, the Turkish Armed Forces might concentrate on low-energy or medium-energy man-portable laser systems and tactical high-energy laser weapons and rely on their allies to develop ABL and SBL systems, especially those more suited to regional or large area defense. As established earlier in this thesis, nations such as the United States, a close ally, have been conducting research and testing for some time on such systems, and Turkey would reasonably expect to benefit from this research and development.
- Active denial system (ADS) is probably the most mature directed-energy system available. Since tunable high-power microwaves like ADS reduce the risks associated with collateral damage, provide attack at the speed of light, give adjustable damage capacity and low operational cost, and reduce logistic support, they might be pursued by the Turkish Armed Forces. In addition to HPM systems, the Turkish Armed Forces might concentrate on transient electromagnetic devices that produce a single spike of energy and radiate electrostatic discharge. These devices are relatively small in size and much lower in average power and cost.
- Since directed-energy weapons are relatively new systems, there is little training information for front-line troops. The Turkish Armed Forces, however, might understand how directed-energy weapons affect their targets and conceptualize the effect of these weapons upon other systems and troops. The Turkish Armed Forces might organize a comprehensive program among its branches to educate and train trainers on the concept of directed-energy weapons and publish introductory training films on directed-energy weapons. These training programs would help Turkish soldiers to prepare for their first encounters with these formidable weapons on the battlefield.
- The Turkish Armed Forces should consider development of a doctrine to fight in a directed-energy environment. This would develop and maximize the effects of tactics and training against directed-energy weapons. Furthermore, this new doctrine would increase the survivability and recoverability of the Turkish Armed Forces against directed-energy warfare.
- In order to have effective countermeasures against directed-energy weapons systems, the Turkish Armed Forces needs to expand its research and development programs on hardening techniques against these systems, and start to apply these programs to high-value nationwide assets with

proper planning. Concentrating on the development of tactical countermeasure against directed-energy weapons is appropriate for the Turkish Armed Forces.

In conclusion, directed-energy weapons are neither simple nor inexpensive systems, but their utility might be well worth the cost and research to ensure the security of Turkey against internal and external risks as well as the contribution to regional and global peace. Directed-energy weapons will one day be a key feature of the future structure of the Turkish Armed Forces and their war-fighting capability. The sooner the nation begins to prepare for this eventuality, the safer Turkey will be against internal and external threats to its security and well-being.

LIST OF REFERENCES

- Abrams, M. 2003. Dawn of the E-bomb. *Spectrum, IEEE* 40, (11): 24-30.
- Active denial system in United States Air Force [database online]. Air Force Research Laboratory, Kirkland AFB, NM, 2006. Available from <http://www.de.afrl.af.mil/Factsheets/ActiveDenial.pdf>. Accessed 9 May 2007.
- Advanced solid-state laser systems in Arete Associates [database online]. 2005. Available from http://www.arete.com/index.php?view=laser_systems. Accessed 9 May 2007.
- Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (France). 1997. *Aerospace 2020. Volume 2 - main report*. Accessed 19 Mar 2007.
- Air University Press Maxwell AFB AL, and William J. McCarthy. 2000. *Directed energy and fleet defense: Implications for naval warfare*.
- Air University Press Maxwell AFB AL, and Eileen M. Walling. 2000. *High power microwaves: Strategic and operational implications for warfare*.
- Air War College Maxwell AFB AL and John A. Brunderman. 1999. *High power radio frequency weapons: A potential counter to U.S. stealth and cruise missile technology*. Accessed 5 Mar 2007.
- AN/VLQ-7 stingray in FAS Military Analysis Network [database online]. 2000. Available from <http://www.fas.org/man/dod-101/sys/land/stingray.htm>. Accessed 17 May 2007.
- Army Aviation and Missile Command Redstone Arsenal Al Short-Range Air Defense (SHORAD) Project OFFICE (PO), J. K. Souder, and D. B. Langille. 2004. *How directed energy benefits the army*.
- Army Command And General Staff College Fort Leavenworth Ks School Of Advanced Military Studies, and Timothy J. Lincoln. 2004. *Directed energy weapons: Do we have a game plan?*
- Barker, Robert J., and Edl Schamiloglu. 2001. *High-power microwave sources and technologies*. IEEE press series on RF and microwave technology. New York: IEEE Press.
- Barnes, P. N., G. L. Rhoads, J. C. Tolliver, M. D. Sumption, and K. W. Schmaeman. 2005. Compact, lightweight, superconducting power generators. *Magnetics, IEEE Transactions on* 41, (1): 268-273.

