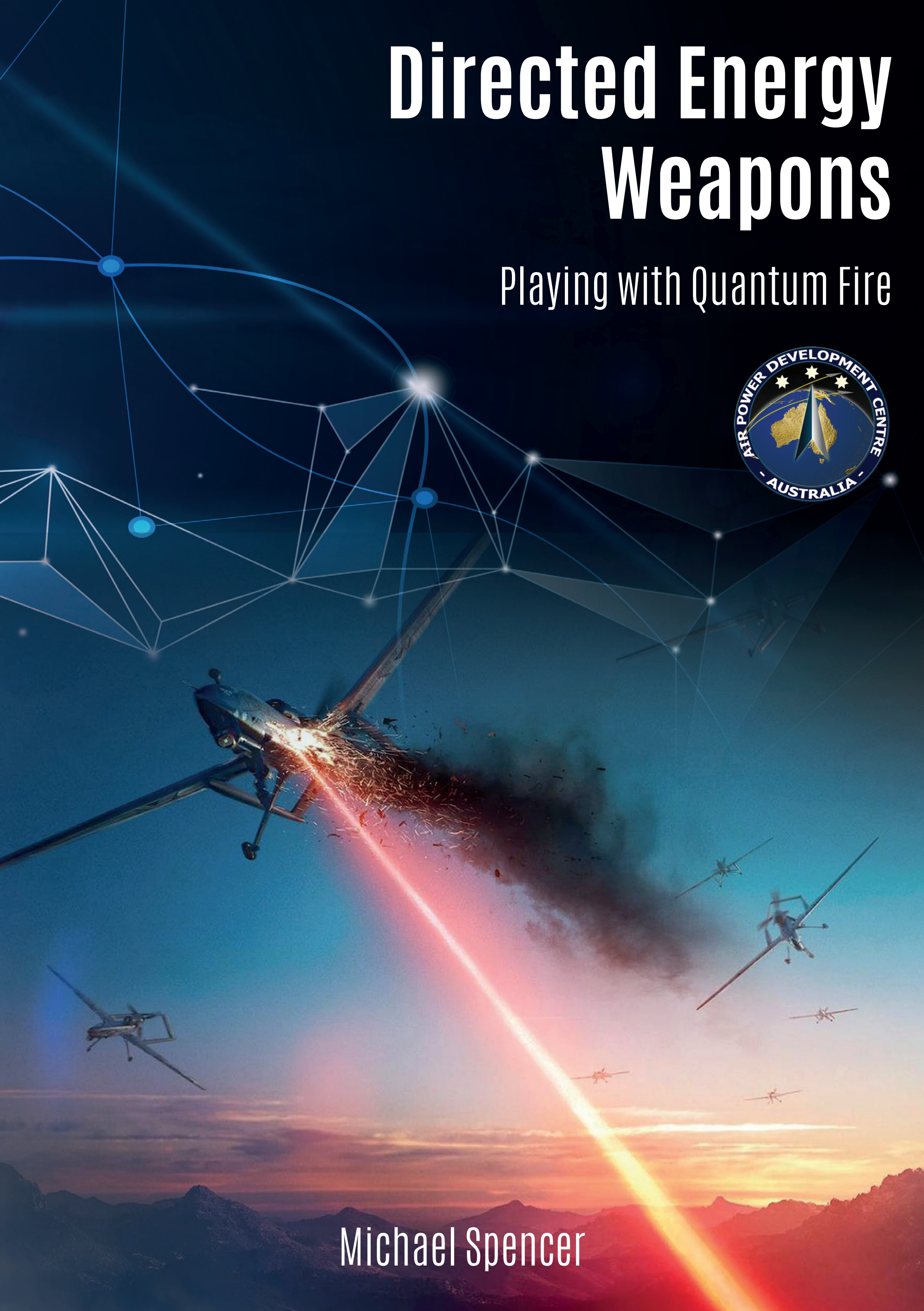
Directed Energy Weapons

Playing with Quantum Fire



Michael Spencer

Directed Energy Weapons

Playing with Quantum Fire

Michael Spencer

AIR POWER DEVELOPMENT CENTRE

AUSTRALIA

Disclaimer
The views expressed in this document are those of the authors and do not necessarily reflect the official policy or position of the Department of Defence, the Royal Australian Air Force, or the Government of Australia. This document is approved for public release; distribution unlimited. Portions of this document may be quoted or reproduced without permission, provided a standard source credit is included.

This document was written for use as an academic text to promote the thinking and discussion on the philosophies and concepts for the Australian employment of air power, in a public domain. The works of APDC are produced for academic purposes and are not intended to be used as technical analyses of foreign military systems. APDC uses information sources and products that are available in the public domain as open sources.

ISBN: 9781925062434
9781925062441 (on-line version)

Published and distributed by:
Air Power Development Centre
F3-G, Department of Defence
PO Box 7932
CANBERRA BC 2610
AUSTRALIA

Telephone: + 61 2 6128 7041
Facsimile: + 61 2 6128 7053
Email: airpower@defence.gov.au
Website: www.airforce.gov.au/airpower

Foreword

Beyond the Planned Air Force (BPAF) introduces topics intended to extend Air Force's perspective beyond the objective force envisioned in Defence White Papers and the Defence Integrated Investment Plan. The broad aim is to identify and explore in greater depth how technological, societal, and environmental disruptors and drivers could shape Air Force's ways and means of providing air power for Australia.

In this working paper, Michael Spencer explores potential future developments in Directed Energy Weapons (DEW) to understand their potential for improving the effectiveness of Australian air and space power. Indeed, many of the science and system design principles used for DEW are already applied to realising and operating technologies such as optical communications, light detection and ranging, laser designation, and laser scanning, resulting in improvements in power combined with reduction in the cost of generating directed energy. In short, air forces can ill-afford to ignore the possibilities on offer, particularly in light of the increasing cost of modern 'exquisite' military platforms. This paper represents a timely primer on the science and operational possibilities of DEW and serves to underscore the utility of directed energy across the spectrum of conflict.

JL Pendlebury
Group Captain
Director, Air Power Development Centre

January 2020

About the Air Power Development Centre

The *Air Power Development Centre (APDC)* was established by the Royal Australian Air Force in 1989. The APDC provides practical and effective analysis and advice on the strategic development of air and space power to the Chief of Air Force, the Royal Australian Air Force, and its partners.

The APDC mission is to support strategic decision-making about the future of air and space power for Air Force and its partners.

Air and space power is a cornerstone of Australia's security, and Australia's unique strategic geography means that will always be so. As the principal provider of Australia's air and space power, the RAAF is tasked with the conduct of air and space operations in pursuit of the nation's security and defence. As exponents of air and space power, all members of the RAAF have an inherent responsibility to be knowledgeable regarding the theory and doctrine of air and space power.

Beyond the Planned Air Force

The APDC published *Beyond the Planned Air Force (BPAF)* in 2017 to introduce a series of topics to extend Air Force perspectives beyond the objective force envisioned in the Defence White Paper and the Defence investment planning guidance. Building upon the culture of innovation engendered by Plan Jericho, BPAF sought to challenge readers to explore how technological, societal, and environmental disruptors and drivers will shape Air Force's ways and means of providing air power in support of Australia's national interests. By encouraging creative and critical thinking, BPAF aims to extend the five vectors of the Air Force Strategy beyond 2027 into an uncertain future.

BPAF is not a prediction or forecast, nor is it a plan for force design beyond 2027. Instead, it aims to promote discussion and creative and critical thought about the future of Australian air power. It is not policy nor a roadmap, but a catalyst that sparks the imaginations of airmen in envisioning the Air Force as it will evolve in an uncertain future.

BPAF was just the start; the APDC has embarked on a program to publish working papers that explore the possible effects of disruption on future air power.

About the Author

Wing Commander Michael Spencer is an Officer Aviation (Maritime Patrol & Response) currently serving in the Air Power Development Centre to analyse the potential risks and opportunities posed by technology change drivers and disruptions to future air and space power. He gained his operational flying experiences with No 10 Squadron on the P-3C Orion long-range maritime patrol aircraft. He has been a student and instructor of the RAAF General Duties Weapons Systems Course at the former RAAF School of Air Navigation and managed the capability development and acquisitions of air-launched guided weapons.

He is an Australian Institute of Project Management certified project manager and an Associate Fellow of the American Institute of Aeronautics & Astronautics. He has completed postgraduate studies in aerospace systems, air weapons systems and weaponeering, information technology, project management, space mission systems, astrophysics, and the Defence Laser Safety Course. His other APDC publications include:

1. (2010) Pathfinder #147: Weapons in Space
2. (2017) Beyond the Planned Air Force
3. (2017, co-author) BPAF Series: Hypersonic Air Power
4. (2018) AFDN 1-19 Air-Space Integration
5. (2019, co-author) MQ-4C Triton: A Fifth Generation Air Force Disruption of Maritime Surveillance
6. (2019) Pseudosatellites: Disrupting Air Power Impermanence
7. (2019) Dragon's Jaw: the Vietnam War target that paved the way to a modern precision air weapon
8. (2019, co-author) Project ASTERIA 2019 – Space Debris, Space Sustainability, and Space Traffic Management
9. (2020, co-author) BPAF Series: Nuclear-Engine Air Power

10. (2020) Remote Sensing for Bushfires – An Air and Space Advantage
11. (2020) BPAF Series: Quantum-Enabled Air Power – microscopic disruption of the macroscopic

Acknowledgements

The BPAF writing team acknowledges the close cooperation it enjoys with the Defence Science Technology Group in the development of this working paper. APDC wishes to thank the expert advice coordinated and provided by Dr Shane Dunn.

APDC gratefully acknowledges the support provided by Mr Damien Kroek to editorially review this document and Mr Graeme Smith to edit and format this document for publishing.

Table of Contents

Foreword......3
About the Air Power Development Centre......4
Beyond the Planned Air Force......5
About the Author......6
Acknowledgements......8
Table of Contents......9
Executive Summary......11

Introduction......15
DEW in Australian Defence Doctrine......17
Australian Governance of Radiation Protection and Safety......19
The Physics of Starting a 'Quantum Fire'......20
DEW Effects......22
DEW Safety and Collateral Damage Risks......30
Generating DEW Effects......33
Environmental Effects on DEW Performance......40
A Generic DEW System Design......44
DEW Mission Attributes......59
Operations Law Considerations......64
Integrating DEW into Air and Space Operations......65
Current and Emerging Applications for Directed Energy......73
Conclusions......80
Glossary......82
Endnotes......83
Endnotes......97

Executive Summary

1. Directed Energy Weapon (DEW) effects originate from exploiting quantum behaviours occurring on the subatomic scale to convert energy from one form into another form for exploiting a vulnerability in a target to cause disruption, damage, or destruction.

2. Specialised laws govern the designs and uses of DEW.

3. The typical designs for a DEW include subsystems for a power supply, energy source, energy converter, beam director, thermal management, and platform integration. The DEW needs to be integrated to other systems needed for mission planning, command and control, and target acquisition and tracking, for example.

4. DEW requires accurate pointing to hold the energy beam steady to dwell on the target for a long enough time to transfer energy adequate to cause a material or design failure in the target or disrupt the electrical circuitry.

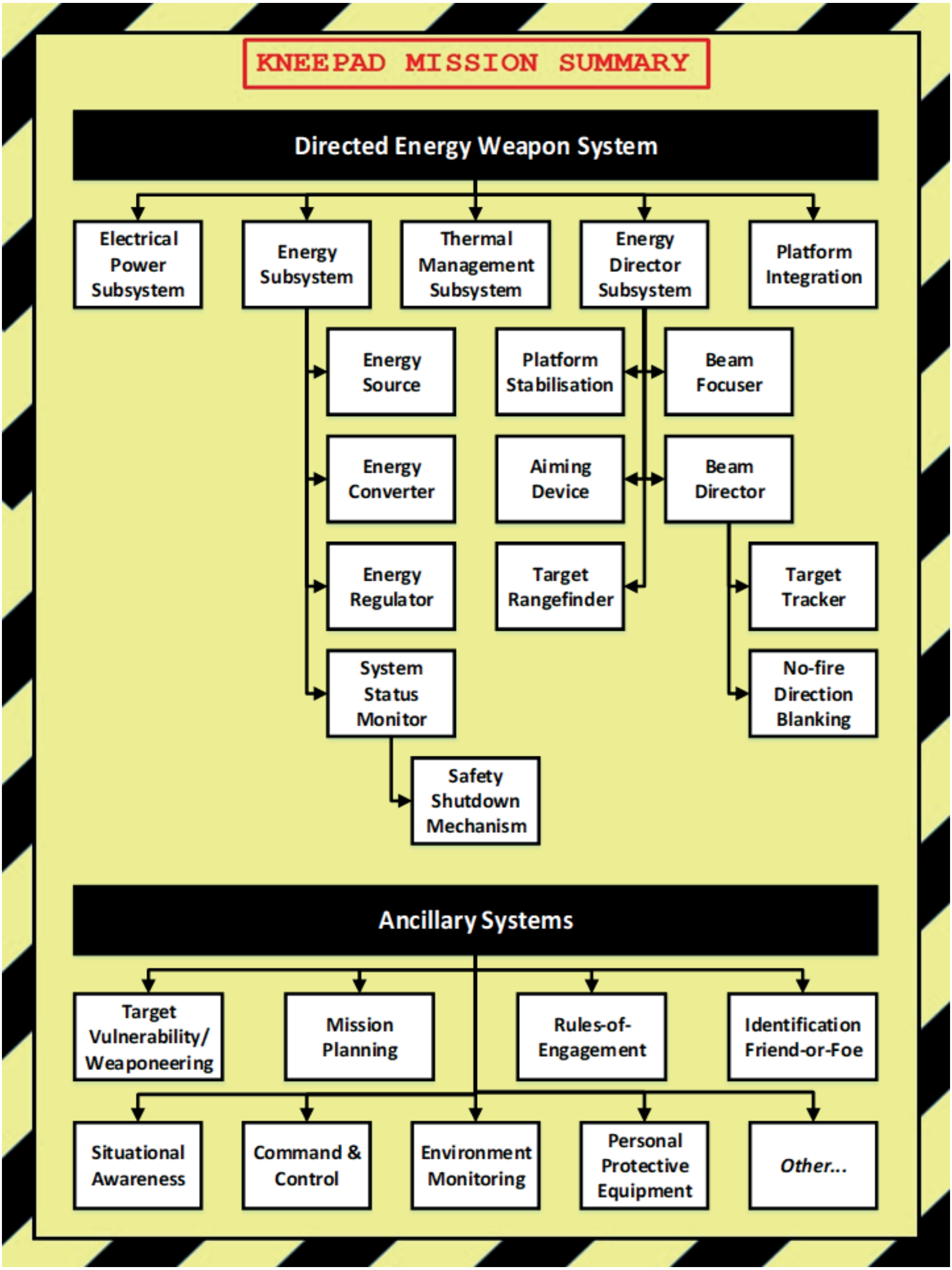
5. DEW damage mechanisms can range from the low-energy temporary dazzling of aircraft/spacecraft optical sensors, inflicting heat discomfort and injury to combatants, to high-energy catastrophic damage of material systems including aircraft and spacecraft.

6. It is not the energy output by a DEW but the energy that is absorbed by the target that is significant to plan the designs and damage effects for DEW. Some targets, such as re-entering ICBM warheads and hypersonic missiles, may use materials that are designed to resist and survive high temperatures; some materials may reflect the light energy away from the target.

7. A cost-benefit of DEW is the significant reduction in the recurring cost of a non-kinetic energy pulse compared to the cost of kinetic weapon rounds used against the targets. However, the non-recurring expense of the DEW launcher systems, especially its energy source, will require more investments into the designs for

energy storage, management, and conversion, and more complex aiming systems.

8. The integration of DEW into domestic and military operations needs to consider the potential for DEW spillover and collateral damage risks.


KNEEPAD MISSION SUMMARY
Directed Energy Weapon System
Electrical Power Subsystem
Energy Subsystem
Thermal Management Subsystem
Energy Director Subsystem
Platform Integration
Energy Source
Platform Stabilisation
Beam Focuser
Energy Converter
Aiming Device
Beam Director
Energy Regulator
Target Rangefinder
Target Tracker
System Status Monitor
No-fire Direction Blanking
Safety Shutdown Mechanism
Ancillary Systems
Target Vulnerability/ Weaponeering
Mission Planning
Rules-of-Engagement
Identification Friend-or-Foe
Situational Awareness
Command & Control
Environment Monitoring
Personal Protective Equipment
Other...

