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DIRECTED ENERGY WARFIGHTER

G. Darl Lewis

3 December 2023

Tech Note

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14. ABSTRACT

Familiarize people with HEL weapons, Directed Energy (DE) Weapons, and both High Power Laser (HEL) and High Power Electromagnetic (HPEM).

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Wargames, Directed Energy, HEL, DE, HPEM

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Welcome to AFRL/RDMW's Directed Energy Weapon: High Energy Laser training course. This is a publicly-releasable presentation developed to familiarize people with HEL weapons.

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Course Scope

- This master course contains three courses on Directed Energy (DE) warfighting
- The intended audience includes
  - Warfighters
  - Technical personnel new to military applications of DE
  - Interested non-technical personnel
- For the layperson, these courses cover and identify:
  - Basic DE physics
  - Basic DE employment concepts
  - Resources for additional study

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Directed Energy (DE) is a highly technical area of knowledge where one can spend an entire career developing specialized expertise in just a few DE phenomena. The scope of this course is a basic introduction to DE weapons (DEW) and associated technologies with focus on directed energy weapons as applied to the battlefield. If you wish to further advance your understanding of the complex topics presented, we provide some suggested resources for additional study.

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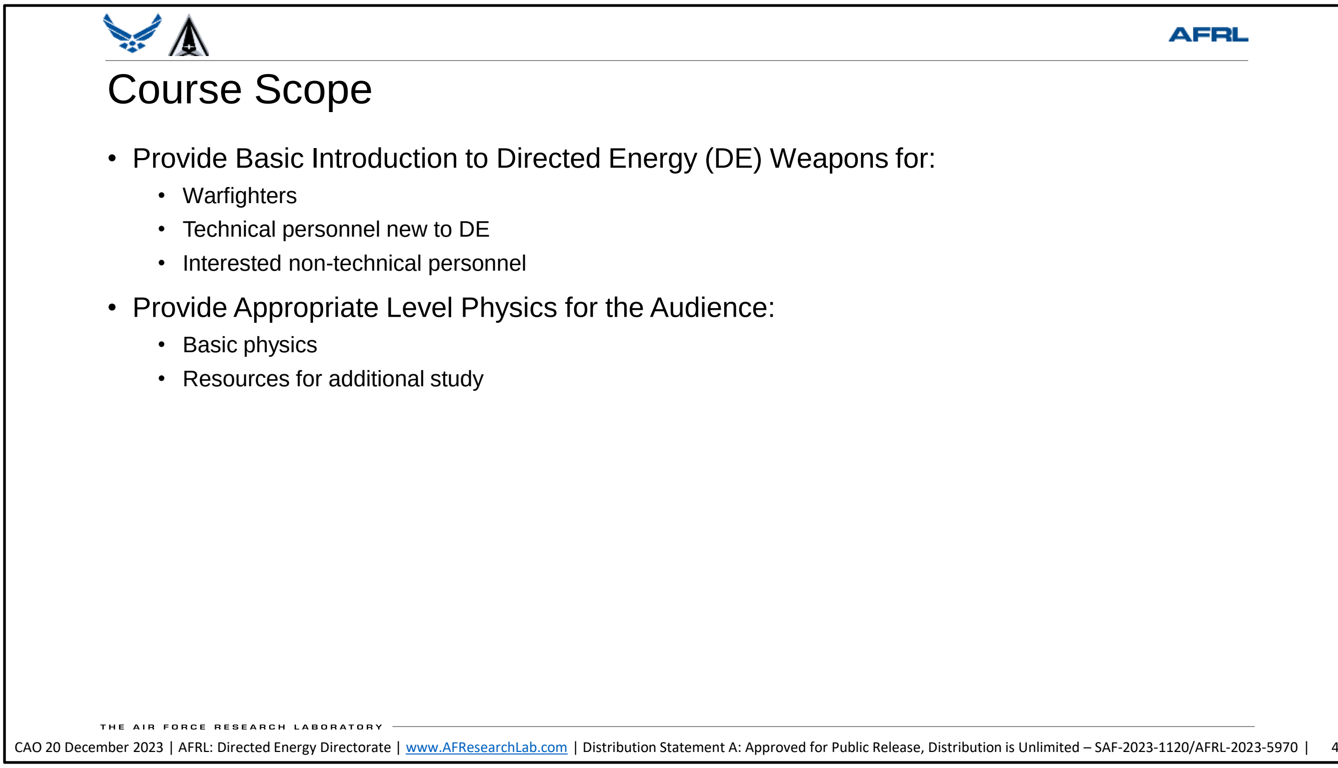
Welcome to AFRL/RDMW's Directed Energy Weapon - Introduction training course. This is a publicly-releasable presentation developed to familiarize people with directed energy (DE) weapons, both high power laser (HEL) and high power electromagnetic (HPEM).



Directed Energy (DE) is a highly technical area of knowledge where one can spend an entire career developing specialized expertise in just a few DE phenomena. The scope of this course is a basic introduction to DE weapons (DEW) and associated technologies with focus on directed energy weapons as applied to the battlefield. If you wish to further advance your understanding of the complex topics presented, we provide some suggested resources for additional study.

Introduction to Directed Energy Weapons

- What are Directed Energy Weapons (DEW)?
- DE vs Kinetic Energy (KE)
- DE and Electronic Warfare (EW)
- The Kill Chain
- Military Utility (MU)

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We present some of the decisions and actions necessary to prosecute threats with DEWs, which is in sharp contrast to the common depiction in Hollywood movies. Besides not being able to visually see most DE systems in action, the damage effects are more nuanced.