- Bayer, Gary C. 1986. The training implications of directed energy weapons for the U.S. army: A preliminary report.
- Beason, Doug. 2005. The E-bomb: How America's new directed energy weapons will change the way future wars will be fought. 1st Da Capo Press ed. Cambridge, MA: Da Capo Press, <http://www.loc.gov/catdir/toc/ecip0513/2005013291.html>; Materials specified: Table of contents <http://www.loc.gov/catdir/toc/ecip0513/2005013291.html>. Accessed May 2007.
- Beason, Douglas. 2000. The need for technical warriors. *Aerospace Power Journal* 14, (1) (Spring): 70, <http://proquest.umi.com/pqdweb?did=53015496&Fmt=7&clientId=65345&RQT=309&VName=PQD>. Accessed May 2007.
- Bolkcom, Christopher, C., and Joseph Tatman A. 1997. Directed energy technologies. *Jane's Defence Weekly* January, (07-Jan-1997): 1-1-16.
- Campbell, Clark P. 1983. Directed-energy weapons. *Infantry* November-December, 8-10.
- Campbell, Rennie. 2000. *Articles on non-lethal weapons*. Unite States: Jane's Information Group, , http://www8.janes.com/Search/documentView.do?docId=/content1/janesdata/srep/srep088/s0880015.htm@current&pageSelected=allJanes&keyword=articles%20on%20non-lethal%20weapons&backPath=http://search.janes.com/Search&Prod_Name=SREP088&. Accessed May 2007.
- Carter, Ashton B., and United States. Congress. Office of Technology Assessment. 1984. Directed energy missile defense in space. Congress of the U.S., Office of Technology Assessment, <http://libproxy.nps.navy.mil/login?url=http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota/disk3/1984/8410/8410.PDF>. Accessed May 2007.
- China markets blinding laser in Jane's Information Group [database online]. 1995 [cited 05/17 2007]. Available from http://www8.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/mags/jir/history/jir95/jir00358.htm@current&pageSelected=allJanes&keyword=Chinese%20ZM-87%20laser&backPath=http://search.janes.com/Search&Prod_Name=JIR&. Accessed May 2007.
- Conflict tech: Israel vs. Hezbollah-Iran in Defense Industry Daily [database online]. Thetford Center, VT, 2006 [cited 05/06 2007]. Available from http://www.defenseindustrydaily.com/images/ABM_THEL-Skyguard_Laser_Concept_lg.jpg.

- Defence Research and Development Canada Ottawa (Ontario), Harold Stocker, John Dick, and Gilles Berube. 2004. *Non-lethal weapons: Opportunities for R&D*.
- Defense Science Board Washington DC, Larry D. Welch, and Donald C. Latham. 2001. *Defense science board task force on high energy laser weapon systems applications*.
- Department of Defense Laser Master Plan. 2000. *High energy laser executive review panel*. Department of Defense, <http://www.wslfweb.org/docs/MasterLaserPlan.pdf>. Accessed May 2007.
- DiMaggio, Cosmo. 1985. *Directed energy weapons research: Status and outlook*. Congressional Research Service, The Library of Congress (1985), 85-183 SPR.
- Erwin, Sandra I. 2001. Directed-energy weapons promise 'low cost per kill'. *National Defense* 86, (574) (Sep): 19, <http://proquest.umi.com/pqdweb?did=79134878&Fmt=7&clientId=65345&RQT=309&VName=PQD>. Accessed May 2007.
- Etter, Delores M. Science and technology for directed energy weapons: LexingtonInstitute.org in Lexington Institute [database online]. Arlington, VA, 2002 [cited 02/26 2007]. Available from <http://www.lexingtoninstitute.org/254.shtml> Accessed 8 Feb 2007.
- Fact file: E-bombs in BBC NEWS [database online]. 2003 [cited 06/26 2007]. Available from <http://news.bbc.co.uk/2/hi/2847029.stm>. Accessed May 2007.
- Forden, Geoffrey E. 1997. Airborne laser. *IEEE Spectrum* 34, (9) (Sep): 40-49.
- Fulghum, David A. 2005. Microwave weapons emerge. *Aviation Week & Space Technology* 162, (24) (Jun 13): 116, <http://proquest.umi.com/pqdweb?did=854251511&Fmt=7&clientId=65345&RQT=309&VName=PQD> Accessed 15 May 2007.
- Gaponov-Grekhov, A. V., and V. L. Granatstein. 1994. *Applications of high-power microwaves*. The artech house microwave library. Boston: Artech House.
- Geis, John P., and Air University (U.S.). Center for Strategy and Technology. 2003. *Directed energy weapons on the battlefield [electronic resource]: A new vision for 2025*. Occasional paper air university U.S. center for strategy and technology; no. 32. Maxwell Air Force Base, Ala: Center for Strategy and Technology, Air War College, Air University, <http://purl.access.gpo.gov/GPO/LPS46941>. Accessed May 2007.
- Ghosh, C. N. 2001. Directed energy weapons. *Strategic Analysis* 16, (11) (February 2001): 1-1-12, http://www.ciaonet.org/olj/sa/sa_feb01ghc01.html. Accessed May 2007.