"Another revolution in weaponry is currently underway, with directed-energy weapons on the cusp of replacing chemical-powered weapons on the battlefield. DEWs use the electromagnetic spectrum (light and radio energy) to attack pinpoint targets at the speed of light. They are well-suited to defending against threats such as missiles and artillery shells, which DEWs can shoot down in mid-flight. In addition, controllers can vary the strength of the energy put on a target, unlike a bullet or exploding bomb, allowing for nonlethal uses".

- A Kochems & A Gudgel[1]

INTRODUCTION

Conventional weapons are based on using energy to propel a projectile with a warhead to interact with the target, and this interaction initiates a damage mechanism that normally releases energy in different forms, tailored for the mission to achieve the desired effect at the target. Directed Energy Weapons (DEW) use a different approach for delivering disruptive or damaging levels of energy to the target; energy is generated from a source and directed towards the target until the accumulative energy absorbed by the target reaches the threshold for causing an appropriate damage effect – disruption, repairable damage, or catastrophic destruction.

Figure 1. Archimedes is credited with inventing the first DEW by deploying sun-reflecting mirrors against Roman ships attacking Syracuse in 212 BCE.[2]

A DEW is a weapon system that uses an energy source and a pointing system to control the delivery of electromagnetic energy (ie electromagnetic, laser, microwave, photonic energy, and nuclear radiation) as a means to damage or destroy enemy equipment, facilities, or injure enemy personnel.[3] An ancient Greek legend describes how, in 212 BCE, Archimedes[4] defended the city of Syracuse from an attack by Roman warships by constructing a glass reflector to deflect and amplify the sun's rays to set the Roman warships afire, as depicted in Figure 1.

The story has been much debated by historians and been dismissed as a myth. However, modern technology is enabling designs for DEW that are 'game-changing' weapons and are currently in development. They may enable targets to be engaged at the speed of light at tactically significant ranges. Whilst a missile warhead functions to rapidly transfer kinetic/thermal energy at the target, the DEW functions to rapidly deliver and accumulate a damaging level of electromagnetic/thermal energy at the target. The desired damage is achieved when the target absorbs a level of energy adequate to disrupt its correct functioning.

DEW IN AUSTRALIAN DEFENCE DOCTRINE

The ADF introduction of advanced Electronic Warfare (EW) capabilities, either as new and enhanced combat platforms, is coordinated to assure the viability of EW and other capabilities tasked to function in a congested and contested electronic spectrum without detriment to the other capabilities integrated into Australian joint force warfighting. The ADF has established the Information Warfare Division within ADF Headquarters to be the capability manager for Information Warfare, including Joint Electronic Warfare, within Defence.[5]

EW is defined by the ADF as "military action to exploit the electromagnetic spectrum, encompassing: the search for, interception and identification of electromagnetic emissions; the employment of electromagnetic energy, included directed energy, to reduce or prevent hostile use of the electromagnetic spectrum; and actions to ensure its effective use by friendly forces".[6] EW consists of three functions: electronic support (ES), electronic protection (EP) and electronic attack (EA), as depicted in Figure 2.

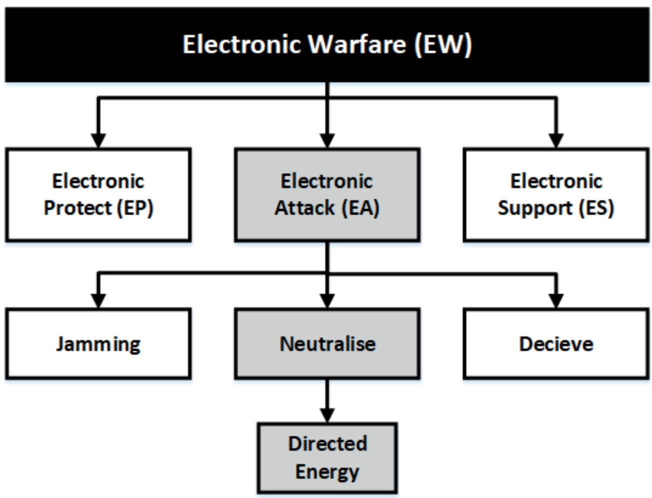


Figure 2. Hierarchy of joint doctrine for electronic warfare and directed energy.

EW contributes to a range of effects. An indicative list of desired effects that may be achievable within the operational environment is described in *ADDP 3.5 Operations Series – Electronic Warfare*[7]. Actions may have second and third-order effects, which require consideration in planning. EW effects include but are not limited to:

- **Disrupt.** A tactical task to break apart an adversary's formation and tempo, interrupt the adversary timetable or cause premature and/or piecemeal commitment of forces.
- **Deny.** A tactical task to prevent enemy use of a specified thing.
- **Destroy.** To physically render a group or organisation ineffective unless it is reconstituted.
- **Neutralise.** A tactical task to render an enemy element temporarily incapable of interfering with the operation.
- **Limit.** The ability of electronic activity to either temporarily or permanently restrict the capacity and actions of an adversary.
- **Protect.** A tactical task to provide safety for an individual, group or force and prevent any loss as a result of adversary or other action.

EA is defined as "that division of electronic warfare involving the use of electromagnetic energy, directed energy, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralising, or destroying adversary combat capability and is considered a form of fires".[8]

"Directed Energy" refers to technologies that are related to the production of a beam of concentrated electromagnetic energy or atomic or subatomic particles. A directed energy weapon is a system using directed energy primarily as a directed means to damage or destroy adversary equipment, facilities and personnel. Possible applications include lasers, radiofrequency weapons and particle beam weapons.[9]

AUSTRALIAN GOVERNANCE OF RADIATION PROTECTION AND SAFETY

Safety in the utility of laser and radiation are controlled by regulations promulgated by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).[10] ARPANSA is the agency responsible as the regulatory authority identified in the legislated framework[11] for regulating the Commonwealth's radiation and nuclear activities. The legislation reflects international best practice in radiation and nuclear regulation and is consistent with the requirements for radiation protection and nuclear safety of the Australian State and Territory regulatory authorities. This responsibility includes the coordination and facilitating of ARPANSA compliance inspections and coordinating the administrative requirements of the Defence Source and Facility licences.

Defence governance of ADF employment of radiation sources and facilities is administered by the Chief of Joint Capabilities (CJC) under a logistics governance structure. Commander Joint Logistics (CJLOG) is delegated the responsibility to manage the licences as Defence's 'Single Point of Accountability' for the radiation sources and facilities in the Defence Radiation Safety Domain. This Defence managed domain covers the Defence owned radiation safety risks arising from controlled radiation sources held under the Defence Source and Facility licences (regulated by ARPANSA), non-controlled radiation apparatus (items of plant regulated by Comcare), and nuclear materials held under safeguards permit (regulated by the Australian Safeguards and Non-proliferation Office [ASNO]).

CJLOG exercises responsibilities across the Defence Radiation Safety Domain for:

1. radiation safety hazard management,
2. radiation regulatory management, and
3. radiation compliance and assurance.

THE PHYSICS OF STARTING A 'QUANTUM FIRE'

DEW operations are largely based on the principles of quantum mechanics and actions occurring on a subatomic scale. Quantum physics is useful to describe the behaviours of light and its interactions with matter at the subatomic scale.[12] When light or electrical energy is pumped into certain laser materials, electrons within individual atoms can be excited to jump from a lower-energy level orbit (ie ground state) to a higher-energy level orbit (ie excited state), in a process called 'spontaneous absorption'. However, the electron will not naturally stay in the excited state forever and, eventually, its energy spontaneously decays for it to drop back to the ground state, in an event called a 'spontaneous emission.'

When spontaneous emission occurs, the decaying electron releases energy, which is the difference between the excited state and ground state, as a massless photon. Now, this new photon travels through the subatomic structures and when it strikes an excited electron in another atom, it causes that electron to itself release a photon before returning to its ground state – this process is called 'stimulated emission' – generating a second similar photon that travels with the original photon in the same phase, with the same wavelength and at the same wavefront.

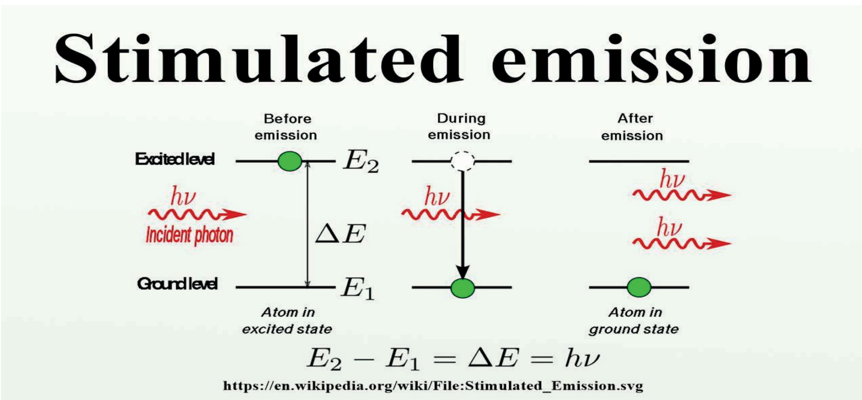


Figure 3. Light amplification by stimulated emission of radiation (LASER).[13]

By reflecting these stimulated emissions back and forth through the laser material, these photons can form larger groups of many photons that continue to be amplified and accumulate into larger groups as they continue to pass electrons in excited states. This increases the number of photons, released from stimulated emissions of radiation, which eventually reaches a threshold level of energy needed to escape the laser medium. The output light energy is characteristically more energetic than natural light because laser light has the following properties:[14]

1. monochromatic light (ie all photons have the same wavelength),
2. coherent (ie all wavelengths are in the same phase) enabling positive interference to increase the power output by accumulating multiple wavelengths, and
3. collimated (ie all photons are travelling in the same direction in parallel) which makes it directional.

Recent innovations, motivated by discoveries in quantum physics and nanotechnology, have resulted in the synthesis of 'quantum dots'[15] as an artificially fabricated material that is a more effective and more efficient laser medium compared to the naturally sourced materials. On the atomic scale, quantum dots can be grown into better organized crystalline lattice structures with a more consistent size and distribution of atoms, compared to the random designs of natural materials. The use of quantum dots as a laser medium increases the efficiency of the energy generated by stimulated emissions and the total energy that can be output by a quantum dot laser, compared to a traditional laser.

Whilst laser is useful for delivery electromagnetic energy in the form of light and heat to damage or destroy material objects, the same quantum process can be used to also generate electromagnetic energy in other parts of the electromagnetic spectrum. By using different chemical mediums, stimulated emissions can generate energy with radio frequencies that may be exploited in electronic attacks to interfere, disrupt, or deny the use of the electromagnetic spectrum by an adversary. When the DEW generates this light energy, amplified by stimulated emissions of radiation (ie LASER) to start a quantum fire.

Purpose of DEW damage mechanism

There are different types of system designs for a DEW to output different forms and varying levels of energy. These design variations are each more efficient in different applications ranging from low-energy systems that cause physical discomfort for controlling crowds, to temporarily disrupting the functioning of electro-optical sensors, through to high energy systems for causing material damage. Some of these designs have already been introduced into service by different military forces around the world.

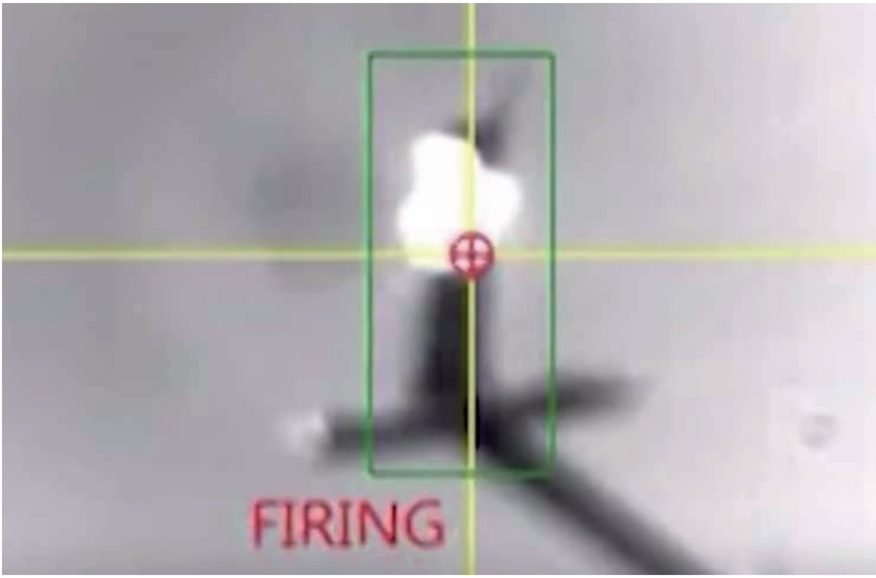


Figure 4. US Navy has trialled the detect-thru-engage laser shoot-down for defending against drone threats.[16]

The quantum effect occurring at the subatomic level can be scaled up to have a damaging effect on a macroscale scale in the physical world as a mechanism that delivers a damaging level of light and heat. A DEW is not a blast weapon - there is no blast, kinetic energy, fragmentation, impact or penetration; there is only thermal energy and light to cause non-kinetic damage effects. Blast, fragmentation, and additional heat damage may occur at the target as secondary effects arising from the initial interaction of the DEW energy and target materials.

The thermal energy damage mechanism relies on the thermal properties of the target materials being vulnerable to the absorption of heat concentrated into a small surface area in a very short duration. When a DEW beam strikes a target, the energy from the photons in the beam heats the target to the point of combustion or melting.

The challenge for using DEW to engage aerial targets is to be able to keep the DEW pointed at the same location on the target to dwell for long enough to deliver the energy needed to cause damage and destruction. Furthermore, some potential targets, like hypersonic vehicles and re-entering Inter-Contintental Ballistic Missile (ICBM) warheads are purpose-designed to survive and function normally in extreme temperatures.

In clear air or the vacuum of space, where there is nothing to interact with the light energy, the energy and momentum of the laser energy are conserved and can potentially travel forever. However, if there are aerosols, particulates, or obscurants in the air (eg water vapour, smoke, dust, etc) then the laser energy will interact with this matter and lose energy by transferring it to these objects, reducing the effectiveness of the laser as a consequence.

Additionally, the intensity of the laser emission is slowly dissipated over distance owing to beam divergence, reducing the density of the energy over a specified area with increasing distance away from the emitter. Manufactured laser optics are not perfect and will emit the laser energy in a nearly straight and parallel beam. However, the beamwidth will slowly spread over increasing distance away from the optical aperture, reducing the density of the energy per area.

Types of DEW damage mechanisms

Laser energy can be used to attack targets susceptible to high dwell times of concentrated light and/or thermal energy; radiofrequency and microwave energy can be used to attack all forms of electronic weapons, sensors, communication systems, and RF receivers.

1. **High Energy Laser (HEL)**. A HEL damages its target by directing energy onto the target for long enough to heat up and damage the surface material of the target. The aim of a HEL design for a DEW is to focus its emitted energy into a small spot area, concentrating the energy to heat up and damage the target as quickly as possible. DEW HEL damage mechanisms can be categorised according to the following descriptors[17]:

(a) High energy effects in all wavelengths that cause injury, damage and destruction (refer Figure 5):

– permanent eye injury;

– overload of charge-coupled devices used for capturing images in electro-optical and electronic sensors;

– disruption of radio frequency communications links (eg communications, remote control signals, GPS, etc); and

– thermal destruction of electro-optical sensors, aircraft, missiles, or spacecraft.

Figure 5. Laser thermal damaged drone target.[18]

(b) Low-energy effects in visible wavelengths, affecting human vision and electro-optical sensors (refer Figure 6):

– temporary flash-blindness;

– glare and disruption; and

– distraction.