The full arsenal for a battlespace includes other weapon types. A brief discussion is provided of the differences and similarities between DE and kinetic energy (KE) weapons, as well as the differences and similarities between DE and electronic warfare (EW) weapons.

The decision to fire a weapon is preceded by a series of events and actions that must take place before the weapon can be effective. This process is known as a kill chain. Presented are some of the decisions, actions and how to prosecute threats for DEW as they fit within a kill chain.

Our final topic reviews how one might define military utility and how DEW can be assessed within a military utility context.

What is a Directed Energy (DE) Weapon?

DE is a beam of concentrated electromagnetic energy

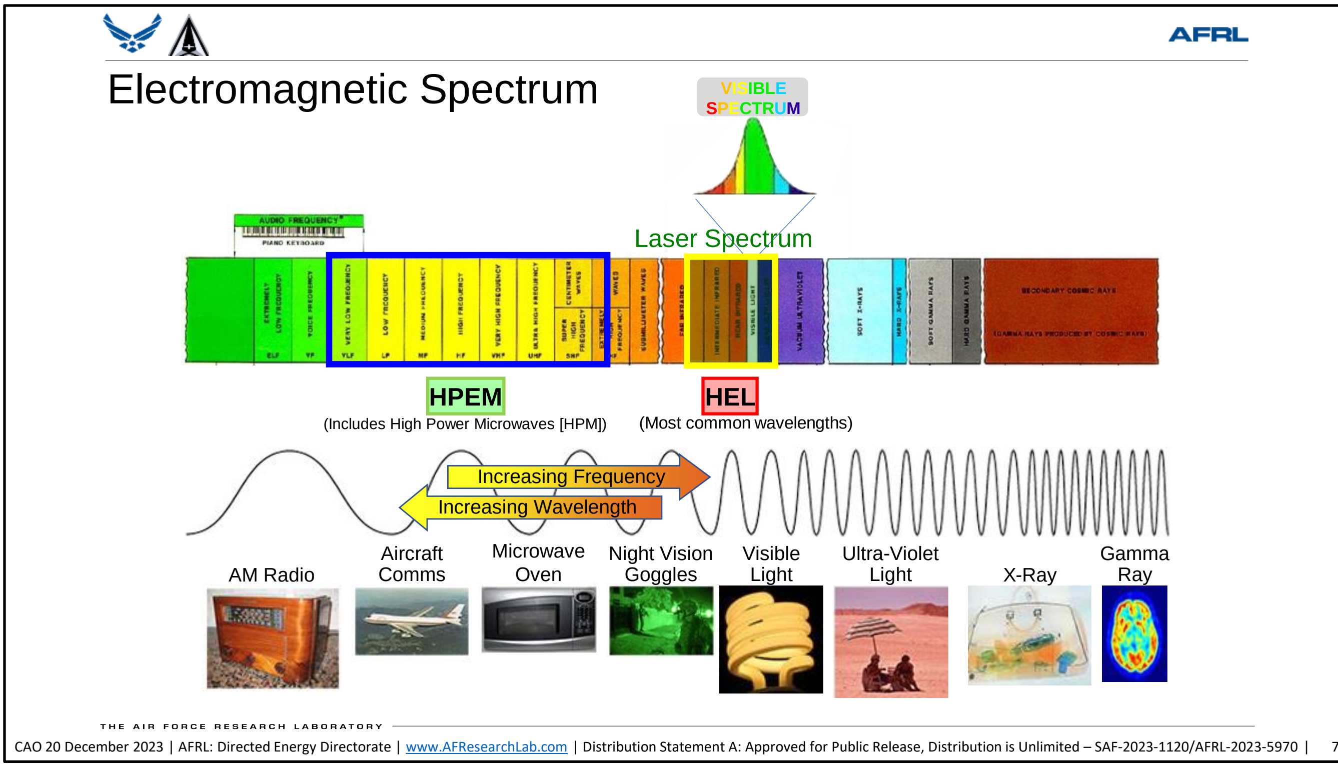
Laser Beam
Note: Pic is Hollywood version

Electromagnetic Beam
Note: Pic is Hollywood version

DE is a beam of concentrated electromagnetic energy and can include lasers, microwaves, and sound beams. Particle and sound beams are not presented in this training series. The directed energy weapon (DEW) uses this concentrated beam of electromagnetic energy to damage a threat without using any solid projectiles. DEW can augment the battlespace in significant ways and these details will be discussed in subsequent training courses.

The beam for a high energy laser (HEL) contains light particles, i.e. photons, which can be very focused, allowing precision aiming. It can travel a very long distance unaffected by gravity, wind and other types physical forces. Its power can be diminished by diffraction and atmospheric effects which will be further discussed in another course.

The electromagnetic beam for high power electromagnetic (HPEM) is more diffuse than a laser beam. Impact from HPEM to a threat is also different than from HEL. In their unique ability to defeat threats, both HEL and HPEM weapons offer renewable magazine, scalable effects and cost effectiveness to the battle logistics.



The electromagnetic spectrum consists of the range of frequencies and wavelengths of electromagnetic radiation as well as the corresponding photon energies. Frequency is the number of peaks of a wave within a specified interval. Wavelength is the distance between one peak of the wave to the next subsequent peak. Frequency and wavelengths are inversely related, that is, as frequency increases, wavelength decreases.

The individual frequencies are divided into separate bands called by different names. Humans are very familiar with the visible band because these frequencies correspond to the colors that our eyes can see. Frequency bands that are lower than visible (left side of figure) include radio waves, microwaves and infrared band. Frequency bands higher than visible (right side of figure) include ultraviolet band, X-rays and gamma rays.