- Goldman, Edward, David Nett, Sidney Putnam, Doug Weidenheimer, Roger White, Tony Wynn, David Price, and Carl Bloemker. 2003. DEW technology at the titan corporation. AIAA Paper 2003-5913,
- Guoqi Ni, Benqing Gao, and Junwei Lu. 2005. Research on high power microwave weapons.
- Hecht, Jeff. 1984. *Beam weapons: The next arms race*. New York: Plenum Press.
- Hewish, Mark. 2000. Beam weapons revolution - directed-energy weapons point the way for battlefield technology. *International Defense Review* August, (08/17/2000): 1-1-13,
http://www8.janes.com/Search/documentView.do?docId=/content1/janesdata/mags/idr/history/idr2000/idr05057.htm@current&pageSelected=allJanes&keyword=beam%20weapons%20revolution&backPath=http://search.janes.com/Search&Prod_Name=IDR& (accessed 02/26/2007). Accessed May 2007.
- Hillaby, Bill. 1997. Directed energy weapons development and potential. *National Network News* 4, (3) (July 1997): 30-30-33.
- Hoerberling, Robert F., and Michael V. Fazio. 1992. Advances in virtual cathode microwave sources. *IEEE Transactions on Electromagnetic Compatibility* 34, (3 pt I) (Aug): 252-258.
- Horkovich, James A. 2006. Directed energy weapons: Promise and reality. Paper presented at 37th AIAA Plasmadynamics and Lasers Conference, Jun 5-8 2006,
- Hostettler, John N. Directed energy and the future of security: LexingtonInstitute.org in Lexington Institute [database online]. Arlington, VA, 2002 [cited 02/26 2007]. Available from <http://www.lexingtoninstitute.org/256.shtml>. Accessed 8 Feb 2007.
- John, Cecil. 1995. Directed energy warfare. *Journal of Electronic Defense* 18, (June 1995): 74-75.
- Joint Chiefs of Staff Washington DC. 2005. *Department of defense dictionary of military and associated terms*. Accessed 07 Dec 2005.
- Kalfoutzos, Aristeidis. 2002. Free electron and solid state lasers development for naval directed energy. Master of Science, Naval Postgraduate School Monterey, CA.
- Keuren, E. Van, and J. Knighten. 1991. Implications of the high-power microwave weapon threat in electronic system design.
- Knowles, J. 1996. Early morning DEW: Directed energy weapons come of age. *Journal of Electronic Defense* 19, (10): 48.