Figure 6. Cockpit windows and air/spacecraft optical sensor functioning may be dazzled by low-power lasers.[19]

2. High Power Radio Frequency (HPRF). HPRF is non-ionising radiation, meaning that it has insufficient energy to break chemical bonds or remove electrons from atoms (ie ionisation). Sufficiently high levels of HPRF energy can increase the temperature and cause heat damage to human tissue. This is a potential cause for injury to personnel because of the body's inability to cope or dissipate the thermal energy that might be generated before tissue damage occurs.[20]

Figure 7. Example of "front door" electronic attack to disrupt the control signals between the drone and its remotely located controller.[21]

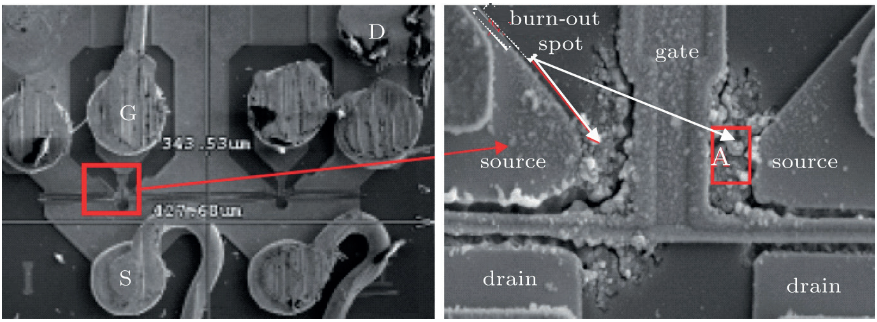


Figure 8. Microscopic scale "rear door" electrical damage to circuitry induced by high power microwave energy.[22]

3. **High Power Microwave (HPM).** The principle to damage mechanism of HPM is similar to controlling thunder and lightning to inflict electrical damage on electronic devices by exposing them to an extremely high powered pulse of electromagnetic pulse

energy through the 'front door' or the 'rear door' to describe the entry path for the damage effect to reach a target vulnerability.[23]

(a) **'Front door' damage**. Front door damage is associated with damage caused by the injection of HPM energy into equipment and systems that are purpose designed to normally receive this type of energy but not necessarily the high power (eg RF receiver antenna), in order to access the primary equipment. The strong incoming electromagnetic pulse is directionally guided to the targeted equipment to disrupt its operation by causing a malfunction or damage.

(b) **'Rear door' damage.** Rear door damage is associated with the damage caused by HPM energy generating an unwanted electrical charge within the electrical componentry such as leads, power cables, telephone lines, and metal shielding. The HPM energy can couple these components to access and disrupt the primary equipment. Semiconductors and modern electronics are particularly susceptible to HPM attacks. Although electronic devices can be shielded by installing conductive metal cages around the protected electronics, high enough power of microwave energy can still penetrate the shielding and cause damage.

(c) **Human tissue damage.** Human exposure to HPM radiation is hazardous because it generates both thermal effects and non-thermal effects on human tissue. Microwave energy can cause thermal heating which generates heat inside the human tissue, resulting in a burn injury. Low energy microwave radiation is also hazardous to human tissue, known as non-heat effect as it may cause neurasthenia and heart blood vessel system disorders.

Typical effects from DEW

A sample of the types of effects that can be achieved by a DEW on specific materials and target components is shown at Table 1.

DEW Type	Target	Typical Effect
High Energy Laser	Aircraft/helicopter canopy	Fogging/flash
	Thin-skinned vehicles	Burn-through
	Optics	Crazing/cracking
Low Energy Laser	Optical sensors	Saturation
	Missile seeker	Detector burnout
	Bio-optics	Vision degradation Temporary blindness Eye injury
High Power Microwave	Electrical systems	Electronic upset/jamming
	Electronic components	Disruption/negation/damage

Table 1. Comparison of generic DEW effects.[24]

A descriptive scale for DEW damage effects

A ratings scale that categorises and defines different levels of DEW damage effects is useful to discriminate damage levels associated with DEW designs with different energy levels. Currently, there is no widely accepted common standard reference for describing DEW damage levels.

Figure 9 shows a suggestion for a damage ratings scale that has been proposed for use in US Air Force Research Laboratories conducting HPM tests. The scale includes consideration for temporary and low-level damage effects such as 'interference' and 'upset', up to 'permanent damage'.

5	PERMANENT DAMAGE	Catastrophic and permanent effect until repaired	Target functioning is disrupted and requires hardware, software, or firmware replacement to repair and restore functionality
4	UPSET	Long-term effect until repaired	Target functioning and requires external intervention to recover (eg manual system reboot or power recycle)
3	DISTURBANCE	Temporary effect until recovered	Effect causes temporary target disruption that endures after illumination ceases; target system is capable of automatically self-managing its recovery to restore functions at some time after the illumination has ceased
2	INTERFERENCE	Temporary effect whilst illuminated	Effect causes temporary disruption of the target functionality only while illumination is occurring on the target
1	NO EFFECT	Known nil effect	Target is known to be unaffected when it is known to be illuminated
0	UNKNOWN/ UNOBSERVED	Unobservable, unknown effect	-

Figure 9. Suggestion for HPM effect scale and descriptions.[25]

DEW SAFETY AND COLLATERAL DAMAGE RISKS

Whilst the desired damage is planned to occur at the target, the nature of the DEW output energy poses a risk for collateral damage. Conventional warheads delivered by aircraft, missiles, and artillery projectiles, can be considered to be damage mechanisms that exist in a point location or travel as a point moving along a trajectory between the shooter and the target. However, the DEW damage mechanism can effectively cause damage along the entire straight-line trajectory between the shooter and the target, including any spillover beyond the target until the energy is absorbed or dissipated by the environment.

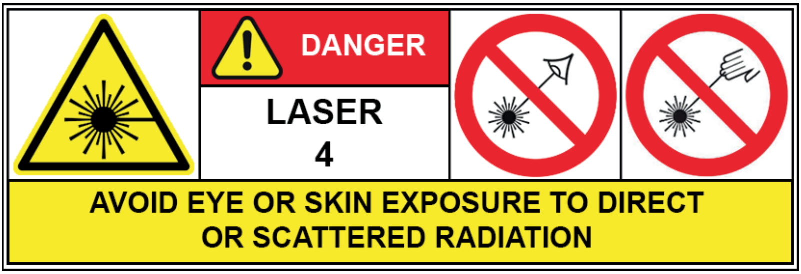


Figure 10. Warning signs for laser hazards.[26]

In a simple sense, a DEW can be likened to steering a 'hot wire' through the air onto the target and beyond; anything that incidentally contacts this 'hot wire' may incur collateral damage. Thus, it is important for mission planners and system operators to understand the optimum DEW-target engagement geometry needed to maximise the likely damage caused to the target and minimise the risks of unwanted collateral damage.

A safety hazard for all air and space activities is that the uncontrolled domestic and scientific use of skyward pointing lasers may inadvertently cause interference with the performance of crews and mission critical electro-optical sensors during critical phases of a flight or space mission.[27]

These hazards can result from direct and deliberate irradiation by DEW. Additionally, accidental spill-over can occur with that part of the laser energy that is not on the target and, because of beam divergence or standoff range, improper bore-sighting of the laser beam, or poor operator pointing procedures, may cause the laser energy to inadvertently extend beyond the target.[28]

Situational awareness around the target and the DEW beam path are essential for assuring mission success and safety in the battlespace, especially with the following hazard types:

1. **Direct intra-beam exposure.** Areas where there are personnel or moving targets in operation need a determination and evaluation of the hazards of operating a DEW in that area with due regard to the ranges for the different levels of danger associated with the different power levels of the DEW as the beam extends down the line-of-sight.
2. **Spill-over.** When the target is smaller than the DEW beamwidth or there is unsteady tracking of the target by the DEW pointing device, there may be energy spill-over around the target (figure 11). This energy spill-over could potentially cause collateral damage wherever the energy of the DEW extends beyond the target. The DEW shooter needs to be aware of the risks of collateral damage around and beyond the target, in line with the DEW beam direction.
3. **Diffuse and specular reflections.** Certain target materials reflect or absorb radiative energy better than others. The surface materials at the target may produce a mixture of effects including mirror-like and scattered reflections, in all directions, and energy absorption. The DEW shooter needs to be aware of the risks of collateral damage, around the target, from DEW reflections.
4. **Accidental intervention between the target and DEW shooter.** The DEW shooter needs to have situational awareness to assure a clear line-of-sight to the target for the duration that the DEW is functioning.

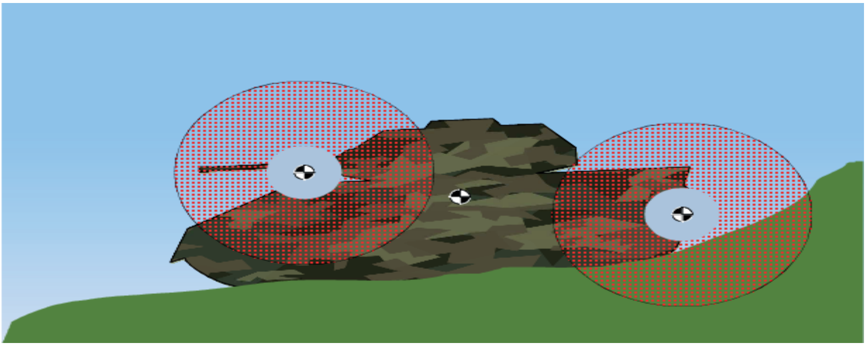


Figure 11. Laser spillover occurs when parts of the laser energy have not been stopped by the target or other obstacle and will continue beyond the target until stopped or energy dissipates.

5. DEW beam divergence. All project beams of electromagnetic energy will diverge over distance. The beamwidth of the DEW output energy increases as the distance away from the DEW increases. It occurs naturally and can be exacerbated by system quality and atmospheric effects.

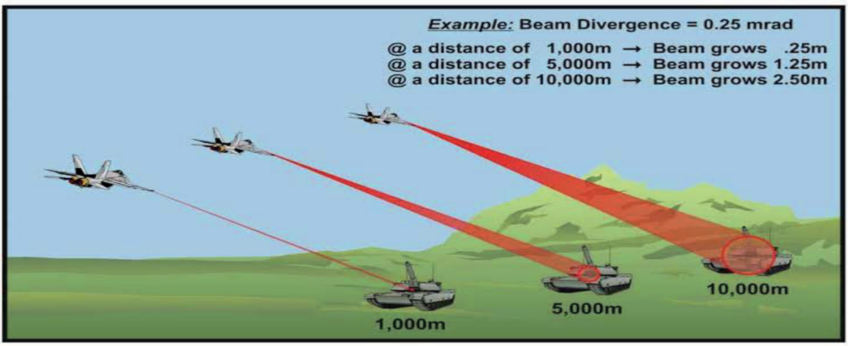


Figure 12. Depiction of beam divergence changes with increasing range-to-target.

GENERATING DEW EFFECTS

Designs for DEW effects

A significant benefit of DEW is to broaden the spectrum of conventional weapons options available to mission planners for engaging targets with an additional suite of non-kinetic effects. Additionally, there is the opportunity to realise cost-savings from using repeatable bursts of energy instead of expensive rounds of propellant filled-missiles and artillery cartridge to propel an explosive warhead system designed to mechanically function at the target. A laser shot may cost about $1 per firing compared to hundreds of thousands of dollars for a missile.[29] However, these savings may fail to be realised when considered together with the capital acquisition and operating costs for the total DEW 'launcher system'.

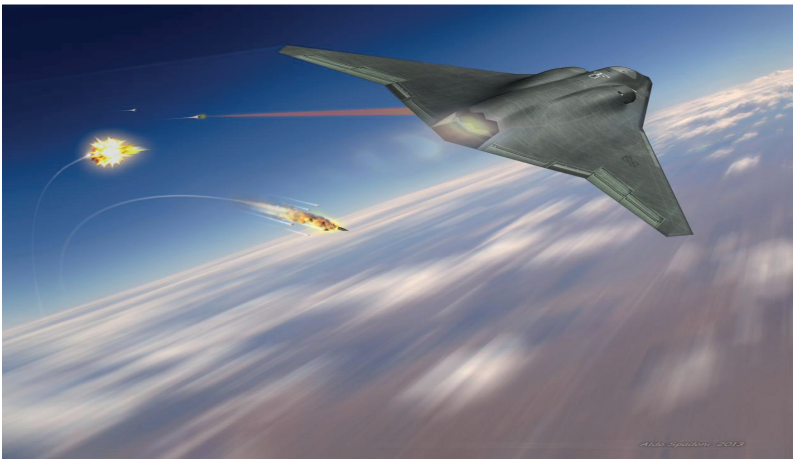


Figure 13. Current generation DEW designs enable aircraft to defend against air threats; future DEW designs may enable air vehicles to destroy air threats.[30]

The typical design for a DEW is based on key components, including the prime energy source, an energy converter to generate the directed-energy, an antenna to output the directed energy, and an antenna pointing system which may itself also include a target 'acquisition and tracking' system. The final mission capability will be based on trade-offs between the size and scale of the DEW system which may determine the energy output and its mission life (ie ground-based systems can be physically larger and more powerful; airborne systems may need to be physically smaller in size, constraining output power).

High-Energy Lasers (HEL) are the mainstay of DEW designs, enabling the delivery of energetic effects at the target that can range from temporary non-damaging effects by low-energy sensor-dazzling lasers through to high-energy laser systems that deliver destructive amounts of electromagnetic/thermal energy at the target. The emerging technically mature designs for HEL weapons are typically being driven by the needs for area air defence systems to rapidly engage multiple small high-speed aerial targets such as drones and missiles. The design for the higher energy systems may also be applied as attack systems. The solid-state and combined-fibre laser systems are more limited in power output than chemical lasers but potentially more useful in shorter-range point defence systems against rockets, artillery, mortars or soft targets such as small boats or unmanned aerial vehicles. The different types of HEL designs function as described below:

1. **HEL solid-state lasers**[31] are diode-pumped solid-state lasers and operate by pumping light-energy into a solid ruby or neodymium-YAG crystal, as the laser medium, in order to stimulate the emission of light photons of the same fixed wavelength and phase, all travelling in the same direction. The laser medium is coated with mirrored reflectors at either end for the coherent laser light beam to be reflected back and forth to 'pump' the laser medium and stimulate more light emissions. Once the amplified light pulse reaches the threshold energy required to pass through the mirror reflectors it exits the laser medium to propagate laser pulses into an optical pointing system.

> **Note**
>
> Solid-state lasers can offer a near-continuous target engagement, depending on the power supply, but their functioning is limited by the need to remove waste heat energy that results as a by-product from generating the laser.

2. **HEL chemical lasers[32],** unlike for solid lasers, use a chemical reaction occurring in a liquid or gaseous state to generate light energy. The chemical laser depends on the energy liberated by an exothermic reaction between two chemicals. Whereas solid lasers typically generate laser pulses, chemical lasers can achieve continuous-wave outputs with power levels reaching multiple-megawatts. The chemicals are consumed in the process; the laser effects cease once the available chemicals have been consumed. Chemical laser outputs can reach megawatts as exemplified by the US Air Force use of with the Airborne Laser Laboratory[33] in 2002 for trials in anti-ballistic missile defence.

> **Notes**
>
> Once the source chemicals, stored in the energy source, are totally consumed by the chemical generation of the laser energy, the laser cannot function until the chemicals are replenished.
>
> A safety risk associated with chemical lasers is the large quantities of highly toxic chemicals needed for storage and conversion to HEL energy which can impact the safety and design requirements for the ground crew, aircrew, host platform, and ground support equipment personnel.[34]

3. **HEL semiconductor fibre lasers[35]** use a fibre optic cable, doped along its length with a sequence of special rare-earth metal (similar to the semi-conductor in a light-emitting diode), as the laser medium. Thus, the fibre optic becomes both the laser generating medium, and a pointing mechanism, integrated into a single system. The fibre laser functions similar to a row of light-emitting diodes that all contribute their energy to amplify a passing light pulse. The energy of the light pulse can be further amplified by stacking together multiple fibres (eg 100 to 10,000 fibres) that separately generate light pulses, which accumulate and output as a single highly efficient continuous-wave HEL beam. Either the fibre

or a supplementary optical system is used to point the outgoing laser energy.

> **Note**
>
> The generation of laser energy in a fibre generates thermal energy as a by-product that radiates outwards and, if not controlled, causes thermal damage to the fibre. As an alternative to relying on a single larger fibre to generate the required high-levels of energy with a heightened risk of thermal damage to the fibre, DEW designers produced a single energy beam by combining the laser outputs from several laser fibres. This allows the individual fibres to function at lower energy levels and temperatures.

4. **HEL free-electron particle accelerators**[36] are more complex and exotic in design in not using a solid or chemical medium for generating the laser. Free electron lasers (FEL) use beams of accelerated electrons (e-beam) as the laser medium. The e-beam is pumped into a particle accelerator and light amplification is achieved by accelerating the free electrons in the e-beam. Generating the e-beam laser requires the creation of an e-beam, typically in a vacuum, with an e-beam accelerator. The greatest attractions for using free-electron lasers are that output light energy is tunable to almost any specific wavelength within a very wide spectrum of wavelengths.

> **Note**
>
> FELs require a high level, high capacity power source to operate at HEL levels.

5. **Nuclear pumped lasers**[37] were researched by the US for potential operational use during the Cold War as an orbiting nuclear weapon. The nuclear laser is pumped with the energy generating from the nuclear fission reactions that occur in a nuclear explosion. The lasing medium is enclosed inside a tube that is lined with radioactive Uranium-235. The fission fragments of the U-235 create an excited plasma which then generates the laser energy. The prohibitively expensive nuclear-pumped lasers were expected to generate multiple x-ray lasers for defending against multiple

incoming intercontinental ballistic missile threats. It was never operationalised.