The laser band includes visible and infrared bands. Laser pointers emit waves that are colored, primarily red or green, and visible to the human eye. The infrared laser bands selected for HELs are not visible to the human eye. The infrared band is further divided into 4 groups, i.e. near infrared (NIR), shortwave infrared (SWIR), mid-wave infrared (MWIR) and longwave infrared (LWIR).

HPEM bands are comprised of electromagnetic waves from millimeter wavelength on through low frequency radio waves.

DE Weapon Types: The Similarities

HEL	HPEM
Line-of-sight (LOS)	
Orientation of target relative to the weapon changes the effect	
Damage mechanism is specific to the mission	
No debris / evidence left behind	
Extremely low cost per shot	
On-board precision sensor are multi-use	

HEL and HPEM weapons share several things in common. First, both beams need an uninterrupted line-of-sight (LOS) between the DE source and the target. The LOS is the imaginary line that directly connects the source of the beam and the intended target.

With both HEL and HPEM, the range and orientation of the target relative to the DE weapon can change the effect of the DEW on the target. For example, one has a better chance of hitting a bullseye if one is standing directly perpendicular to the dart board rather than at an angle to the board. Of, course, being closer to the dart board would make that bullseye shot even more probable. This directionality also applies to DEW.

If the target was a flush-mounted antenna on one side of a drone and the DEW was facing the other side of the mount, the energy would need to go through the entire body of the drone before getting to the antenna. If the DEW was facing the antenna side, it would obviously be more effective. Again, being closer to the target makes the shot more probable.

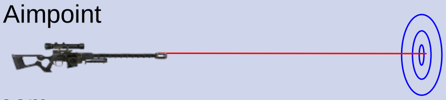
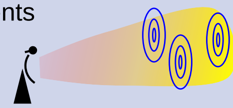
Damage mechanisms for directed energy are either temporary or permanent, depending on the mission objective. A laser could be used to disrupt a sensor denying its use or to destroy the sensor's focal plane completely depending on the power and delivery time. An HPEM weapon could be disruptive by causing a drone's flight control computer to reboot. The ability to potentially control the level of damage to a target is an advantage of a DEW.

Neither HEL nor HPEM leave behind anything in the way of shell casings, sabots, projectiles, unexploded ordnance, fragments or explosive residue.

Both HEL and HPEM are extremely low cost-per-shot weapons because their cost is based on the expense of the power required for a shot. The power required is based on dwell time, which is how long the energy is on the target to achieve a successful shot. DEWs also can recharge their energy to prepare for their next target engagement.

DEW systems are more than just weapons. They need precision sensors to track their aimpoint. These sensors may be used for other tasks in the battlefield when the weapon is not used for the fight. Thus, DEW has the potential for multi-use functionality.

DE Weapon Types: The Differences

HEL	HPEM
Precision Aimpoint  Narrow Beam	Area Components  Wider Beam
Dwell for cumulative effect (in seconds)	Can be near-instantaneous or cumulative (in nanoseconds)
Irradiance in W/cm^2 Dwell in seconds; power in 10W to MW	Power density in W/cm^2 Pulse duration in nanoseconds; power in many W
Damage Mechanism: Typical Thermal Effects	Damage Mechanism: Electronic disrupt

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In addition to several similarities, HEL and HPEM weapons have some significant differences. The first difference is how the directed energy impacts threat vulnerability. The beam of HEL weapons is narrower than the beam of HPEM weapons. Hence, a HEL can be more precise in targeting an aimpoint and able to focus on a single, small area of the target.

The wider beam of the HPEM weapons provide the advantage of being able to target multiple vulnerable components that are inside the beam. The difference in aiming can be understood by likening the HEL to a rifle and the HPEM to a shotgun. On the battlefield, HELs can achieve specific effects for single threats while HPEMs can be more effective with swarms of threats.

The second difference is how a cumulative effect can be achieved. Once a HEL is focused on an aimpoint, the dwell time determines its cumulative effect. Each effect requires a certain amount of dwell. If the dwell time is too short, there may be no effect from a HEL. In contrast, the HPEM can have an effect nearly instantaneously. Cumulative effects are still achievable with HPEM.

The next difference is mainly a matter of physics terminology for beam intensity. The HEL physicists use the term irradiance while the HPEM experts use the term power density. Both terms refer to the power transferred per unit area and have the same units of W/cm2.

The importance of dwell time has been mentioned. Dwell time for HEL is measured in seconds while dwell time for HPEM is measured in nanoseconds. Power is energy transferred per unit of time and measured in watts.

The mechanism for damage is the last difference discussed in this course. HEL weapons cause damage based on thermal load with the objective of changing the characteristics of the target material. The level of heat transfer determines the type of damage. Damage on targets will be discussed in more details in subsequent HEL and HPEM training.

How is DE different from KE

	KE	DE
Speed of Flight	Sub-second to hours	Speed of light
Effect	Typically, catastrophic	Less than lethal to catastrophic
Cost per Shot	$ - $,$$$,$$$	¢¢
Magazine	Limited	Replenishable
Path to Target	Flight profile, feet to global range	Line of sight
Availability	Now	Near future
Collateral Damage	Blast radius, debris	Probabilistic risk assessment, scatter
Clandestineness	Trackable, debris	Low probability of intercept, no debris
Doctrine	Established	TBD

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Kinetic energy weapon (KEW) is the traditional artillery for battle. DEW can augment the battlespace with lower costs per shot, nearly infinite magazines, and speed-of-light engagements.