- Kochems, Alane, and Gudge, Andrew. The viability of directed-energy weapons in The Heritage Foundation [database online]. 2006 [cited 02/09 2007]. Available from <http://www.heritage.org/Research/NationalSecurity/bg1931.cfm>.
- Kopp, C. 1996. *An introduction to the technical and operational aspects of the electromagnetic bomb*, Air Power Studies Centre.
- Kopp, C., and R. Pose. The impact of electromagnetic radiation considerations on computer system architecture.
- Kumar, C., N. Patel, and Nicolaas Bloembergen. 1987. Strategic Defense and Directed-Energy Weapons. *Scientific American* 257, (3): 39-45.
- Laser weapons in Jane's Information Group [database online]. 2007 [cited 05/17 2007]. Available from <http://www8.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/binder/jsws/jsws0514.htm@current&pageSelected=allJanes&keyword=Chinese ZM-87>. Accessed May 2007.
- Mansfield, Robb P. 2005. High energy solid state and free electron laser systems in tactical aviation. Master's Thesis, Naval Postgraduate School Monterey, CA.
- Mark, Hans. 2002. The airborne laser from theory to reality: An insider's account. *Defense Horizons* 12, (April 2002): 1-1-6, <http://www.ndu.edu/inss/DefHor/DH12/DH12.htm> Accessed 22 Feb 2007.
- Monash University Clayton (Australia), and Carlo Kopp. 1996. *The electromagnetic bomb - A weapon of electrical mass destruction*.
- Mowthorpe, Matthew. The revolution in military affairs and directed energy weapons in *Air & Space Power Journal* [database online]. 2002 [cited 02/09 2007]. Available from <http://www.airpower.maxwell.af.mil/airchronicles/cc/mowthorpe02.html> Accessed 9 Feb 2007.
- NASA. The electromagnetic spectrum in NASA [database online]. March 17, 2006 [cited April 2007]. Available from http://www.nasa.gov/centers/glenn/images/content/83574main_fs013fig4.gif. Accessed May 2007.
- National Air Intelligence Center Wright-Patterson AFB OH, Hui Li, and Zibin Wang. 1996. *Development of foreign high-powered microwave weapons and prospects of future applications in space-based target defense and air defense*.
- National Air Intelligence Center Wright-Patterson Afb OH, and Zhu Zhihao. 1996. *Trends of microwave weapon development*.

- National Defense Univ. Washington DC Center for Counterproliferation Research, and Dennis B. Herbert. 1999. *Non-lethal weaponry: From tactical to strategic applications*.
- National Defense University Washington DC Center for Technology and National Security Policy, and Elihu Zimet. 2002. *Defense horizons. Number 18, October 2002. High-energy lasers: Technical, operational, and policy issues*.
- Naval Air Warfare Center Aircraft Div. Patuxent River MD, and Sam Frazier. 2000. *Radio frequency weapons*.
- Naval Postgraduate School Monterey CA, and Aristeidis Kalfoutzos. 2002. *Free electron and solid state lasers development for naval directed energy*.
- Naval War College Newport RI Joint Military Operations Dept., and Sean L. Jersey. 2003. *Twenty first century warfare -- theater operations at the speed of light*.
- Nicholas, Ted, and Rita Rossi, eds. 2006. *U.S. weapon systems costs*. Fountain Valley, CA: Data Research Associates.
- Nielsen, Philip E., and National Defense University Press. 1994. *Effects of directed energy weapons [electronic resource]*. Washington, D.C: NDU Press, <http://purl.access.gpo.gov/GPO/LPS36040>. Accessed May 2007.
- Niles, Segan P. 2005. High energy laser applications in a Surface Combatant: Terminal phase Theater Ballistic missile defense, low Atmosphere Propagation, and free electron laser gain. Master's Thesis, Naval Postgraduate School Monterey CA.
- Noam, Kogan, Shavitt Yuval, and Wool Avishai. 2003. A practical revocation scheme for broadcast encryption using smart cards. Paper presented at a practical revocation scheme for broadcast encryption using smart cards; 2003 IEEE Symposium on Security and Privacy, May 11-14 2003,
- Office of the Secretary of Defense Washington DC. 2001. Special technology area review on lost cost, mass producible, solid-state lasers.
- Olsen, Richard C. 2005. Remote sensing from air and space, Naval Postgraduate School Monterey, CA.
- Personnel halting and stimulation response (PHaSR) in United States Air Force [database online]. Kirtland AFB, NM, 2006 [cited 05/22 2007]. Available from <http://www.de.af.mil/FactSheets/PHaSR.pdf>. Accessed May 2007.
- Phillips Lab Kirtland AFB NM. 1996. *Advanced weapons technology area plan FY96*.