> **Note**
>
> Australia does not possess any nuclear weapons and is not seeking to become a nuclear weapons state. Australia's core obligations as a non-nuclear weapon state are set out in the Nuclear Non-Proliferation Treaty (NPT).[38] This includes a solemn undertaking by Australia not to acquire nuclear weapons.

High-Powered Radio Frequency (HPRF) DEW[39] are designed to deliberately disrupt two aspects of the target: injecting machine-generated electromagnetic energy into the electronic circuitry of the targeted electronic hardware and interfering with the data or control signals that are essential for the correct functioning of the target. Air Force has introduced into service the EA-18G Growler[40] with airborne electronic attack capabilities.

1. **HPRF damage.** The electromagnetic energy is used in electronic attacks to disrupt the correct functioning of the electronic equipment or cause damage to the electronic components. HPRF DEW can be employed to defeat smart weapons; disable command and control systems; remotely neutralise improvised explosive devices; counter uninhabited aerial systems; and remotely stop small motorised vehicles (ie air, land or sea).

2. **HPRF interference.** HPRF DEW can be transmitters or energy generators for emitting radio signals that intentionally block, jam, or interfere with communications traffic (eg system control signals, text messages and data signals, television broadcasts, GPS systems, Wi-Fi networks, etc).[41] Their purpose is to disrupt the target's dependency on a remote controlling authority (eg remote pilot), broadcast service, or global navigation satellite system (eg GPS).

Notes

Electro-Magnetic Pulse (EMP)[42] is not a DEW; EMP weapons (eg E-bombs[43]) deliver indiscriminate omni-directional electromagnetic radiation, specifically designed for disrupting electrical systems and electronics, with reduced risks to humans and buildings when compared to traditional kinetic weapons effects.

E-bomb effects use a flash of radio frequency or microwaves as a by-product resulting from a nuclear energy event. Electromagnetic energy is released that causes steady electrons to become excited and generate an unwanted current in unprotected electrical circuits. These new electrical currents can cause unwanted and unplanned electrical events such as causing computer binary bits to flip states, trigger malfunctions in dormant circuits and cause damage to unprotected electrical circuits from power overload.

Directed High-Power Microwave (HPM) is used in aircraft self-protection tools included in the Directed Infrared Countermeasures (DIRCM)[44] system to defend against incoming optically guided air-to-air and surface-to-air missile threats. A microwave laser is automatically aimed to emit modulated pulses of infrared signals at the incoming missile's optical seeker. These pulses' infrared signals are sequenced to overwhelm the missile's guidance system through presenting larger and rapidly changing infrared signal information into the missile's seeker head to break its optically guided missile-lock on its target.

Counter-Personnel Directed Radio-Frequency weapons use millimetric wavelength RF emitters that generate short bursts of uncomfortable and injurious levels of heat for applications in area denial systems and counter-personnel operations for crowd control or perimeter security.[45] The duration and energy-level of millimetric wave RF energy are limited and aim to provide a quick and reversible skin surface heating sensation that does not penetrate the tissue of the human target.

Neutral Particle Beam (NPB)[46] weapons will theoretically work by using a particle accelerator to accelerate neutrons to speeds close to the speed of light and directing them towards a target. The accelerated neutrons use their kinetic energy to knock protons out of the nuclei of particles in the target, causing nuclear fission and generating damaging levels of heat in the target. Since the neutrons all have zero electrical charges, they can propagate along a straight trajectory, unaffected by the Earth's magnetic field and environmental effects that would disturb a charged particle. Such explosive applications have been considered by US Defense to counter hypersonic ICBM rocket boosters and re-entry vehicles.[47]

Comparison of Generic DEW Power Outputs

The nature and form of laser and radiofrequency weapon effects generated by the different DEW designs can vary considerably. Figure 14 depicts a generalised comparison of the likely effective ranges for use in comparing the different designs for DEW. Environmental conditions, atmospheric effects, weapon employment altitude, target material and motion, and other variables also affect a DEW system's actual performance.

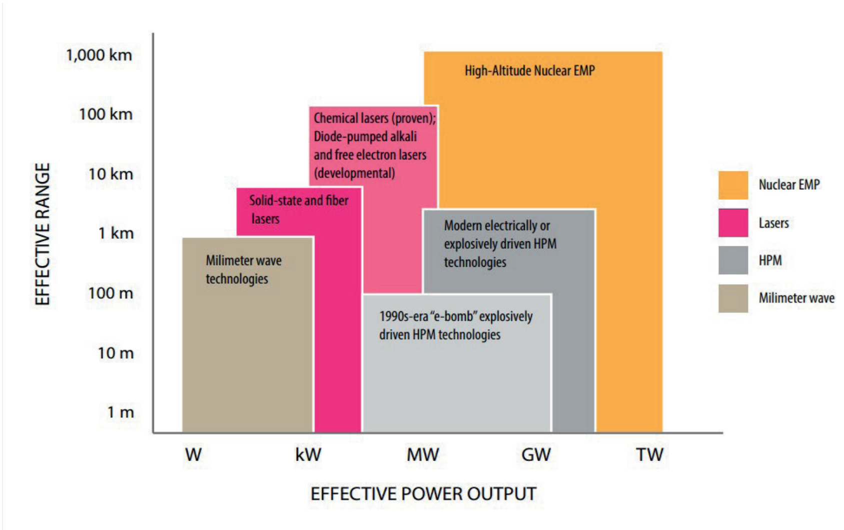


Figure 14. A generalised representation of the effective range and power output of the various laser and radiofrequency DEW types.[48]

ENVIRONMENTAL EFFECTS ON DEW PERFORMANCE

Kinematic effects in ambient air

When considering target vulnerability, it is not the DEW output but rather the radiant energy (light and heat) that is arriving at the target that is the more important consideration.[49] To be effective, the DEW must steadily deliver an uninterrupted flow of energy to the target, over a finite dwell time, and accumulate a level of energy at the target adequate to cause the desired damage mechanism.

Atmospheric weather conditions (eg cloud, rain, fog, changing air density, atmospheric refraction, etc) can disrupt and attenuate DEW energy transmissions, preventing all-weather use. DEW are not all-weather weapons. However, there may be useful situations beyond the atmosphere where, if the DEW could be deployed above the atmosphere, the DEW outputs would travel in a perfectly straight line without atmospheric perturbations or attenuation in the vacuum of space, to engage transiting missiles or orbiting spacecraft. Turbulence can cause the air over long distances to act as a refracting lens, resulting in diffusion and distortion of the DEW beam, degrading its energy and performance over long-distances.

The configuration of the DEW into a moving platform will introduce additional motion-related atmospheric effects during its operation. The motion of the host platform will introduce additional complications such as dynamic variations in the air medium as the platform moves and manoeuvres. Furthermore, the motion of the target exposes the DEW damage mechanism to airflow and windchill which may dissipate the energy arriving at the target, delaying the accumulation of energy needed to cause the damage.

Atmospheric effects

Different atmospheric effects need to be accounted for to understand what happens to a DEW beam of energy as it propagates through the atmosphere.[50]

Thermal blooming. Thermal blooming is a non-linear effect that worsens as the DEW output power level is increased, especially for HEL. Whilst it is intuitive to consider that a high-power level may assure the DEW emission over a much longer distance, the air along the path of the energy beam is being heated by absorption of the DEW energy, and the heated air has a different optical refraction index compared to ambient temperature air. This refraction produces a similar effect as if the DEW energy beam was passing through a "concave lens" that widens and diverges the beam, reducing its energy intensity, measured per unit area, when the beam reaches the intended target.[51] Thermal blooming does not occur in space.

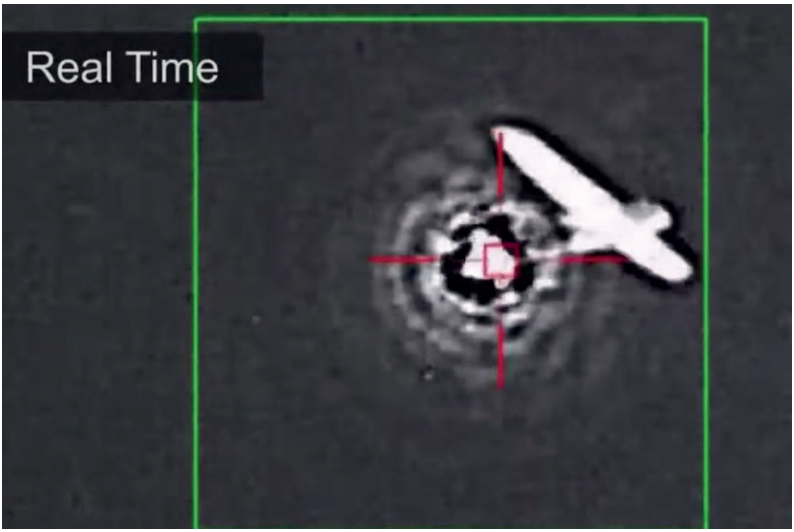


Figure 15. Thermal blooming occurs when heat from HEL beam changes the air density causing the air about the beam to act as a refracting lens.[52]

Beam diffraction. An unavoidable consequence of the nature of light is that it will naturally tend to spread out the energy and widen the beamwidth as the beam propagates over distance, even in a perfect vacuum. This implies that there is a fundamental physical limit to the smallest possible spot-size that a DEW beam can be focus down to. The energy beam widens with wavelength and decreases as the diameter of the optical/transmitter aperture increases; larger apertures emitters and energy with smaller wavelengths will reduce the effects of diffraction for long-distance propagation.

Beam scattering. The atmosphere is a non-uniform medium with many constituents that prevent the beam form travelling in a perfectly straight line; variations in air density can refract and alter the paths of the total beam and parts of the beam. The result is that after the beam is emitted from the DEW, it can be spread into a wider and less intensive beam by atmospheric scattering effects. Scattering effects by atmospheric particles can be reduced by using energy with longer wavelengths that tends to reduce the effect of scattering for the same science reasons the daytime sky appears blue and sunsets are red.[53]

Atmospheric absorption. The absorption of DEW outputs by matter in the atmosphere will decrease the power that arrives at the target. Different atmospheric constituents will absorb different wavelengths at different rates leads to the DEW system performance having a dependence on geographic location, climate, time of year, weather, and environmental factors. Furthermore, DEW operations at low-altitudes over water will be affected more by water vapour absorption than operations at higher altitudes. Additionally, as the atmosphere heats up around the DEW beam, thermal blooming occurs.

Energy disruption from atmospheric turbulence. In addition to diffraction, atmospheric turbulence that varies the density of the air, along the line travelled by the beam, will cause the beam to spread and refract, changing the beam's path, and reducing power and intensity at the target.

Space environmental effects

The space environment is different to the terrestrial environment. Space includes a vacuum, extreme temperatures and thermal cycling (eg Earth orbiting satellite transit between Earth shadow and direct sunlight), space weather and cosmic radiation effects such as electrons, protons, gamma radiation, and space debris. However, none of the atmospheric effects caused by the air exist in space, especially the path bending caused by atmospheric refraction and thermal blooming in air. Directed energy can propagate further and more easily in the vacuum of space.

NASA has developed a new laser beam pointing technology for use in optical communications to access space missions and for spacecraft to better communicate with each other. With further development, optical communications could be used between the Earth and spacecraft in Earth orbit and in deep space, including orbiting spacecraft and habitats on the Moon and Mars. The advantage of optical communications is the significant improvement in data rates when compared to radio systems.

Notes

Australia is a state party to the 1967 Outer Space Treaty that prohibits the placement of weapons of mass destruction in outer space or on celestial bodies.[54]

Australia works hard to counter the spread of weapons of mass destruction and is in favour of the prevention of an arms race in outer space for which, currently, there is no international treaty or agreement.[55]

A GENERIC DEW SYSTEM DESIGN

Generic operational concept

Numerous components are required for a DEW system to accurately deliver the directed energy to the target and cause disruption or damage. Separate to the platform that may be deployed with the DEW system, a surveillance and detection radar may be needed to detect the air threat on its trajectory in the air or space, and sensors slewed to acquire and track the target.

The target types may range from swarms of small tactical sized drones at low-altitude, adversary high-speed aircraft at altitude, or hypersonic missiles re-entering the Earth's atmosphere. The motion stabilised DEW is coupled to the target tracking system to accurately direct the energy onto the moving target for a long enough period for the energy to dwell on the same point on the target and accumulate the required level of light, thermal, or electromagnetic effect on the target.

Fundamental design principles

A HEL, HPRF and HPM are fundamentally similar in that they are systems that convert one form of energy (eg electrical, chemical, electromagnetic energy) into a concentrated beam of another type of processed energy, as depicted in Figure 16. The HEL generates light/thermal energy; HPRF/HPM converting electromagnetic energy into a concentrated beam of electromagnetic energy of a particular frequency and power level.

Figure 16. Fundamental design for a notional DEW system.

The key design requirement is to deliver the minimum amount of energy at the target to achieve the required level of damage. This will be dependent on the power density across the beamwidth, which decreases with distance away from the emitter, and the dwell time required at the target to accumulate the amount of energy needed to cause the necessary level of damage. The weapon design problem is made complicated when the DEW is mounted on a moving platform and is designed to engage another moving platform through any obstructing dust, water, or aerosols in the cool and refracting air of the atmosphere.

The description of the design for any DEW will be optimised to assure the delivery of the required effect at the target, and include specifications for the following:

1. intended damage mechanism (eg laser dazzling versus thermal destruction),
2. optimum distance from the emitter to the target,
3. amount of energy delivered at the target within a set 'dwell' period,
4. dispersion and beamwidth at the target,
5. accuracy of the beam director to achieve the damaging level of energy at the target in the dwell time,
6. standard environmental conditions for the abovementioned specifications, and
7. risks to personnel safety (eg eye safety and nominal ocular hazard determinations).

A fundamental DEW system design

Discussion about a generic DEW system design is useful to illustrate the design opportunities and constraints that will affect their mission employment. A generic DEW system can be described as comprising the subsystems depicted in Figure 17.

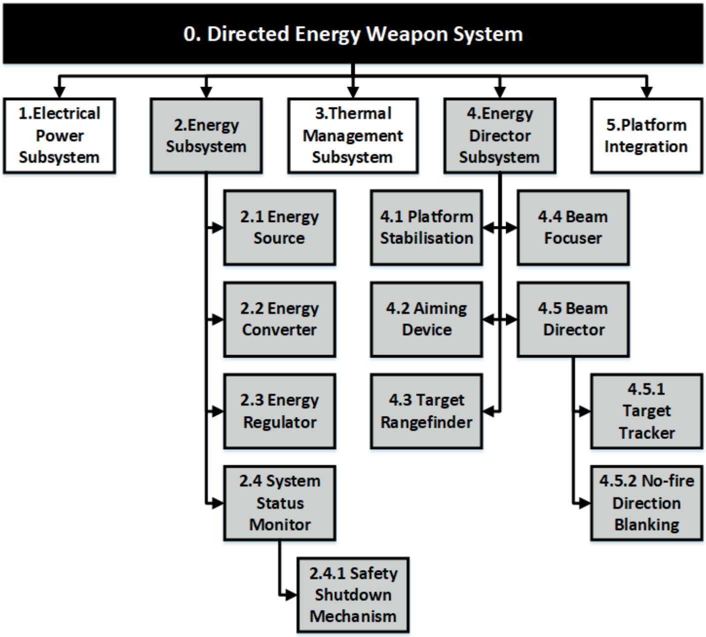


Figure 17. Product breakdown structure for a notional DEW system design.

1. DEW ELECTRICAL POWER SUBSYSTEM

The electrical power subsystem is the power supply that will enable the DEW to function and will likely be utilised as a single power source that is commonly shared to power all electrical systems integrated into a single combat platform. The power distribution system will need to cope with the rapid changes in the combined demands for electrical power from the total integrated system carrying the DEW when the DEW is functioning.

> **Note**
>
> The challenge for system designers is to maximize the power and effectiveness of the DEW system without impacting the host platform performance during the DEW operation.

2. DEW ENERGY SUBSYSTEM

"Energy magazines" will provide the energy necessary for multiple engagements by either accessing a continuously generated power supply and/or a recharged power storage subsystem. Each different type of DEW requires different integration solutions for storage and carriage by the platform and operator to access to the DEW.

2.1 **Energy source**. The energy source options for the different types of DEW outputs include chemical, electrical, light, and electromagnetic using power cells typically based on a system configuration with different options for power generators, batteries, and storage capacitors.[56]

2.2 **Energy converter**. The energy converter is the mechanism for transforming energy from one form into the desired form that delivers the mission effect. Refer to the section on 'Generating DEW Effects'.