DEW travel at the speed of light, which is 3x10^8 m/s. KE weapons follow the physics of projectiles or guided ballistics with flight speeds of up to Mach 25 (~8500 m/s). DE flight speeds are essentially 35,000 times faster than KE flight speeds. DEW can provide varying levels of damage ranging from lethal to less than lethal

KE systems typically produce a one-to-one effect, one shot to one target. Munition costs for KE systems range from a few dollars for a pistol bullet to millions of dollars for ballistic missiles. DE weapons can be recharged, so the cost per shot ranges from milli-cents to a few dollars.

KE "magazine" is limited to the munitions on hand, DE weapons are limited to the storage capacity of batteries and capacitors. However, these may be recharged between shots, thus extending the magazine life beyond its initial capacity. This ability to recharge the system, while on mission, is why DE weapons can claim the ability to have a "deep magazine." Rate of fire is a limit which can apply to KE and DE. They are both affected by thermal load which can accumulate and require a cooling period between one shot and another or one group of shots and another.

KE flight paths can take on many forms, from the basic projectile of bullets to cruise missile that can follow a more complicated guided ballistic flight profile. DE's path to the target is via LOS.

KE weapons have been available since the first conflict. DE systems remain at the prototype stage.

Collateral Damage is unintended or inadvertent damage caused by the military weapon. For KE systems, this can include projectile pass-through, blast radius, unexploded ordnance, and toxic debris. For DEW, the reflected, scattered or pass-thru energy may damage unintended objects. Both KE and DE can be employed in clandestine manner, but KEW may be tracked in flight and can leave debris (munition casings, bullets and fragments, explosive residue, unexploded ordnance, etc.) behind. DEW leave no trace except the effects of their energy on targeted systems

Military doctrines are fundamental principles that are officially sanctioned for battle management and to solve military problems. Because KE weapons have been used for centuries, there are established, and evolving doctrines for KE weapons. Similar doctrines are not in place for DE weapons mainly because of lack of experience in using these weapons for real battles.

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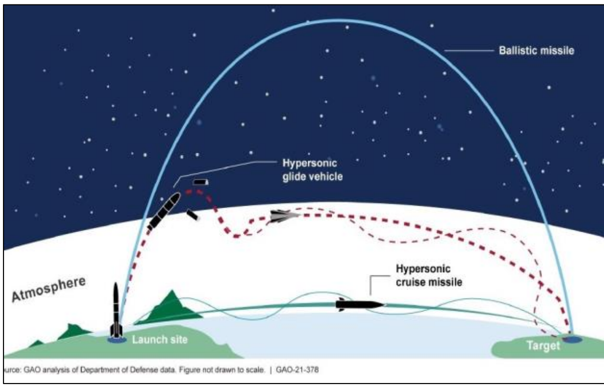
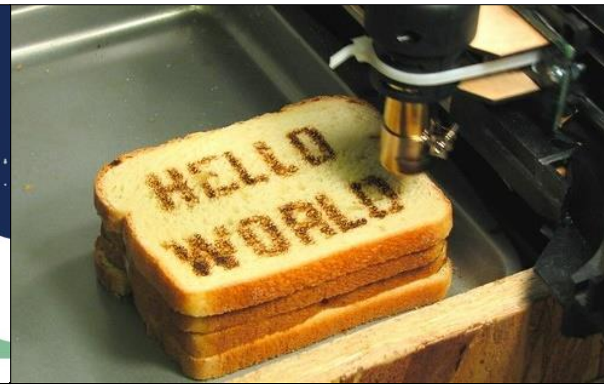
How KE & DE Weapons Work