- Possel, William H., and Air University (U.S.). Center for Strategy and Technology. 1998. *Lasers and missile defense: New concepts for space-based and ground-based laser weapons*. Occasional paper air university U.S... Center for strategy and technology; no. 5. Maxwell Air Force Base, Ala: Center for Strategy and Technology, Air War College, Air University, <http://www.au.af.mil/au/awc/awcgate/cst/csats5.pdf>. Accessed May 2007.
- Qu, W. Y., and J. L. Wang. 2003. Analysis on atmospheric breakdown of high power microwave pulse.
- Royal Institution of Naval Architects. 2004. *International conference: Warship 2004: Littoral warfare & the expeditionary force*. London: Royal Institution of Naval Architects.
- Richard J. Dunn, III. Operational implications of laser weapons in Northrop Grumman Corporation [database online]. United States of America, 2006 [cited 05/12 2007]. Available from http://www.analysiscenter.northropgrumman.com/files/Operational_Implications_of_Laser_Weapons.pdf. Accessed May 2007.
- Scannell, Edward P. 2003. Progress in directed energy weapons part II: High power microwave weapons. *Weapon Systems Technology Information Analysis Center 4*, (3) (Fall): 1-8.
- Schamiloglu, E. 2004. High power microwave sources and applications.
- Schroerer, Dietrich. 1987. *Directed-energy weapons and strategic defense: A primer*. London: International Institute for Strategic Studies.
- Scientific Advisory Board (Air Force) Washington DC. 1995. *New world vistas: Air and space power for the 21st century. Directed energy volume*. (Accessed 09 Apr 1997).
- Scleher, D. Curtis. 1999. *Electronic warfare in the information age*. Boston: Artech House.
- Scott, Mark. Progress in directed energy weapons part I: High energy laser in Weapon Systems Technology Information Analysis Center [database online]. Alexandria, VA, 2003 [cited 02/09 2007]. Available from http://wstiac.alionscience.com/NewsAndEvents/Wstiac_NewsLetter.html. Accessed May 2007.
- Sforza, P. M., and H. Zmuda. 2003. Journal of directed energy. *Journal of Directed Energy 1*, (Fall 2003): 1-1-92.

- Sheymov, Victor. The low energy radio frequency weapons threat to critical infrastructure in Joint Economic Committee United States Congress [database online]. GlobalSecurity.org, 1998. Available from http://www.globalsecurity.org/intell/library/congress/1998_hr/sheymov.htm. Accessed Feb 2007.
- Sirak, Michael. 2005. Directed-energy protection systems unveiled by raytheon. *Jane's Defence Weekly* October, (09/30/2005): 1-1-3, http://www8.janes.com/Search/documentView.do?docId=/content1/janesdata/mags/jdw/history/jdw2005/jdw12140.htm@current&pageSelected=allJanes&keyword=protection%20systems%20unveiled%20by%20raytheon&backPath=http://search.janes.com/Search&Prod_Name=JDW&. Accessed 26 Feb 2007.
- Spencer, Jack, James Jay Carafano, and Heritage Foundation (Washington, D.C.). 2004. *The use of directed-energy weapons to protect critical infrastructure*. Backgrounder; No.1783. Washington, DC: Heritage Foundation, <http://www.heritage.org/Research/NationalSecurity/bg1783.cfm>. Accessed Feb2007.
- Steward, Charles. 2006. Weapons of mass casualties and terrorism response handbook. *Scitech Book News* 30, (2) (Jun): n/a, <http://proquest.umi.com/pqdweb?did=1051038911&Fmt=7&clientId=65345&RQT=309&VName=PQD>. Accessed Feb 2007.
- Sweetman, Bill. 2006. High-power microwave weapons - full power ahead? *Jane's Defence Weekly* (AUG).
- Tactical Weapons Guidance and Control Information Analysis Center IL, Eric J. Borg, Paul Lavalee, James Lawson, W. K. Fluhler, and Kim Eubank. 1993. *AMC-SWMO countermeasures study. Volume 1. Guide to how countermeasures affect smart weapons*.
- Taylor, Clayborne D., and D. V. Giri. 1994. *High-power microwave systems and effects*. Electromagnetics library. Washington, D.C: Francis & Taylor.
- Thompson, Loren B. Future Challenges Facing U.S. Air: LexingtonInstitute.org in Lexington Institute [database online]. Arlington, VA, 2005 [cited 02/26 2007]. Available from <http://www.lexingtoninstitute.org/701.shtml>. Accessed 8 Feb 2007.
- The emerging promise (and danger) of directed-energy weapons: LexingtonInstitute.org in Lexington Institute [database online]. Arlington, Virginia, 2002 [cited 02/26 2007]. Available from <http://www.lexingtoninstitute.org/255.shtml>. Accessed 8 Feb 2007.
- Thompson, Loren B., and Daniel Goure. 2003. *Directed-energy weapons technologies, applications and implications*. Arlington, Virginia: Lexington Institute.
- Tirpak, John A. 2002. Attack at the speed of light. *Air Force Magazine* 85, (12): 26-32.