2.3 **Energy regulator**. Energy conversion is based on different methods for different designs but need to be regulated to assure the safety of the system, sustainability for re-use, and functioning with defined operating limits that are compatible with other integrated subsystems. An important by-product of energy conversion is the generation of heat that, if not regulated, may at the least introduce inaccuracies in the system outputs or, if unchecked, may result in systems failure (refer to the section on the Thermal management subsystem). Some design options may be limited in the range of operating modes that need to be regulated. For example, design options may vary the types and ranges of control as follows:

(a) **Limited option outputs.** A solid-state laser may only produce a single level of output energy. Thus, its energy output can only be regulated to be one of only two levels based on its two operating modes – on and off.

(b) **Outputs as a range of control steps.** The output of a fibre laser can be controlled by managing the number of light-emitting diodes that are activated (ie one per fibre) to contribute to the total energy output.

(c) **A continuous range of controlled outputs.** The energy output from HPM DEW is controlled by the input energy enabling the variation of output energy across a broad range.

DEW can be purpose-designed with different energy outputs to alternate between a low-energy setting to 'disrupt' the control signals to a target, and a high-energy setting to send out a burst of energy sufficiently powerful enough to induce electrical charges to cause damage and destruction to electronic components inside the target. Similarly, a HEL DEW might use a low-energy laser output to only dazzle a human observer or disrupt an electro-optic sensor, and use a high-energy output option to destroy material targets.

2.4 DEW System status monitoring

Operator awareness of the status and trust in the correct functioning of any system is important for assuring mission effectiveness. If a system is faulty or degraded in its performance, it may not support the operator to deliver the planned mission effect, adverse to the mission outcome. Additionally, knowledge of the system status may support the operator to make decisions to manually re-optimise the available functionalities, or a decision support system to autonomously re-optimise the system configuration, to support the continuation of the mission with an acceptable degraded mode of operation (ie 'graceful degradation'); there will be a threshold below which the capability is no longer useful and DEW operation would be aborted.

2.5 Safety shutdown system

Safety shutdown mechanisms are normally installed into the system design to control risks of component failures and assure the safe use of the system in normal, degraded, and faulty operating modes. It may be possible that degraded and faulty operating modes may pose new and unacceptable hazards to the safety of personnel and equipment, including the preservation of the DEW. A safety shutdown system will support the operator to manage the risks associated with these hazards.

Typically, the integration of components that are assessed as key risks may be connected with physical, electronic or software interlocks that are gateways that can stop the DEW from functioning until certain conditions have not been satisfied. For example, if the system detects that the power subsystem is supplying maximum power but the detected level of output DEW energy is lower than predicted, then the system may automatically shutdown to indicate a fault or damage in the energy conversion subsystem.

Additionally, software-driven controls might be used to assure planning for safety in the mission planning phase and safe operations in the mission execution. For example, geospatial data of no-fire areas in the battlespace might be used by a software control system to control the geographic areas where an operator can activate the DEW.

3. DEW THERMAL MANAGEMENT SUBSYSTEM

During the functioning of the HEL, only a portion of the electrical power is converted into light energy; the remainder is lost as heat, as a by-product of the energy conversion process. The build-up of that thermal energy poses a number of issues for the HEL as a whole and, in particular, control over the stability and beamwidth of the output energy.

If not controlled, the changing temperature of the laser system will affect the laser light quality, which is most apparent in the stability of the laser wavelength, since the output wavelength correlates to laser temperature. Additionally, if the thermal energy is not controlled, excessive heat may damage the laser system, especially the energy conversion and light-emitting components, degrading the quality and quantity of the light energy being produced and the accuracy of the mechanical DEW pointing system.[57]

Techniques for the cooling the DEW include the following typical design options:

1. **Passive heat sink.** A passive heat sink conducts heat away from the DEW and dissipates it into the ambient airflow.
2. **Active cooling system.** For example, a Peltier device, also known as a thermos-electric cooler (TEC), is a small, flat, thermally conductive ceramic that uses the electrical power

supplied by the temperature controller to cool one of its surfaces while heating the opposing surface. Some designs may be further enhanced with a water-cooling system. The advantage of using the TEC is that it can be used to actively control the temperature and cool the DEW for optimum performance. Additionally, it can be used to heat the DEW for stable energy outputs in changing environments with varying temperatures. A HEL equipped with a Peltier device will be capable of heating as well as cooling, allowing for faster system warmup, stabilisation, and response times.

Figure 18. Chinese media has reported that the People's Liberation Army Navy is testing a prototype HEL DEW (displaying possible beam director, target tracker, and rangefinder).[58]

4. 4. DEW ENERGY DIRECTOR SUBSYSTEM

The energy beam director functions like a steerable antenna/radiator that controls the shape of the emitted beam (eg beamwidth, focus, radiation pattern, dispersion, etc) and its direction of emission. Additionally, the director subsystem is important to delivering the energy to the intended target and keeping the energy arriving at the same aimpoint (ie ‘dwell time’ on the target) for the energy to accumulate and cause the required damage effect at the target. The beam director subsystem is an integrated system-of-systems.

4.1 Platform stabilisation

Current and future air power roles may rely on DEW systems that are integrated into mobile and relocatable platforms. Motion stabilisation aids to remove pointing errors that are caused by movement and manoeuvring of the platform being used to deploy the DEW system.

4.2 Aiming device

Since the DEW is not visible on the target, it needs a separate subsystem to align it to the target. The aiming device is a separate subsystem to the beam director that can acquire and track the target. The aiming device is usually calibrated and ‘bore-sighted’ to be aligned with the beam director so that the DEW energy beam follows the line-of-sight of the aiming device to the target. The aiming device also gives a safety assurance that the line-of-sight to the target is clear.

> **Note**
>
> To be effective, the aiming device must be capable of detecting and maintaining tracking of the target signature given the expected operating range and environmental conditions and manoeuvring characteristics of the target.

The aiming device is also significant for use in determining when the DEW can be available to leave the target and point to a different target. Since the DEW damage is based on the accumulation of energy at the target, and the time needed to achieve this may vary with different target materials, target manoeuvres, and environmental conditions the aiming device needs to monitor the DEW damage being delivered to the target to positively confirm the damage status before the DEW can be available to be reassigned to another target.

4.3 Target rangefinder

The target rangefinder is used to measure the distance between the DEW and the intended target. Information on the distance to the target is useful to optimising the shape of the DEW output to maximise the energy converging on the target.

4.4 DEW beam focuser (optical or RF antenna)

The beam focuser shapes the beam and optimises the convergence of the DEW output energy onto the target, based on the measured distance between the DEW and the target. If the beam was not focused, it may not have an adequate density of energy over the spot area to cause the required effect when it arrives at the target.

4.5 Beam director

The beam director steers the DEW energy beam towards its intended target. Similar to any pointing system for directing weapons effects, the beam director must be agile to move and follow the required range of speeds, accelerations, and manoeuvre that are characteristic of the potential targets. Additionally, it must have the freedom of movement to maintain a clear line-of-sight to the target without damaging the host platform or compromising the safety of the crew or the mission.

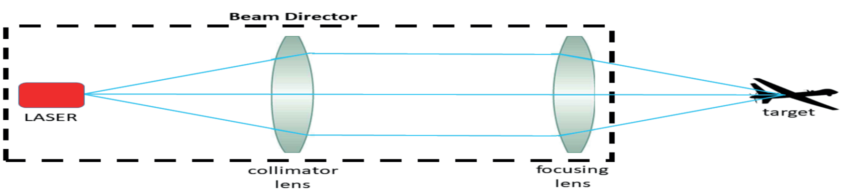


Figure 19. Notional beam director using the focusing lens to converge DEW energy onto the target.

Corrosion and contamination of optical windows by aerosols, atmospheric particulates, smoke and debris, airborne foreign objects, and airfield dirt, can pose technical challenges to the correct functioning of DEW systems. Protective housings are needed to protect the DEW during normal operations in the different operating environments of the air, on the ground, and over water.

Additionally, atmospheric turbulence caused by changing weather conditions, atmospheric moisture, and dust can also be problematic to the propagation and directional accuracy of optical and electromagnetic energy. Specialised adaptive optics sensors and compensating computer algorithms can be used to adjust and improve the accuracy of the pointing by the beam director.

4.5.1 Target tracker

The target tracking problem is typically based on making observations to first locate, identify, and fix the target. Once two or more observations have been made that indicate the position and the rate of change of the position, then tracking can be attempted either by manual (contingency mode) or an automated tracking system (primary mode).

Target tracking for traditional weapons has normally required that a minimum number of target observations be made to establish a tracking vector. The tracking vector is necessary for conventional weapons to project a weapon aimpoint ahead of the target to compensate for the time-of-flight of the weapon and fly the weapon along the most efficient trajectory ahead of the target to engage the target. The advantage of the speed-of-light engagement made possible with DEW is that it negates the need to have to wait until enough observations have been made to accurately calculate a projected weapon impact position ahead of the moving target.

The most common form of automated target tracking uses an optical system that can contrast the target against its operating environment, and visually discriminate the target's unique signature from its background. The imaging of the scene can be manipulated by software and imagery enhancements to optimise the contrast between the target and its background. Autonomous

tracking algorithms can then be engaged to track the contrast edges (ie the edge between target and its background that is the boundary between light and dark); more sophisticated software algorithms can track the changes in light intensity in individual image pixels and adjust the aiming of the sensor to keep the changing pixels centred in the sensor view, as depicted in Figure 20.
As shown in the example system configuration depicted in Figure 18, the DEW aiming device, target rangefinder, target tracker and beam director are all calibrated to be in alignment when bore-sighted to point along the same line-of-sight.

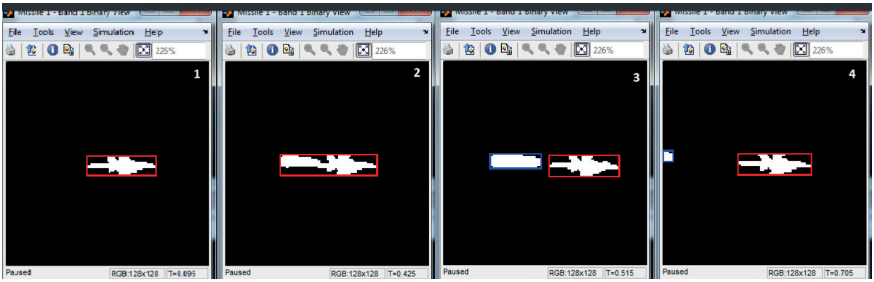


Figure 20. Example of an autonomous imaging contrast tracking algorithm.[59]

4.5.2 No-fire direction blanking

While the location of the DEW in the platform is optimised for integration into the platform design and for maximum viewing of the potential battlespace, there will always be a risk of self-damage if the DEW is enabled to fire in all directions. In the Second World War, aircraft gun turrets in the heavy bombers were modified with the lock mechanism in the ring mount of the turret to prevent the guns from firing on the aircraft in which it is mounted (ie especially vertical tail fins, radio antennas, other gun turrets, etc).[60]
Similarly, platforms configured with DEW need to be surveyed for the risks of self-damage and this data should be used in mechanical or software controlled system that prevents the DEW from firing in any direction that may damage the platform, disrupt sensors and vulnerable equipment, and/or compromise its mission.

5. DEW and platform integration

The subsystem is comprised of a collection of fragile optics, sensors and other components that require precise alignment to be maintained. The energy director subsystem must be maintained as a clean, dust-free and temperature-controlled environment. Optical elements for the HEL are very sensitive to defects and are vulnerable to foreign object damage from flying operations and must be kept meticulously clean and protected from the flying environment.

The DEW must also be mechanically isolated with active shock and vibration damping to impede the transfer of vibrations from the working platform during DEW operations. The vibrations may affect the accuracy and alignment of the director subsystem, in addition to the effects of platform acceleration and manoeuvring.[61]

Ancillary DEW systems and additional design considerations

In this discussion, the DEW system is described as a discrete weapon system. However, its effective employment in the battlespace will be critically dependent on its role being integrated with the following systems:

1. **Mission planning system**, including target/weapon vulnerability analysis, damage estimation, and collateral damage risk estimations, for use in planning and reviewing the feasibility of the mission, tactics, and risk contingencies.
2. **Target vulnerability analysis and weaponeering.** Weaponeering is a statistical analysis to support the estimation of the operator efforts and DEW energy needed to achieve a specific level of damage against a given target, considering the target's vulnerability to DEW damage effects, pointing accuracy errors, dwell time, damage criteria, system reliability, environmental conditions, etc.
3. **Rules-of-engagement** are the Defence directives and internal *rules* that define the circumstances, conditions, degree, and manner in which the DEW may be employed.

4. **Command and control system** outputs will enable the optimised employed of the DEW in synchronisation with the coordinated effects of other force elements and deconflicting with unwanted and inadvertent risks in the battlespace.

5. **Battlespace situational awareness** will enable the appropriate and timely employment of the DEW to have the best effects in the battlespace, including deconflicting mission areas, supporting collateral damage risk assessments, and estimating risks of DEW spillover to other force elements and other vulnerable mission sensors and equipment.

6. **Identification-Friend-or-Foe** will be essential to enhance the battlespace awareness when the DEW is capable of shooting at the speed-of-light, disrupting targets after short engagements, engaging with different power options for non-lethal and lethal effects, and rapidly slewing to engage new and multiple targets.

7. **Atmospheric characterisation and predictions** will be essential to support the mission planning system and enable an understanding of the environmental impact on DEW performance.

8. **Personal protective equipment** and access to a safe and protected maintenance facility will be essential.

Figure 21. Laser safety goggles[62] are designed to filter specified wavelengths (ie matching the visible or invisible wavelengths of a specific laser) and provide ocular protection for an operator to function with a reduced risk of harm or disruption from a low-energy laser.

DEW MISSION ATTRIBUTES

DEW capabilities are of interest to the warfighter because they provide the potential for the "speed-of-light" engagements of multiple targets, with instantaneous fly-out times, and no lead-angle is required. However, it must be understood that even though DEWs can engage targets at light speeds, the effects on the target are typically not instantaneous and require some dwell time on the moving target. Some of the other attributes are discussed below.[63]

A DEW COMPARISON WITH KINETIC ENERGY WEAPONS

Combined offensive and defensive weapon. DEW systems can be designed to be multi-roled systems for use as both an offensive and defensive weapon system. For example, the same DEW system, designed with tailorable effects and scalable power outputs, could be used to provide both novel force protection and precision-strike options.

Instant and silent delivery. The DEW output travels at the speed-of-light and is silent. However, the quantity of energy needed to damage the target may require a minimum period for the DEW to dwell on the target in order to accumulate adequate energy to achieve the required level of disruption or thermal damage.

Precision line-of-attack direct to the target. Light from a laser beam can reach a target nearly instantly. This eliminates the need to calculate a projected intercept course, similar to proportionally navigated interceptor missiles. After disabling its target, the DEW can be immediately available to be redirected to the next target.

Low counter-detection (ie small and silent signature). DEW energy is not necessarily visible to the naked eye. The wavelength of the laser light depends on the source material used to generate energy. Depending on the source material, laser light wavelengths can vary from invisible infrared through to visible wavelengths. Additionally, quantum effects can enable special optical filters to change the original laser light into different wavelengths, especially for a DEW to output ultraviolet light with higher energy.

Trajectory not affected by gravity. The forces of motion, kinematics, and aerodynamic effects that normally affect conventional ballistic and flying weapons do not affect HEL engagements with the target. The DEW energy does not follow a ballistic trajectory and is unaffected by gravity as it propagates to the target.

Speed of light delivery. The energy is delivered to the target by using an intense beam of coherent light. The energy appears at the target nearly instantaneously upon emission from the source (weapon system). There is no delay time between launch and interface with the target as with conventional kinetic energy weapons. Additionally, depending on the beam director, the HEL is readily agile to change tracking and aim to engage targets that attempt to use traditional countermeasures based on high-G and evasive manoeuvres.

Focused and coherent over long distances. Laser light is different from normal light in that it can be controlled and projected as a train of pulses or a continuous wave of energy, all with the same wavelength. The wavelength is determined by the activity occurring at the quantum level in the source material that is releasing light energy when excited electrons return from a stimulated higher energy level to their natural lower energy level, with each electron releasing the energy difference in the form of a light photon. Additionally, laser light is coherent since all photons travel together in the same direction, unlike normal light that has multiple wavelengths and is scattered in all directions. Whereas a torch beam outputs light that is diffuse and fades over distance, laser light naturally remains as a coherent and tightly focused beam, even when projected over vast distances.