KE
Launch → Flight Time → Impact

DE
Trigger → Dwell → Effect





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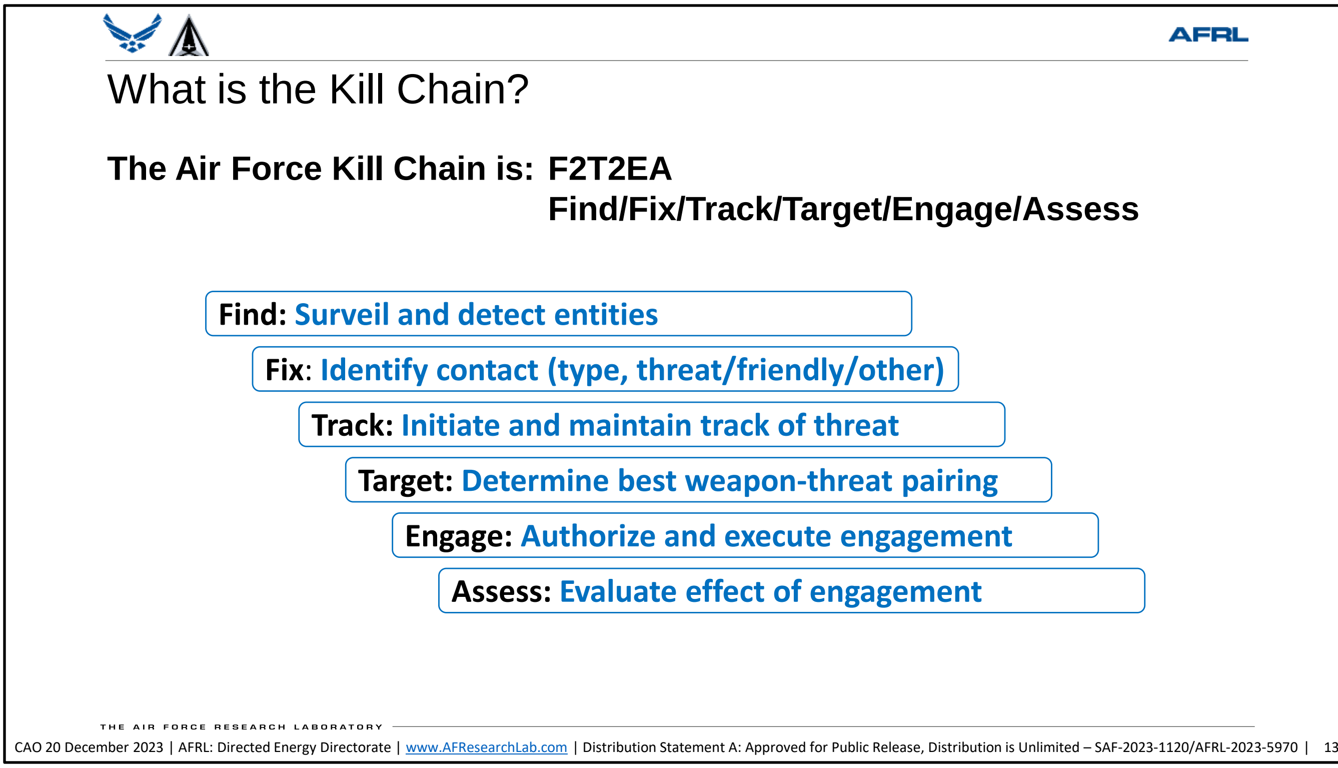
Kinetic Energy Weapons (KEWs) follow a launch-flight time-impact model, while DEWs follow a trigger-dwell-effect model. KEWs can be launched from ground or air, either released to fall, shot from a rifle, or launched ballistically. Launch parameters include launch rates, gravitational effects, flight profiles and flight time to reach and impact the target. KE flight times can vary greatly, from transonic bullets traveling distances of single-digit feet – in a fraction of a second to subsonic cruise missiles, flying terrain-following flight paths, for hours. They aim to hit or detonate near the intended target.

Once the KE projectile hits or detonates near the target, the resulting collision can produce immediate catastrophic destruction of the threat. The specific vulnerability of the target depends on the size and speed of projectiles or fragments, location of the hit, overpressure from explosion or impact, and amount of heat generated.

Because DEWs travel at the speed of light, they essentially reach their target instantaneously. HEL weapons need to hit a precision aimpoint, while HPEM weapons simply need to get the target in the beam to have the desired effect.

While both DE weapons and Electronic Warfare (EW) use energy in the electromagnetic spectrum, they each have different purposes. DE weapons seek targets that are vulnerable to their energy for the purpose of damaging the system.

EW's main role on the battlefield is to deny use of the enemy's systems. This denial can be in the form of jamming, spoofing or misdirection.



The "Kill Chain" is the term for six distinct steps of dynamic targeting designed to maximize the effects of the use of force. Rules of Engagement (ROE) spell out what threats to engage, when to engage and how to ascertain the results and subsequent actions necessary..

The six steps are Find, Fix, Track, Target, Engage, and Assess (F2T2EA). We will unpack this chain using example scenarios. Note that the steps of the F2T2EA chain are not completely sequential.

The first step, Find, has surveillance sensors that are used to detect entities within their reach. Surveillance sensors are not typically known for their accuracy, but they have long range to provide a heads-up that something is out there.

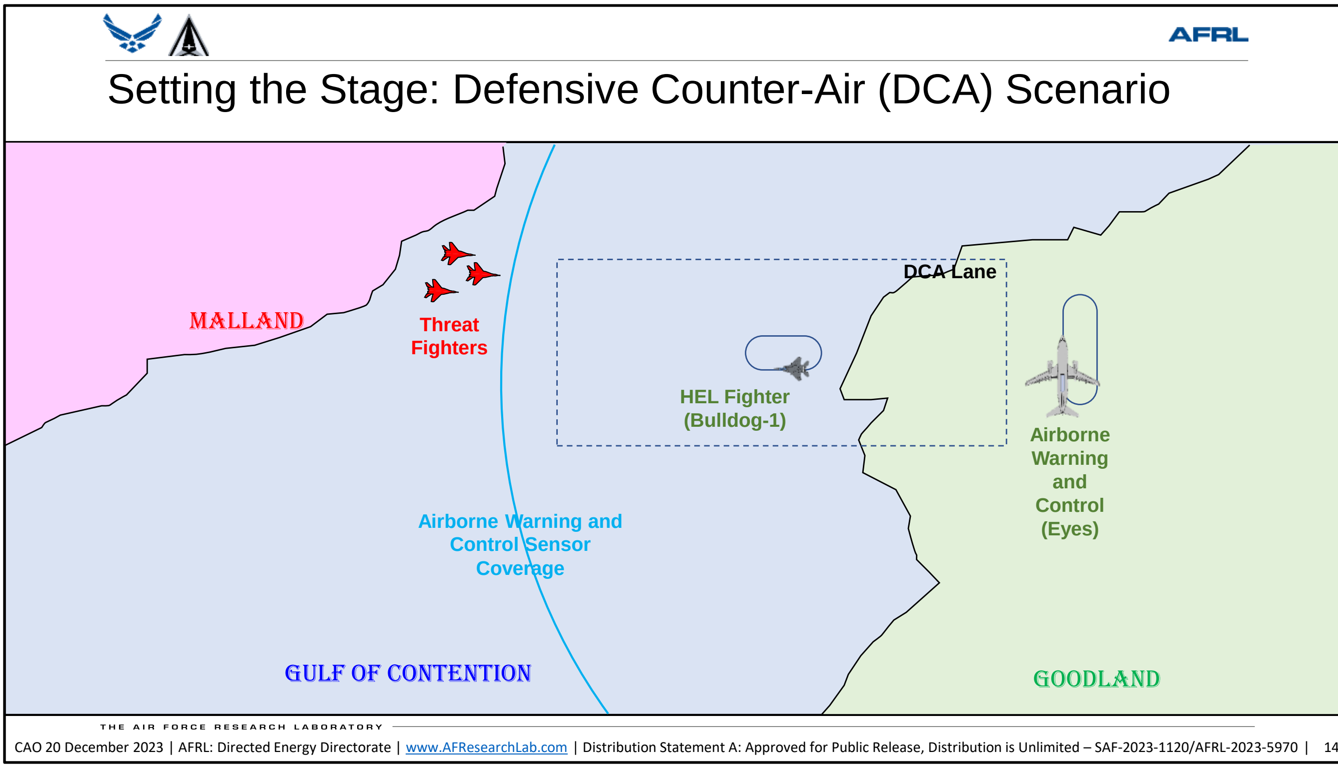
The Fix step attempts to identify the entity. This goal is to determine whether it is a friendly, a threat or a neutral. This decision can be augmented by radio contact, Identification Friend-or-Foe (IFF) equipment, and perceived behaviors (Does it walk and talk like an F-35 or an in-bound cruise missile?). Other sensors may be called upon to help with the identification.