- Turkish General Staff. Turkish armed forces mission in Turkish General Staff [database online]. Ankara, 2007. Available from http://www.tsk.mil.tr/eng/genel_konular/gorevi.htm. Accessed Apr 2007.
- U.S. Air Force unveils hand-held laser gun in Jane's Information Group [database online]. Washington, DC, 2005. Available from <http://www8.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/mags/jdw/history/jdw2005/jdw12758.htm@current&pageSelected=allJanes&keyword=%22Personnel%20Halting%20and%20Stimulation%20Response%22&backPath=http://search.janes.com/Se>. Accessed May 2007.
- U.S. Army tests anti-mine laser. *Jane's Defence Weekly* September, (08/30/2002): 1-1-2, http://www8.janes.com/Search/documentView.do?docId=/content1/janesdata/mags/jdw/history/jdw2002/jdw02474.htm@current&pageSelected=allJanes&keyword=us%20army%20tests%20anti-mine&backPath=http://search.janes.com/Search&Prod_Name=JDW&. Accessed 26 Feb 2007.
- United States. Congress. Joint Economic Committee. 1998. Radio frequency weapons and proliferation, potential impact on the economy: Hearing before the joint economic committee, congress of the United States, one hundred fifth congress, second session, February 25, 1998. United States. Congress. Senate. S. hrg. ; 105-445. Washington: U.S. G.P.O.
- Van Keuren, E., and J. Knighten. 1995. Use of high power microwave weapons.
- Vehicle-mounted active denial system (V-MADS) in GlobalSecurity.org [database online]. 2007. Available from <http://www.globalsecurity.org/military/systems/ground/v-mads.htm>. Accessed May 2007.
- Vetrovec, John. 2002. Solid-state laser high-energy laser. Paper presented at Laser and Beam Control Technologies, Jan 21-23 2002, <http://dx.doi.org/10.1117/12.469752>. Accessed May 2007.
- Vollin, Jeff. 2006. Vigilant eagle: Ground-based countermeasure system against MANPADS. *Optics and Photonics in Global Homeland Security II*.
- Weichel, Hugh. 1990. *Laser beam propagation in the atmosphere SPIE-International Society for Optical Engine*.
- Weise, Th H. G. G., M. Jung, D. Langhans, and M. Gowin. 2004. Overview of directed energy weapon developments. Paper presented at 2004 12th Symposium on Electromagnetic Launch Technology - Selected Papers from the 12th Symposium on Electromagnetic Launch Technology; 2004 12th Symposium on Electromagnetic Launch Technology, Snowbird, UT, United States.

Wells, H. G. 1898. *The War of the Worlds*.

Wilkenfeld, J., J. Knighten, and E. Van Keuren. 1991. Utilization of high-power microwave sources in electronic sabotage and terrorism.

Williams, Robert E. 2004. *Naval electric weapons: The electromagnetic railgun and free electron laser [electronic resource]*. Monterey, CA; Springfield, VA: Naval Postgraduate School; Available from National Technical Information Service, <http://library.nps.navy.mil/uhtbin/hyperion/04Jun%5FWilliams.pdf> (1.26 MB); <http://handle.dtic.mil/100.2/ADA424845>. Accessed May 2007.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California
3. Professor Dan Boger
Department of Information Sciences
Monterey, California
4. Professor Edward Fisher
Department of Information Sciences
Monterey, California
5. Terry Smith
Lt. Col. USAF
IW/EW Program Officer
Monterey, California
6. Bayram Mert Deveci
Turkish Army
Ankara, Turkey
7. Kara Harp Okulu Savunma Bilimleri Enstitüsü
Ankara, Turkey
8. Deniz Harp Okulu
Deniz Harp Okulu Kütüphanesi
İstanbul, Turkey
9. Hava Harp Okulu
Hava Harp Okulu Kütüphanesi
İstanbul, Turkey