Ability to counter radically manoeuvring missiles. The photons in the laser have no mass and can more easily follow and maintain their moving beam trajectory, even on radically manoeuvring missiles. Traditional designs for precision-guided manoeuvring weapons will have speed, range, and manoeuvre limits based on mechanical design limits that might be exploited by a highly agile target seeking to outmanoeuvre or outrun the missile.

Same target, same damage, but different engagement periods. The time required to damage a target may be different in every engagement situation due to variations in target vulnerability, target aspect, target manoeuvring, environmental conditions, etc. All these factors may affect the rate of transfer of DEW energy needed to be accumulated at the target above a damage threshold level. Target speed and manoeuvring, and environmental conditions may degrade and delay the energy accumulating at an aimpoint on the target.

Deep magazines. The DEW typically derives its energy from the conversion of fuel into electrical energy. The DEW use of electrical energy represents a weapon system design that has 'deep magazines' to produce a relatively unlimited number of laser shots unconstrained by the time and mechanical forces needed to store, reload and consume magazine ammunition. This capability represents a significant reduction in logistics and the cost that is usually associated with the expended rounds and ancillary parts (eg shell casings). Since there are no consumable parts expended in the functioning of a solid-state HEL, the magazine depth is limited only by the capacity of the power supply; chemical fuel HEL are more limited since their magazines rely on the availability of stores of laser-enabling chemical agents which are consumed in the laser firing process.

Insensitive munition. Defence has defined 'insensitive munition (IM)' as:

> "those munitions which reliably fulfil their performance, readiness and operational requirements on demand, but which minimise the probability of inadvertent initiation and severity of subsequent collateral damage to weapon platforms, logistic systems and personnel when subjected to selected accidental and combat threats".[64]

Whilst DEW systems are not IM, they offer similar benefits for reducing the inadvertent hazards which is advantageous to the mission planners and designers for host platforms, training systems, test and evaluation, combat logistics (ie handling, transport and storage systems), etc.

A DEW COMPARISON WITH KINETIC ENERGY WEAPON MISSIONS

Lethal and non-lethal capabilities. An advantage of the HEL design is the capability it provides for the user to control both the energy level (ie damage level) and the delivery location at the target (ie aimpoint). This control and variability can enable a single HEL system to be designed to perform both lethal and non-lethal missions with an economy of effort.

Rapid re-direction to engage new targets. Since the DEW output energy has no mass, it only needs very little mechanical energy to be able to direct the energy onto a target, including high-speed targets, and/or rapidly redirect the DEW onto a new target.

It is not a fire-and-forget weapon. The DEW energy does not function like a fire-and-forget guided missile or artillery round; the DEW needs to be continually pointed at the same aimpoint on the target to accumulate enough energy to cause damage to the target, taking into consideration target motion and environmental effects that may slow the time taken for the accumulating energy to reach the damage threshold. Thus, a single DEW cannot engage multiple targets concurrently; the DEW can only engage multiple targets one at a time, in a sequence, and would normally have to stay directed on a target until it is confirmed to be damaged.

Defensive and offensive non-kinetic effects. DEW are precision-effects weapon systems. HEL and HPM systems have been deployed by the US military in both defensive and offensive mission applications, with research aspirations for realising airborne offensive strike capabilities. Green laser 'dazzlers' are a part of the arsenal of offensive weapons to disrupt adversary missions by using a non-lethal attack option against personnel and sensors to reduce non-combatant casualties.

Cost-effective force multiplier. Similar to kinetic weapon systems, DEW weapons undergo extensive and costly developmental and certification processes. However, once fielded, mature DEW systems are expected to deliver favourable cost-benefits per firing event when compared with the unit cost of individual kinetic weapons rounds.

Graduated and scalable mission responses. Some HEL and HPM weapons are capable of adjusting the DEW output energy up or down, tailored to meet specified emission requirements to meet the mission need.

This increases the scalability of the single DEW system to provide an agile weapon system with different energy output levels, for different mission needs, as an alternative to a family of separate discrete kinetic weapons that deliver different weapon yields and effects. Tailoring the range of DEW effects, ranging from non-lethal and disruptive to destructive effects, provides a capability to tailor the damage level and improve compliance with the laws of armed conflict, rules-of-engagement, and collateral damage risks.

Design options for alternative mission effects. The design for "scalable effects" also provides options for delivering different types of damage effects to the target, ranging from temporary disruption to permanent damage, depending on the target vulnerability and the range from the DEW to the target. Lasers can perform functions other than destroying targets, including target marking, detecting and ranging, and producing nonlethal disruptive effects, including reversible jamming of electro-optic sensors. Lasers offer the potential for graduated responses that range from warning targets to causing reversible jamming effects to electro-optic systems, causing limited but not disabling damage (as a further warning), and then finally turning up the output power to cause damage.

Mission flexibility. The ability to integrate different types of DEW into air, land, and sea platforms (ie treaties prevent deployment of weapons in space) provides a range of non-kinetic attack options for the warfighter. In some cases, DEW may potentially have multiple roles — weapon, surveillance sensor, navigation, communication, target range-finding, target designation and illumination, etc.

DEW versus saturation attacks. Since a laser can attack only one target at a time, it may require several seconds of dwell time on the target in order to disable it, and then several more seconds to be redirected onto the next target. Thus, a single DEW can disable only so many targets within a given period of time. This places an upper limit on the ability of an individual laser to deal with saturation attacks—attacks by multiple weapons that attack simultaneously or follow within a few seconds of one another. This limitation can be mitigated by installing more than DEW into a layered defence system, integrated with legacy air defence weapons.

DEW versus hardened targets and countermeasures. Less-powerful lasers—that is, HEL with beam powers measured in kilowatts (kW) rather than megawatts (MW)—are made less effective against targets that incorporate protective thermal/electrical shielding, ablative material, or highly reflective surfaces. Additionally, highly manoeuvrable targets that can rapidly change their orientation, or rotate and tumble rapidly, may prevent the DEW from achieving the minimum dwell time needed on the same point on the target to accumulate the minimum energy needed to cause damage.

OPERATIONS LAW CONSIDERATIONS

The designs and utility of DEW must be considered with respect to the Laws of Armed Conflict and International Humanitarian Law. Protocol IV to the Certain Conventional Weapons Convention (Protocol on Blinding Laser Weapons) prohibits the design of laser weapons specifically to be used an anti-personnel weapon to cause permanent blindness to unenhanced vision (ie, the naked eye) or the naked eye with corrective eyesight devices.[65]

For all other types of lasers, such as those used for detection, targeting, range-finding, communications, and target destruction, that may incidentally cause blindness, parties to the Protocol have an obligation to “take all feasible precautions to avoid the incidence of permanent blindness to unenhanced vision”.[66]

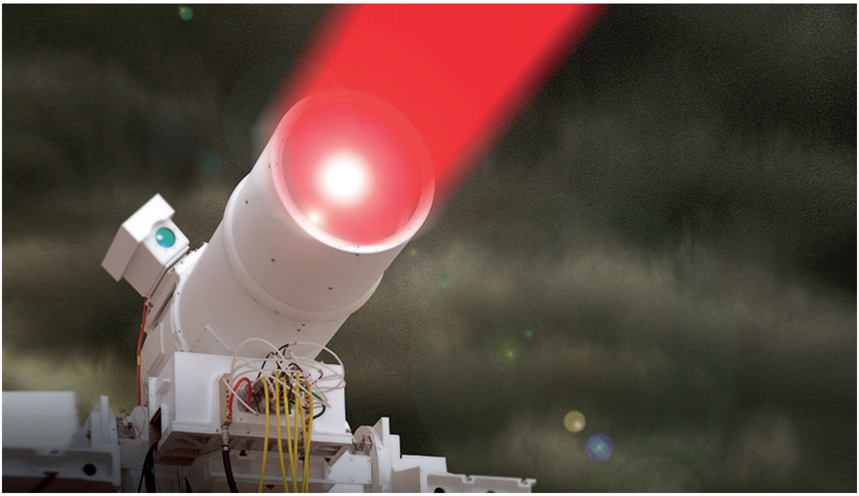


Figure 22. Designs for employing lasers in new lethal and non-lethal DEW need to comply with international humanitarian laws. [67]

INTEGRATING DEW INTO AIR AND SPACE OPERATIONS

DEW in air-to-space integration

Air Force has effectively employed laser target designators, operated from ground and airborne designators, to guide its Pave Way laser-guided bombs onto ground and maritime targets. Whilst the design and utility of laser target designators are controlled, similar to DEW, in accordance with the Protocol IV requirements of humanitarian law, they are not considered to be DEW. The experiences gained with integrating safety considerations into air operations with the laser target designators provide a useful baseline for understanding the safety measures that would be required with any consideration of the potential uses of DEW in any future Australian operations.

The US FAA regulations provide a good model for regulating the behaviours of laser operators and flight crews planning to use the same airspace. Even if the beam is being operated below the FAA's minimum altitudes for controlled flight (eg between two city buildings), the FAA's rationale is based on the example when a police or emergency helicopter needs to fly along a trajectory through a laser beam. The FAA has assumed that it is not up to the helicopter pilot to have to avoid the beam; the onus is on the laser operator to detect the helicopter and render the laser safe for the helicopter to pass.

Since FAA regulations only apply up to 60,000 feet, US operators using more powerful lasers must coordinate laser activities with a Laser Clearing House managed by US Strategic Command in order to deconflict their laser activities with military flights and spacecraft activities that might be inadvertently affected directly in front of the debris or by spillover radiation that extends beyond the target. If operated from an Australian site, then similar physical and procedural designs will need to be in place to assure the safety of fixed-based and deployable military aviation and space activities.

Figure 23. Ground-based lasers, with adequate energy, may be used in the future to access space and slowly remove space debris.[68]

The Australian Civil Aviation Safety Authority has similar regulatory requirements to the FAA and centrally regulates the operation of lasers and high-intensity lights for the "protection of pilots against accidental laser beam strike have become a serious factor in aviation safety with the advent of the laser light display for entertainment or commercial purposes"[69], following the requirements of federal legislation. Event organisers and system operators are obliged to centrally register their laser activities with CASA. Lasers operated by CASA recognised authorities, in a manner compatible with flight safety, can be excluded from these restrictions.

Integrating fixed, relocatable, and mobile DEW into air operations

The attributes of speed-of-light engagements, rapid-fire, rapid mode changes (ie power output changes between lethal to non-lethal effects), and deep magazines will make DEW a worthwhile consideration for control of the air and defending against incoming ISR and strike weapons. DEW systems are being considered to counter air threats ranging from small individual or swarming drones, tactical ground artillery, rockets, missiles, hypersonic weapons, and combat aircraft. However, to be effective, the battlespace situational awareness and C2 systems will need to be capable of responding to the rapid changes occurring in the battlespace as fast as the

DEW can make the changes happen, at light speed, including the potential risks for collateral damage and HEL spillover and reflections.

Whilst an artillery round or missile warhead functions to rapidly transfer kinetic/thermal energy at the target, the DEW functions to rapidly deliver and accumulate a damaging level of electromagnetic/thermal energy at the target. Additionally, the unitary warhead occupies a single point in space and time on a trajectory between its launcher and the target; the damaging effect of the DEW occupies the length of the trajectory between the launcher and the target or any obstacle that wholly absorbs it, out to distance until the environment dissipates the DEW energy. However, unlike with artillery and missiles, if the DEW is only partially obstructed or intercepted, the unaffected portion of the energy beam will continue along its original trajectory, in the same direction but extending beyond the target or obstacle.

Whilst the DEW kill chain can deliver its effects at the speed-of-light, its responsiveness may well depend on a sequence of manual and machine decisions coupled to activities such as target detection, weapon allocation, deconfliction of friendly elements, target analysis, weaponeering recommendation (eg determine power level for a non-lethal or lethal effect) and dwell time (ie estimation of minimum time needed to point and accumulate the energy at the target to achieve the damage effect). Additionally, the C2 system will need to make real-time adjustments to deconflict and protect friendly force elements from the HEL beam and the potential spillover and reflections out to the distances where the energy levels pose a hazard.

Noting that DEW systems are not necessarily all-weather weapons, they are likely to be complemented with weapons that can function in adverse weather to provide a total integrated all-weather weapon system.

Fixed site DEW

The utility of a fixed site for a DEW has benefits for both the operational user and the system designer. The ground siting of the DEW enables it to be supported by ground infrastructure negating size, mass, and power constraints that exist when integrating into a mobile platform. Free of these design constraints, the DEW can be designed with a bigger optical aperture for HEL or antenna for HPM. Furthermore, the solid and grounded base provides better stability in the controls needed for shaping and stabilising the beam shape and to accurately and steadily point the beam at the target.

The ground-based DEW is optimal for engaging incoming and crossing air threats from a diverse range of sizes, operating speeds, and attack trajectories, including mortars and artillery, ICBMs, individual and swarming drones, combat aircraft, and space-based threats passing overhead at orbital altitudes. However, operators need to be aware of the volume of airspace that can be reached by a hazardous level of energy from the DEW and who and what else may be using the same volume and be vulnerable to the DEW energy.

Integrating the DEW into ground operations will require risk assessments of the potential for collateral damage against friendly personnel, force elements and ground infrastructure. Since the ground station and its infrastructure has permanence in its presence, it can be easier to gain geospatial data and generate a digitised representative map to indicate "no-firing" directions for blanking the DEW firing arcs, and keep friendly personal and infrastructure safe.

Figure 24. Fixed site ground-to-air DEW.[70]

Relocatable DEW platform

Relocatable and mobile platforms integrated with DEW system be distinguished by the pointing systems used to direct the DEW energy: relocatable systems can be considered as a relocated DEW system that can operate only when the host platform is fixed and steady to point the DEW beam at the target; mobile systems can detect and maintain pointing of the DEW beam towards the aimpoint on the target whilst the host platform is in motion.

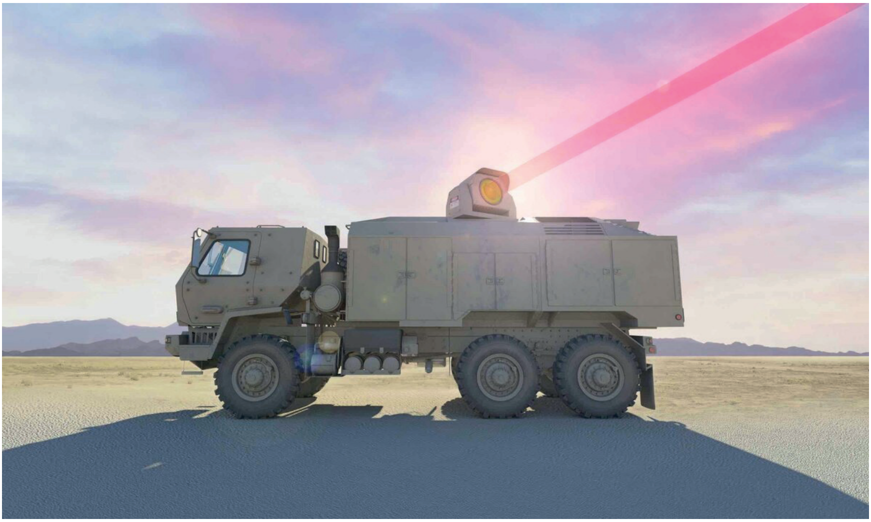


Figure 25. Relocatable ground-to-air DEW.[71]

Mobile DEW platform

Directional Infrared Countermeasures (DIRCM) are a type of DEW system and already commonly used with combat aircraft. When alerted to an incoming missile threat, operators initiate the DIRCM to scan in the direction of the incoming missile in order to detect the electro-optical seeker head of the infrared-guided missile. On detecting a signal reflected off the seeker head, the DIRCM directs an energy beam into the missile seeker, with a wavelength measured in the infrared spectrum, to disrupt the missile's seeker guidance and evade the missile engagement.

The DIRCM can be considered to be a low-energy DEW designed for dazzling electro-optical systems rather than inflicting damage against the missile. The militarisation of the DIRCM demonstrates the validity of employing a DEW integrated into a manoeuvring aircraft to engage a manoeuvring missile threat. The key point to note is the challenges of being able to detect, track, point, and maintain the DEW beam emission from one moving object to maintain an unbroken line-of-sight to the manoeuvring target.

This proven target engagement system can be used as the basis for designing a higher power output DEW for a manoeuvring platform to inflict a damaging level of energy against an incoming threat. The significant design differences between the mobile DEW and the fixed and relocatable variants will be the need to dampen and negate the thermoacoustic vibrations from the aircraft propulsion system and aerodynamics, and the shared power systems that may affect DEW functions and performance.