Track determines where the entity is, where it is going and assigns a track number. Multiple sensors, such as radar or electro-optical, can be used to gather information on the tracks.

With knowledge that the track is a threat, where it is, and where it is going, Target gathers the data to decide what weapon to engage the track. The best weapon/track pairing is based on the type of threat and the available weapons. If it is an incoming theater ballistic missile, an anti-aircraft gun is not going to stop it in time to do anything; if it is a small drone, using a $800,000 surface-to-air missile (SAM) might be a bad cost tradeoff.

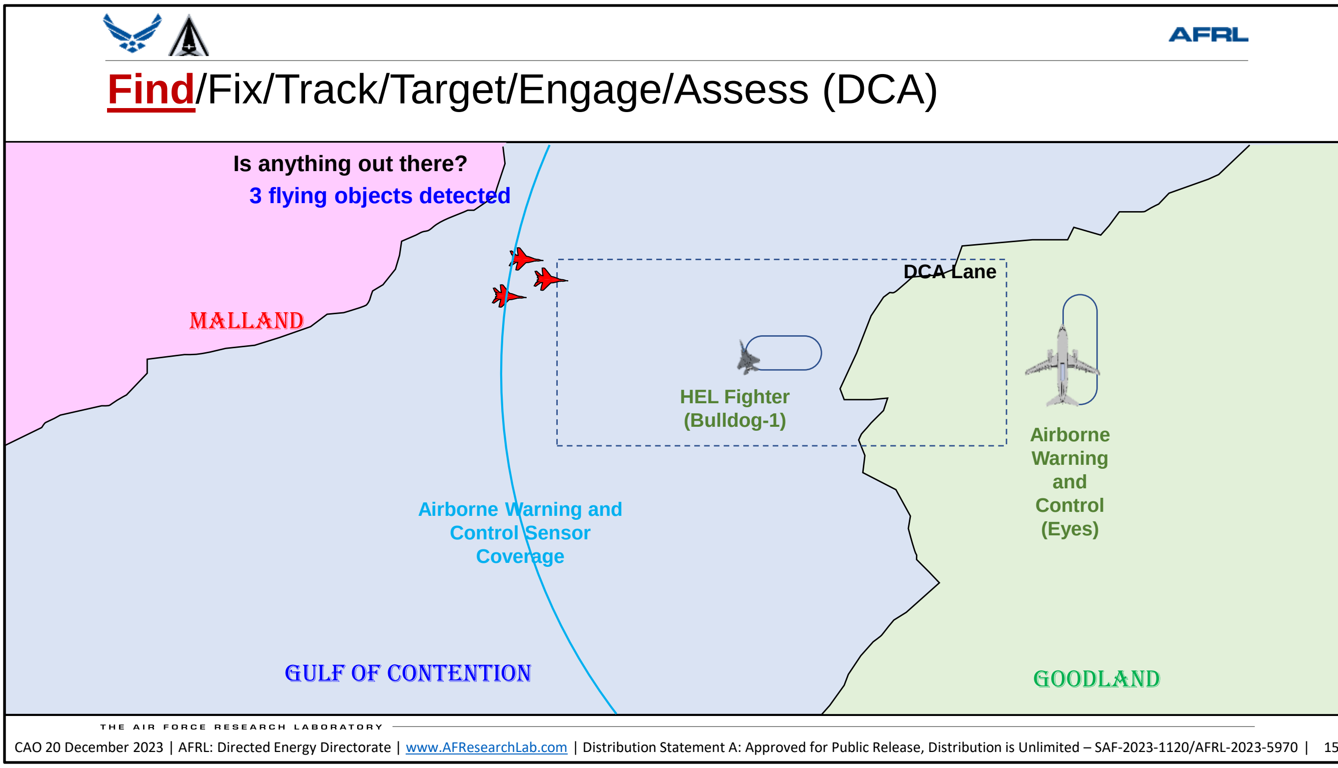
Engage assigns the DE system to employ its weapons against the tracks. An asset may engage the threats more than once to accomplish a successful mission.