Tactically, the aircraft configuration may constrain the types and ranges of aircraft manoeuvres in order to optimise the aiming and dwell time of the DEW on the target – any interruption to keeping the DEW beam pointed at the target may result in the target cooling down, and require that even more energy be applied, and for longer, to achieve the necessary damage. Additionally, the DEW does not deliver a 'fire-and-forget' effect and, if confronted by a salvo of multiple incoming threats, it would need to prioritise an order of engagement since the one DEW beam can only engage the one threat at a time – the dwell time will require that the platform focus on only the one threat for the finite time needed to damage it, before redirecting the energy beam onto the next priority threat.

The trade-off for the design limitation posed by the minimum dwell time is to design a DEW to deliver an overkill level of energy to inflict light and thermal damage more quickly, enabling the aircraft to rapidly disengage and move on to the next target more quickly. However, this will change the risk assessments needed for deconflicting with other friendly force elements in the area and beyond the target that may be exposed to the direct beam, reflections, or spillovers that extend beyond the intended target.

Figure 26. Mobile air-to-air DEW.[72]

The DEW is not an all-weather weapon. For this reason, the DEW is useful as one of a number of different air-to-air engagement weapons. DEW will need to be complemented with different weapons to provide combat aircraft with all-round engagement options in all weather conditions.

Small-sized combat aircraft present design constraints to the size, mass and power available for the DEW which, in turn, constrains the energy output by the DEW. More powerful energy beams are readily associated with the largest DEW systems using bigger energy sources and power supplies. The option of configuring DEW into large aircraft may provide an airborne option for deploying the more powerful DEW systems, that have typically been designed for fixed ground sites and warships.

In 2015, the US Air Force posed a challenge to the US industry to consider design options for configuring a 120 kilo-Watt chemical laser into a next-generation Air Force Special Operations Command AC-130J Ghostrider gunship, as depicted in Figure 27.[73] The C-130J Ghostrider was suggested in order for the US Air Force to consider the option of replacing the air-to-ground artillery gun system with a chemical powered HEL for precision ground attack missions. It was expected that the HEL and its 'deep magazine' would weigh less than the artillery gun and gun magazine, and enable more engagements using bursts of energy tailored to the different types of targets to enable an economy of effort.

Figure 27. Mobile air-to-ground DEW.[74]

CURRENT AND EMERGING APPLICATIONS FOR DIRECTED ENERGY

Laser rangefinder

The rangefinder emits a laser beam, on command by its user, in the direction steered by the user towards the target object. The beam bounces off the object and the rangefinder's high-speed clock measures the total time from when the beam was triggered unit until it returned. The distance is a calculation based on the time for the laser signal to return, knowing that the laser signal travels at the speed-of-light, as a constant. When used in combination with GPS, the rangefinder can provide accurate 3D positional data and accurate range, azimuth, and elevation information.[75]

Laser spot tracker (LST)

The LST is used to aid visual and sensor acquisition of the target to be attacked by another weapon. An LST is typically mounted on fixed-wing attack aircraft and helicopters and combat land vehicles.[76]

Laser target designator (LTD)

Laser target designators are employed to mark targets for LST and laser-guided weapons (LGW). LTD and LGW provide the joint force with the ability to locate and engage targets with an increased first-round hit probability. Laser-guided systems can effectively engage a wide range of targets, including moving targets. LGWs can reduce the number of weapons and/or weapon systems required to create an effect to achieve an objective because of increased accuracy.[77]

Smoke detector alarm

In a photoelectric smoke detector, an LED emits laser light into an open sensing chamber that is designed to keep out ambient light while allowing smoke to freely enter. Any particles of smoke (or dust) entering the chamber will scatter the laser light. The detectors measure the scatter laser signals, to discriminate smoke from dust and other aerosols, before triggering the alarm.[78]

Optical communications

Optical communication is any type of communication in which light is used to carry a signal, instead of electrical current or radiofrequency. Optical communication relies on the use of optical fibres to propagate their signals over long distances. The main benefit of optical communication is the much higher transmission bandwidth that is available for transmitting data, exceptionally low signal loss, great transmission range, and no susceptibility to electromagnetic interference when compared to radiofrequency communications.[79]

Laser scanning

Laser scanning provides the advantage of being able to measure differences in length and distance down to the scale of a part of a wavelength of light (eg 380 to 700 nanometres). On the microscale, laser scanning supports the manufacturing process by generating a digital 3D image file of an object that can be used by a 3D digital printer to produce a replica from the digital file.

On the macroscale, laser scanning is primarily used to develop 3D surveys for use in creating digital models of building elevations, floor plans, tunnel profiling and motorways, bridges and mapping topography and terrain. Laser scanning is effective on-site locations where very accurate 3D measurements need to be recorded quickly for a very large number of data points to generate accurate digital models. Thus, the comparison of laser scans of terrain could be used to detect disturbances in the surface soil that may indicate the new placement of a buried Improvised Explosive Device, for example.

Light detection and ranging (LIDAR)

LIDAR is used in a similar manner to radio detection and ranging (RADAR) systems. Laser energy is directed towards the target and a collocated receiver receives the return signal, using precise time measurements to accurately determine the distance down to a part wavelength of the laser light.

NASA and the European Space Agency have deployed orbital space missions, configured with LIDAR, to digitally map the Earth's surface accurate to a part wavelength of light. The precisely made digital models of the Earth are used in computer-based analyses and experiments in other sciences that require precise measurements of the Earth surface dimensions, such as climate change, melting ice caps, changing snow cover, changing ocean water levels, etc.

Figure 28. Laser energy has been reflected from reflectors mounted on artificial objects left on the Moon surface by the NASA Apollo program.[80]

Laser water depth measurement and seafloor characterisation

The laser airborne depth sounder (LADS) is a purpose-designed infrared laser mounted in an aircraft. An optical coupler splits the laser output into two discrete frequencies: visible green light pulses that propagate in the clear ocean and coastal waters are reflected from the seafloor; and infrared pulses are reflected off the water's surface. The measured time differences between the two different returned signals are used to calculate the depth of the water beneath the aircraft and provide a digital hydrographic survey to characterise the seafloor.[81]

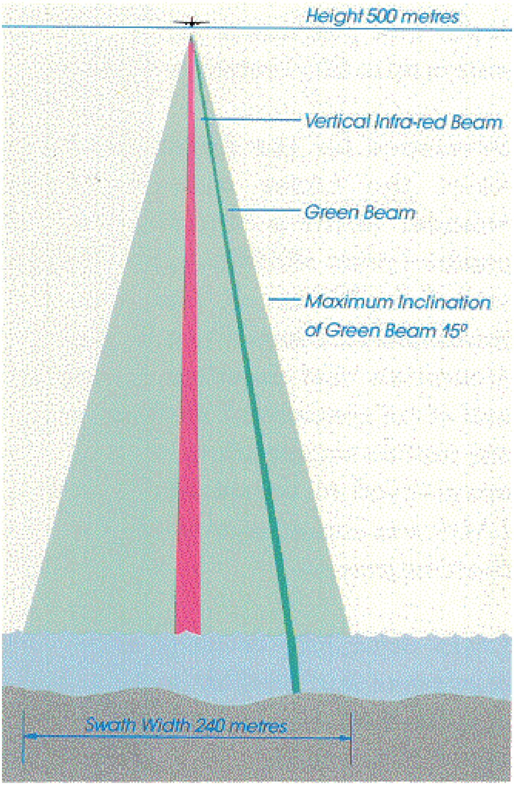


Figure 29. A system characterisation of the Laser Airborne Depth Sounder used by the Australian Hydrographic Office.[82]

Laser space debris removal

Space debris in Earth orbit poses significant risks to satellites, human space activities, and space access. Experimental research is being conducted to use laser energy to remove small-sized space debris objects. The laser is used to change the momentum of the orbiting debris object as it ascends above the horizon and before it passes the zenith. After a number of successive laser applications, over a series of orbital flyovers, the object is slowed and, with less kinetic energy, slowly descends until the atmosphere captures it, and it burns up on Earth re-entry.[83] There are two different approaches, at different energy levels:

1. **Laser ablation.** The laser energy heats up and ablates a small surface area on the small debris objects. The laser ablates the surface material, generating a gas that is discharged from the object as a 'plasma plume'. The gaseous discharge changes the momentum of the space object, and if occurring in a direction opposite to the direction of travel, reduces the object's kinetic energy.
2. **Laser pushing.** Laser pushing or radiation pressure (ie photonic pressure) is applied to the debris opposite to the direction of travel. These massless photons act like matter to collide with the debris and change the debris' momentum, reducing its speed and altitude.

Laser energy transfer

Lasers generate phase-coherent electromagnetic radiation at optical and infrared frequencies. This laser energy can be used for the wireless transmission of power to a receiving station similar to the manner that solar panels can convert solar radiation into electrical energy.[84] In the 2009 NASA Centennial Challenges competition, a laser-powered robot was developed to climb a 900-metre long cable, suspended from a hovering helicopter, in less than 7.5 minutes to demonstrate the feasibility of using laser energy to transfer power to a spacelift vehicle.[85] The benefit of using laser is that there is more control over the locations and environmental conditions that energy can be delivered, unlike with sunlight which is only available in daylight and under favourable weather conditions.

Photonic propulsion in space

NASA scientists have been investigating alternative propulsion techniques for spaceflight, including a 'photonic propulsion' system that relies on using the momentum of photons (ie massless particles of light) to provide the thrust to push an object forward. Spacecraft designs have been considered with sails to capture freely available photons emanating from the Sun and use radiation pressure for thrust. NASA has considered the concept of using large ground-based laser emitters to direct energy towards the sails of a spacecraft. Radiation pressure from the directed photons would push the large inflated sails attached to a spacecraft.[86]

CONCLUSIONS

The generation of DEW effects is based on exploiting quantum behaviours occurring on a subatomic scale. DEW effects can generate a concentration of light, heat, or electromagnetic energy that can be aimed to travel a straight line from the shooter to the target. Whereas a kinetic projectile or missile is a point object, the DEW output effect is a continuous or pulsed line of energy between the shooter and the target that is capable of causing disruption or collateral damage anywhere along that line, leading up to the target or beyond the target, until the point where the energy is dissipated below the damage/injury threshold.

The typical design for a DEW system includes the prime power source, the mechanism for generating energy in the form needed for the effect, a target acquisition and tracking system, and a beam pointing system for directing the energy onto the target. Ancillary systems will provide support for mission planning and situational awareness to assure the appropriate and safe use of the DEW in an operational area that may be shared with other users and systems.

DEW requires accurate pointing to hold the laser steady on the target to enable time to transfer adequate energy to cause a material or design failure at the target or prevent the target from functioning correctly. DEW damage mechanisms can range from the temporary dazzling of aircraft/spacecraft optical sensors, inflicting heat discomfort and injury to combatants, to high-energy catastrophic damage of material systems including aircraft and spacecraft.

It is not the DEW energy output but the DEW energy that is absorbed by the target that is the significant system performance measure to be used in planning DEW damage effects and effectiveness against different targets. This normally requires a steady delivery of energy over a finite dwell time for a damaging level of energy to accumulate at the target. Additionally, whilst some target materials may be vulnerable to DEW effects, other targets such as re-entering ICBM warheads and hypersonic missiles may use materials that are purpose-designed to resist and survive high temperatures and be less vulnerable to weapons using light or thermal energy; some materials may reflect the light energy away from the target.

A major cost-benefit of DEW is the significant cost reduction in using repeatable bursts of energy as an alternative to the costs of expensive weapons rounds and missiles. However, the total system development and acquisition DEW launcher system will require more complex systems for energy storage, mission planning, and weapon aiming than previously used with kinetic weapons systems. Additionally, tailoring the energy output of a DEW enables this same energy to be used for a number of different purposes ranging from rangefinding, sensing, target marking and designation, disruption, and destruction.

There are international humanitarian laws that need to be considered with the designs and employment of lasers and DEW, for lethal and non-lethal effects. Additionally, the integration of DEW into domestic and military operations needs to include consideration for the potential for DEW spillover and collateral damage risks.

GLOSSARY

ADDP	Australian Defence Doctrine Publication
ADF	Australian Defence Force
AEA	Airborne Electronic Attack
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ASNO	Australian Safeguards and Non-proliferation Office
BCE	Before Common Era
CASA	Civil Aviation Safety Authority
CJC	Chief of Joint Capabilities
CJLOG	Commander Joint Logistics
DEW	Directed Energy Weapon
DIRCM	Directed Infra-Red Counter-Measures
e-bomb	Electromagnetic bomb
EA	Electronic attack
eDEOP	Electronic Defence Explosive Ordnance Publication
EMP	Electro-Magnetic Pulse
EW	Electronic warfare
FAA	US Federal Aviation Authority
GPS	US Global Position System
HEL	High Energy Laser
HPM	High Power Microwave
HPRF	High Power Radio Frequency
ICBM	Inter-Continental Ballistic Missile
IM	Insensitive munition
LADS	Laser airborne depth sounder
LASER	Light amplification by stimulated emission of radiation
LIDAR	Light detection and ranging
LGW	Laser Guided Weapons

LST	Laser Spot Tracker
LTD	Laser Target Designator
NPB	Neutral Particle Beam
TEC	Thermo-Electric Cooler
U-235	Uranium 235 Thorium

ENDNOTES

1 Kochems, A; Gidgel A (2008). *The Viability of Directed-Energy Weapons*. Competitive Technologies for National Security: Review and Recommendations. Chapter 1. Heritage Special Report SR-21 February 29, 2008. The Heritage Foundation. p3. Online at https://apps.dtic.mil/dtic/tr/fulltext/u2/a477700.pdf. Accessed 28 September 2019.

2 Vargic, M (2013). *Did Archimedes Really Invent the "Death Ray"?* History Rundown. Online at www.historyrundown.com/did-archimedes-really-invent-the-death-ray/. Accessed 6 September 2019.

3 Defence (2019). Australian Defence Glossary definition for *Directed Energy Weapon* is "a system using directed energy primarily as a direct means to damage or destroy enemy equipment, facilities, and personnel." Accessed 6 September 2019.

4 Massachusetts Institute of Technology (2019). *Archimedes Death Ray.* 2.009 Product Engineering Processes. Online at http://web.mit.edu/2.009/www/experiments/deathray/10_ArchimedesResult.html. Accessed 6 September 2019.

5 Information Warfare Division (2018). *Information Warfare Strategy 2018-2028*. Joint Capabilities Group. p15.

6 Australian Defence Glossary (2019). *Electronic Warfare.* Online at Defence intranet.

7 Australian Defence Force (2013). Op cit. p1-10.

8 Australian Defence Glossary (2019). *Electronic Attack.* Online at Defence intranet.

9 Australian Defence Force (2013). ADDP 3.5—Electronic Warfare, edition 2. Operations Series. Australian Defence Doctrine Publication. p1-5. Online at Defence intranet.

10 ARPANSA (2019). *ARPANSA*. Australian Government. Online at www.arpansa.gov.au/. Accessed 20 September 2019.

11 Australian Government (2018). *Australian Radiation Protection and Nuclear Safety Regulations 2018.* Federal Register of Legislation. Online at www.legislation.gov.au/Details/F2018L01694. Accessed 20 September 2019.

12 IOP (2014). *Case Study: Lasers.* Institute of Physics. Online at www.iop.org/cs/page_43644.html#gref. Accessed 7 September 2019.

13 Wikipedia (2019). *Stimulated Emission.* Online at https://en.wikipedia.org/wiki/Stimulated_emission. Accessed 7 September 109.

14 LibreText (2019). *Laser Radiation Properties.* Chemistry. LibreText. Online at https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Analytical_Sciences_Digital_Library/JASDL/Courseware/Introduction_to_Lasers/03_Basic_Principles/01_Laser_Radiation_Properties. Accessed 8 September 2019.

15 Paschotta, R (2019). *Quantum Dots.* RP Photonics Encyclopedia. Online at www.rp-photonics.com/quantum_dots.html. Accessed 9 September 2019.

16 Dukowitz, Z (2017). *Out of This World Anti-Drone Technology: Lasers, UTMs, Bullets with Nets, and More. UAV* Coach. Online at https://uavcoach.com/futuristic-anti-drone-tech/. Accessed 6 September 2019.

17 Murphy, P (2009). *Lasers and Aviation Safety, International Laser Display Association.* Online at www.laserist.org/files/Lasers-and-aviation-safety_2pt2.pdf. Accessed 7 September 2019.

18 Clark, C (2019*). Raytheon's Latest Counter Drone Tech: Programmable Laser.* Breaking Defense. Online at https://breakingdefense.com/2019/06/raytheons-latest-counter-drone-tech-programmable-laser/. Accessed 26 September 2019.