Assess determines if the desired result was achieved using available sensors. If the desired outcome was the catastrophic, the sensors determine if it was obliterated, fell to the ground, or still flying to its intended destination. The outcome of an assessment can determine if reengagement is needed. Next is a specific example of the kill chain.

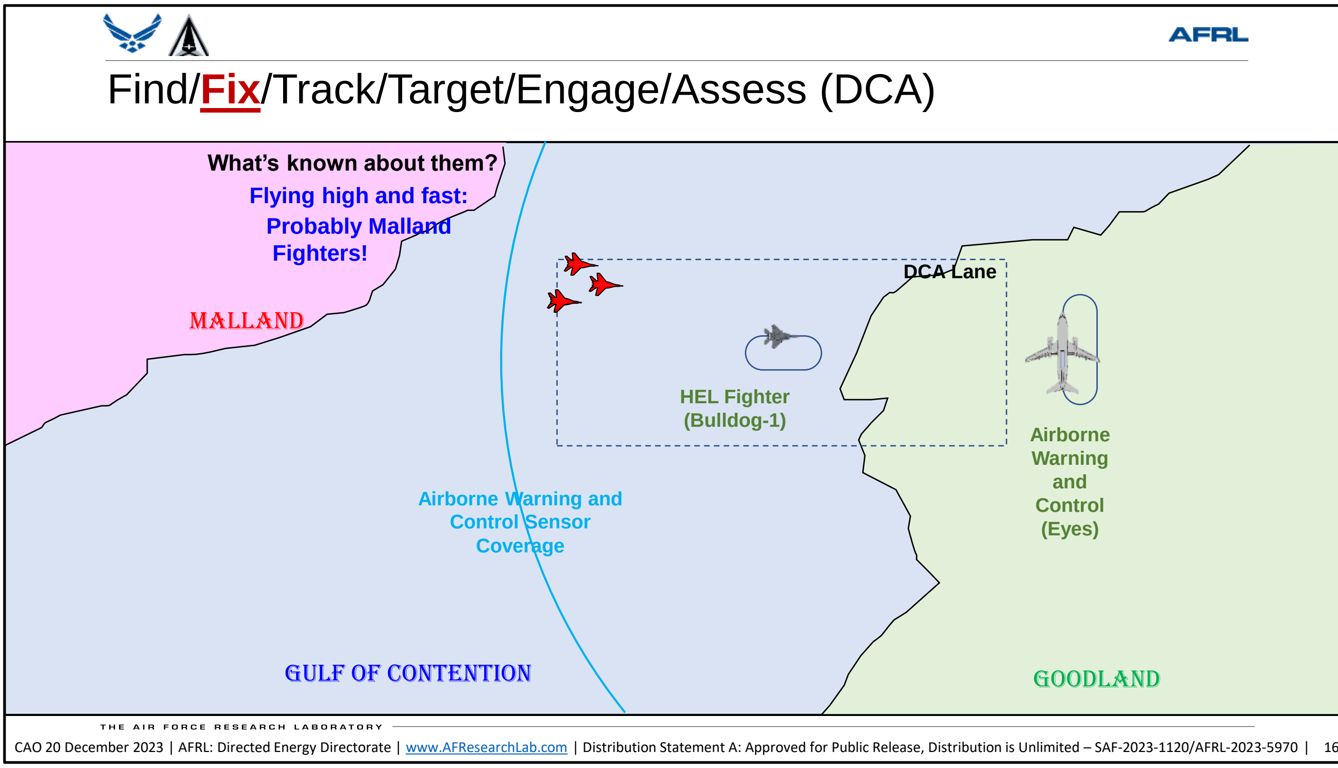


Welcome to the Defensive Counter-Air (DCA) scenario.