19 Patel, P (2019). *How to Protect Pilots from Laser Pointer Attacks.* IEEE Spectrum. Online at https://spectrum.ieee.org/tech-talk/aerospace/aviation/how-to-protect-pilots-from-laser-pointer-attacks. Accessed 6 September 2019.

20 ARPANSA (2019). *What are the health effects of radiofrequency radiation exposure?* Radiofrequency radiation. Online at www.arpansa.gov.au/understanding-radiation/what-is-radiation/non-ionising-radiation/radiofrequency-radiation. Accessed 23 September 2019.

21 Boyd, E (2017). *G7 country buys DroneShield's drone jamming gun*. The Daily Telegraph. Online at www.dailytelegraph.com.au/business/g7-country-buys-droneshields-drone-jamming-gun/news-story/247f6a8dfb728c0861327344ed993a20. Accessed 27 September 2019.

22 Yang, L; et al (2016). *Damage effect and mechanism of the GaAs high electron mobility transistor induced by high power microwave.* Chinese Physical Society and IOP Publishing Ltd. Online at http://cpb.iphy.ac.cn/article/2016/1820/cpb_25_4_048504/cpb152718f10_hr.jpg.html. Accessed 26 September 2019.

23 Ni, G; Lu, J; Gao, B (2005). *Research on High Power Microwave Weapons*. Griffith University. Online at https://research-repository.griffith.edu.au/bitstream/handle/10072/2648/30861.pdf. Accessed 23 September 2019.

24 US Army (1992). *AMC-SSWMO Countermeasures Study" Volume 1: Guide To How Countermeasures Affect Smart Weapons.* US Army Materiel Command. p3-7. Online at https://apps.dtic.mil/docs/citations/ADA263833. Accessed 11 October 2019.

25 Tatum, J (2017). *HPM DEWs and Their Effects on Electronic Targets.* Defense Systems Information Analysis Center. Summer 2017: Volume 4 Number 3. Online at www.dsiac.org/resources/journals/dsiac/summer-2017-volume-4-number-3/hpm-dews-and-their-effects-electronic-targets. Accessed 25 September 2019.

26 Queensland Government (2019). *Labelling of laser apparatus.* Queensland Health. Online at www.health.qld.gov.au/system-governance/licences/radiation-licensing/resources/labelling-of-laser-apparatus. Accessed 27 September 2019.

27 Murphy, P (2017). *Laser hazards to aviation - Visual interference with pilots.* Online at http://laserpointersafety.com/aviation/laser-hazards/index.html. Accessed 7 September 2019.

28 APDC (2018). *Ground-based Lasers in Space Operations.* Pathfinder, Issue 31, June 2018. Air Power Development Centre. Online at http://airpower.airforce.gov.au/APDC/media/PDF-Files/Pathfinder/PF312-Ground-based-lasers-in-space-operations.pdf. Accessed 6 September 2019.

29 Peralta, E (2013). Loc cit.

30 Ward, R (2018). *Here Come the Lasers: The Dawn of Energy Weapons is Here.* The National Interest. Online at https://nationalinterest.org/blog/buzz/here-come-lasers-dawn-energy-weapons-here-26671. Accessed 9 September 2019.

31 Sheppard, L (2019). *Solid-State Laser.* How Products are Made. Online at www.madehow.com/Volume-6/Solid-State-Laser.html. Accessed 6 September 2019.

32 Allen G; et al (2019). *Overview of Lasers.* LibreTexts. Chemistry. Online at https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Instrumental_Analysis/Lasers/Overview_of_Lasers. Accessed 6 September 2019.

33 Air Force Technology (2019). *Airborne Laser System (ABL) YAL 1A*. Projects. Air Force Technology. Online at www.airforce-technology.com/projects/abl/. Accessed 17 September 2019.

34 ibid.

35 University of Southampton (2019). *How Fibre Lasers Work*. Optoelectronics Research Centre. University of Southampon. Online at www.orc.soton.ac.uk/how-fibre-lasers-work. Accessed 6 September 2019.

36 Szondy, D (2018). *Laser weapons: Is this the dawn of the death ray?* Military, New Atlas. Online at https://newatlas.com/laser-weapons-future-warfare/52801/. Accessed 6 September 2019.

37 Hecht, J (2008). *The History of the X-ray Laser*. Optics & Photonics News. The Optical Society. Online at www.osa-opn.org/home/articles/volume_19/

issue_5/features/the_history_of_the_x-ray_laser/#.UX3l-spUK0h. Accessed 6 September 2019.

38 Australian Government (2019). *Australia and Nuclear Weapons.* Nuclear Issues. Department of Foreign Affairs and Trade. Online at https://dfat.gov.au/international-relations/security/non-proliferation-disarmament-arms-control/nuclear-issues/Pages/australia-and-nuclear-weapons.aspx. Accessed 27 August 2019.

39 DST (2018). *High-power radio-frequency directed energy weapons*. Fact Sheet. Defence Science and Technology Group. Online at www.dst.defence.gov.au/publication/high-power-radio-frequency-directed-energy-weapons. Accessed 6 September 2019.

40 Braz, G (2014). *The EA-18G 'Growler' - Force Level Electronic Warfare (FLEW) in the ADF.* Air Power Development Centre. Online at http://airpower.airforce.gov.au/APDC/media/PDF-Files/Contemporary%20AirPower/AP31-The-EA-18-Growler.pdf. Accessed 6 September 2019.

41 ACMA (2018). *Mobile phone & GPS jamming devices FAQ.* Australian Communications and Media Authority. Online at www.acma.gov.au/theACMA/faqs-mobile-phone-and-gps-jamming-devices-acma. Accessed 7 September 2019.

42 Wright, M (2019) *US would be crippled by an EMP attack, which we pioneered nearly 60 years ago.* The Hill. Online at https://thehill.com/opinion/technology/427633-us-would-be-crippled-by-an-emp-attack-which-we-pioneered-nearly-60-years. Accessed 8 September 2019.

43 UNTERM (2019). *E-bomb.* The United Nations Terminology Database. Online at https://unterm.un.org/UNTERM/Display/record/UNHQ/E-bomb/669B3539F8FB256485256AFD00693E5C. Accessed 9 September 2019.

44 DST (2018). *Defeating Infra-Red Missiles*. Australian Defence Force capability driven by science and technology partnerships with industry. p12. Online at www.dst.defence.gov.au/sites/default/files/publications/documents/DST-Partnerships.PDF. Accessed 6 September 2019.

45 US Defense (2019). *Active Denial System FAQs.* Joint Non-Lethal Weapons Program. US Department of Defense. Online at https://jnlwp.defense.gov/About/Frequently-Asked-Questions/Active-Denial-System-FAQs/. Accessed 6 September 2019.

46 GlobalSecurity.Org (2019). *Neutral Particle Beam [NPB].* GlobalSecurity.Org. Online at www.globalsecurity.org/space/systems/npb.htm. Accessed 6 September 2019.

47 Greenwood, M (2019). *The Pentagon Wants a Particle Beam Weapon.*

Engineering.com. Online at www.engineering.com/DesignerEdge/DesignerEdgeArticles/ArticleID/18844/The-Pentagon-Wants-a-Particle-Beam-Weapon.aspx. Accessed 6 September 2019.

48 Ellis, J (2015). *Directed-Energy Weapons: Promise and Prospects.* Center for a New American Security. Online at https://s3.amazonaws.com/files.cnas.org/documents/CNAS_Directed_Energy_Weapons_April-2015.pdf?mtime=20160906081247. Accessed 11 October 2019.

49 Stoudt, D (2018). *Cloudy and a chance of rain need not sideline high-energy lasers.* Opinion. C4ISRNET. Online at www.c4isrnet.com/opinion/2018/02/26/cloudy-and-a-chance-of-rain-need-not-sideline-high-energy-lasers/. Accessed 7 September 2019.

50 Perram, G; Marciniak, M; Goda, M (2004). *High energy laser weapons: Technology overview.* Proceedings of SPIE - The International Society for Optical Engineering 5414 · September 2004. Online at www.researchgate.net/publication/238581076_High_energy_laser_weapons_Technology_overview. Accessed 26 September 2019.

51 Zimet, E; Mann, C (2009). *Directed Energy Weapons—Are We There Yet? The Future of DEW Systems and*

Barriers to Success. Center for Technology and National Security Policy National Defense University. p3. Online at www.hsdl.org/?view&did=15708. Accessed 26 September 2019; Rourke, R (2015). *Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for*

Congress. Congressional Research Service. p5. Online at https://fas.org/sgp/crs/weapons/R41526.pdf. Accessed 11 October 2019.

52 Atherton, K (2015). *Boeing Unveils Its Anti-Drone Laser Weapon.* Popular Science. Online at www.popsci.com/boeing-unveils-compact-anti-drone-laser/. Accessed 27 September 2019.

53 NASA (2019). *Why is the Sky Blue?* Space Place. NASA Science. Online at https://spaceplace.nasa.gov/blue-sky/en/. Accessed 27 September 2019.

54 UNOOSA (1966). *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.* United Nations Office for Outer Space Affairs. Online at www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html. Accessed 27 September 2019.

55 Payne, M (2018). *Speech, Lowy Institute, Sydney, 30 November 2018.* Online at https://foreignminister.gov.au/speeches/Pages/2018/mp_sp_181130.aspx. Accessed 27 September 2019.

56 Chappell, S (2019). *Power Generation and Storage for Directed Energy Systems.* Defense Systems Information Analysis Center. DSIAC Journal. Spring 2018: Volume 5 Number 2. Online at www.dsiac.org/resources/journals/dsiac/spring-2018-volume-5-number-2/power-generation-and-storage-directed-energy. Accessed 26 September 2019.

57 Corr, P; Klima, P (2019). *Photonics - Buyer's Guide*. Online at www.photonics.com/Articles/Laser_Operation_Temperature_Control_and_Mount/a57161. Accessed 25 September 2019.

58 Tate, A (2019). *Chinese navy trials laser weapon.* Jane's 360. Online at www.janes.com/article/87820/chinese-navy-trials-laser-weapon. Accessed 27 September 2019.

59 Viau, C (2011). *Expendable Countermeasure Effectiveness against Imaging Infrared Guided Threats.* Semantic Scholar. Conference Proceedings. Online at https://pdfs.semanticscholar.org/4783/4ec45f24453d1263b94f633aa6e6bc7e2387.pdf. Accessed 27 September 2019.

60 Flight Global (1941). *Bristol Hydraulics.* Flight Global/Archive. November 20th, 1941. P364. Online at www.flightglobal.com/pdfarchive/view/1941/1941%20-%202764.html?search=shooting%20off%20the%20tailplane. Accessed 27 September 2019.

61 Hafften, M; Stratton, R (2004). *High-Energy Laser Weapon Integration with Ground Vehicles*. Paper presented at the NATO RTO AVT Symposium on "Functional and Mechanical Integration of Weapons and Land and Air Vehicles", held in Williamsburg, VA, USA, 7-9 June 2004, and published in RTO-MP-AVT-108. p58-7. Online at https://pdfs.semanticscholar.org/5486/72e3415b7d8c00a8dcdf7db13fc28a89da24.pdf. Accessed 25 September 2019.

62 Army (2016). *Ballistic and laser ocular protection system.* Australian Army. Online at www.army.gov.au/our-work/equipment-and-clothing/soldier-combat-ensemble/ballistic-and-laser-ocular-protection-system. Accessed 9 October 2019.

63 Hafften, M; Stratton, R (2014). Loc cit.

64 Defence (2019). *Glossary of Terms.* EDEOP 101 - Department of Defence Explosives Regulations. Online at www.defence.gov.au/jcg/jlc/Documents/DEOP_101/Glossary_of_Terms.pdf. Accessed 11 October 2019.

65 ICRC.Org (2019). *Laser Weapons.* How Does Law Protect in War? Online at https://casebook.icrc.org/glossary/laser-weapons. Accessed 6 September 2019.

66 ICRC (2011). Section B. *Laser systems incidentally causing blindness.* Practice Relating to Rule 86. Blinding Laser Weapons. Customary International Humanitarian Law. Online at https://ihl-databases.icrc.org/customary-ihl/eng/

docs/v2_rul_rule86. Accessed 8 September 2019.

67 Harper, J (2018). *Support Growing for Directed Energy Weapons.* National Defense Magazine. Online at www.nationaldefensemagazine.org/articles/2018/5/4/support-growing-for-directed-energy-weapons. Accessed 9 September 2019.

68 EOS (2019). *Space Debris Management.* EOS Electro Optic Systems. Online at www.eos-aus.com/space/space-debris-management/. Accessed 9 September 2019.

69 CASA (2007). AC 139-23 Laser Emissions which may Endange*r the Safety of Aircraft.* Online at www.casa.gov.au/files/139c23pdf. Accessed 10 September 2019.

70 Szondy, D (2018). *Laser weapons: Is this the dawn of the death ray?* New Atlas, Military. Online at https://newatlas.com/laser-weapons-future-warfare/52801/. Accessed 27 September 2019.

71 ibid

72 ibid

73 Mizokami, K (2015). *The Air Force Wants to Put Huge Lasers on Its Gunships.* Popular Mechanics. Online at www.popularmechanics.com/military/weapons/a17461/the-air-force-wants-to-put-lasers-on-gunships/. Accessed 28 September 2019.

74 Sisk, R (2018). *Air Force Special Ops Short on Funding for AC-130 Gunship Laser.* Defense Techy. Military.com. Online at www.military.com/defensetech/2018/04/11/air-force-special-ops-short-funding-ac-130-gunship-laser.html. Accessed 28 September 2019.

75 US Defense (2019). *Joint Publication 3-09 Joint Fire Support*. Joint Force Development, Joint Chiefs of Staff. pB-1. Online at www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_09.pdf. Accessed 27 September 2019.

76 ibid

77 ibid

78 Areej (2018). Working of Laser Smoke Detector. AutomationForum.Co. Online at https://automationforum.co/working-of-laser-smoke-detector/. Accessed 27 September 2019.

79 Techopedia (2018). Optical Communication. Networking. Online at https://www.techopedia.com/definition/24942/optical-communication. Accessed 27 September 2019.

80 Lennard, D (2013). *Scientists Bounce Laser Beams Off Old Soviet Moon Rover.* SpaceNews. Online at https://spacenews.com/35181scientists-bounce-laser-

beams-off-old-soviet-moon-rover/. Accessed 9 September 2019.

81 Defence (2019). *LADS II (Laser Airborne Depth Sounder).* Inside the AHO, Australian Hydrographic Office. Online at www.hydro.gov.au/aboutus/lads.htm. Accessed 11 October 2019.

82 ibid.

83 Choi, S; Pappa, R (2019). *Assessment Study of Small Space Debris Remo*val by Laser Satellites. NASA Technical Report. NASA Langley Research Centre. Online at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120009369.pdf. Accessed 27 September 2019; EOS (2019). *Space Debris Management*. Electro Optic Systems. Online at www.eos-aus.com/space/space-debris-management/. Accessed 27 September 2019.

84 Summerer, L; Purcell, O (2009). Concepts for wireless energy transmission via laser. Online at www.esa.int/gsp/ACT/doc/POW/ACT-RPR-NRG-2009-SPS-ICSOS-concepts-for-laser-WPT.pdf. Accessed 27 September 2019.

85 NASA (2009). *LaserMotive Wins $900,000 from NASA in Space Elevator Games.* News. Armstrong Flight Research Centre. Online at www.nasa.gov/centers/dryden/status_reports/power_beam.html. Accessed 28 September 2019.

86 MacDonald, F (2016). *NASA Researchers Are Working on a Laser Propulsion System That Could Get to Mars in 3 Days.* Online at www.sciencealert.com/nasa-scientists-are-investigating-a-propulsion-system-that-could-reach-mars-in-3-days. Accessed 28 September 2019.

Directed Energy Weapons

Playing with Quantum Fire

The militarisation of high-energy Directed Energy Weapons (DEW) might be regarded as a game-changer for defending against high-speed missiles, remotely piloted aircraft and swarms of drones. Low powered DEW systems have been militarised to dazzle electro-optical sensors and Australia has already integrated Directed Infra-Red Counter Measures into air mobility aircraft for self-protection.

DEW may provide a speed-of-light option, with a lower cost per round, as an alternative to high-end precision-guided weapons that cost more than the targeted incoming threat systems. However, in trade-off analyses with other weapons effects, DEW may increase the burdens on technology, power, mission planning and integration, and collateral damage risks. Additionally, there are unavoidable physical constraints to the employment of the DEW damage mechanism caused by weather, environment, and target characteristics such as aerodynamic cooling, reflectivity, ablation effects, and heat resistance.