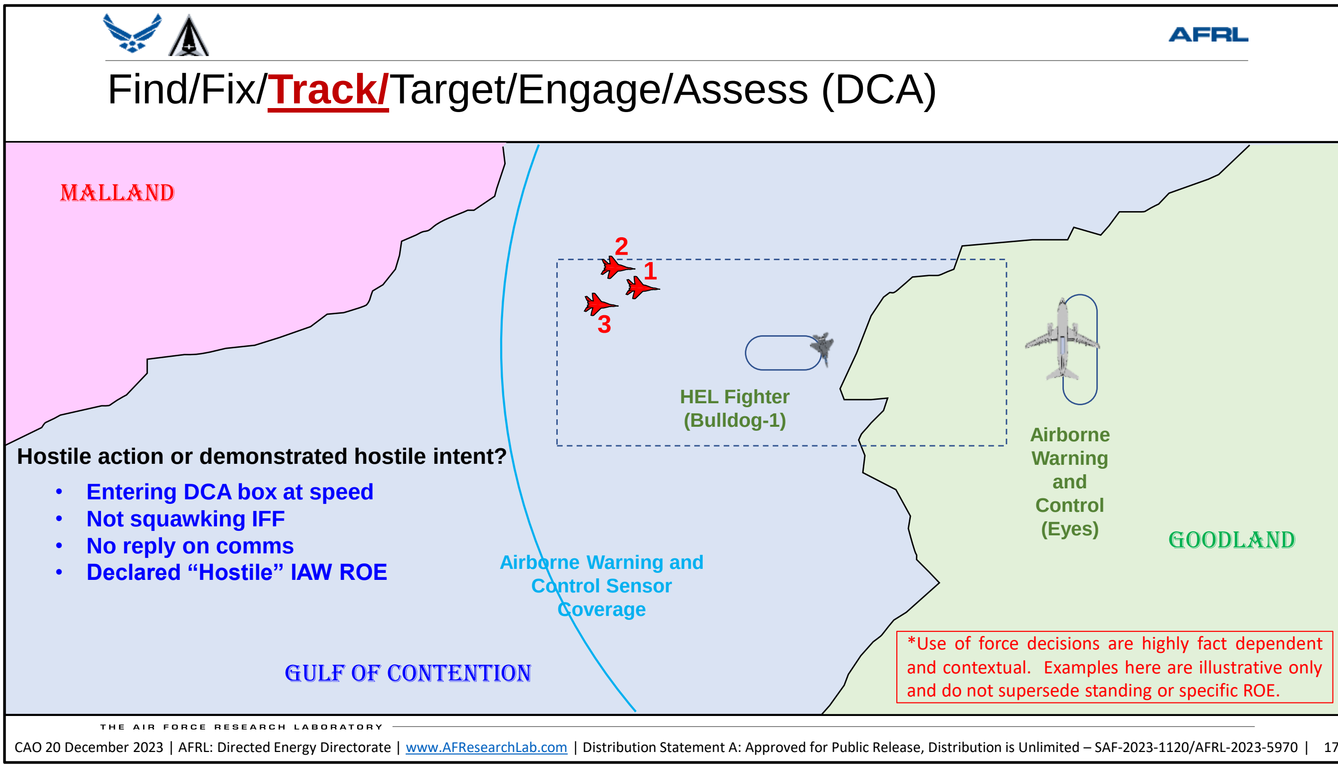
The good people of Goodland are under the threat of fighter attack by the malicious people of Malland, across the Gulf of Contention. The Goodlanders have set up a DCA lane with a single HEL-equipped fighter, Bulldog-1, currently in orbit in its lane. The job of Bulldog-1 is to engage enemy fighters in its DCA lane. The environment includes an airborne warning and control aircraft – Eyes – in a surveillance role which can provide radar detection and tracking capability that covers beyond Bulldog-1's sensors, as well as beyond the DCA lane. All live in peaceful coexistence, until some Malland fighters show up.



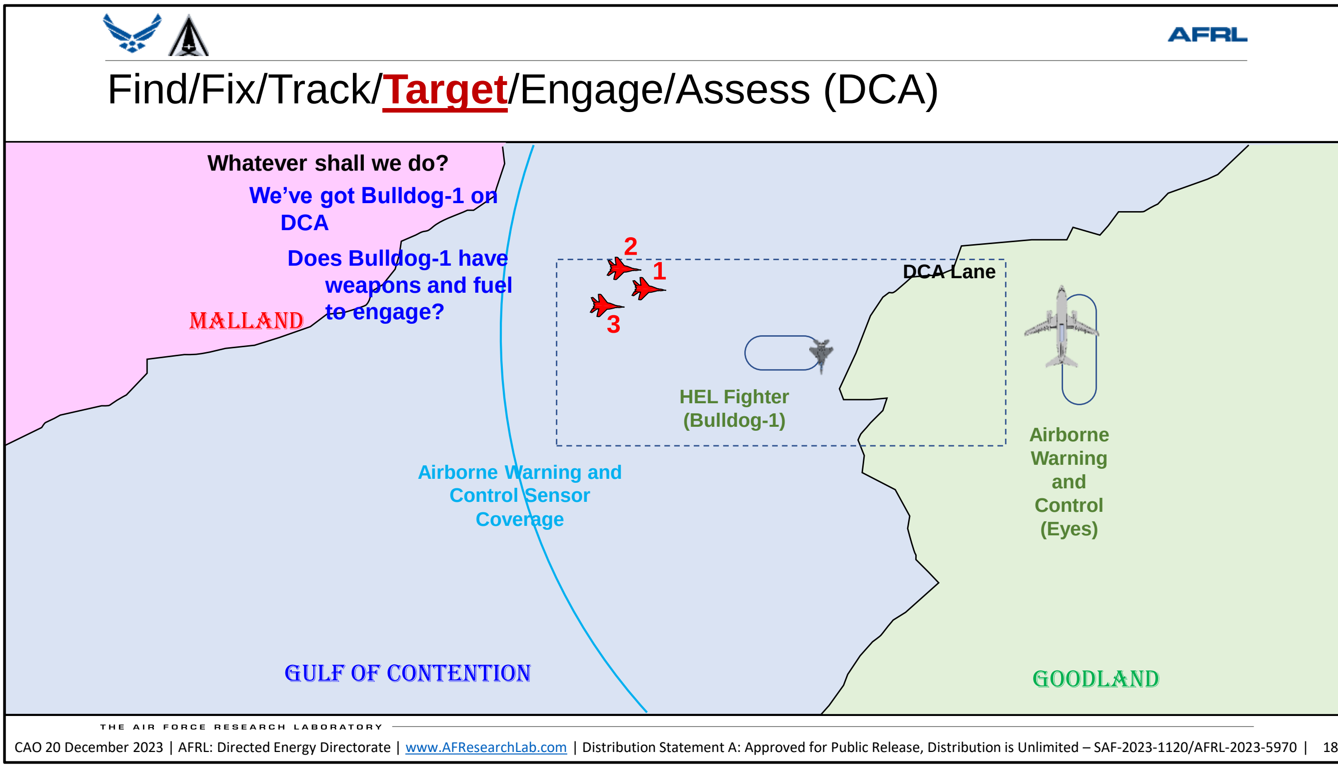
In the Find step, three entities enter the Eyes radar range and are detected. There is something out there!



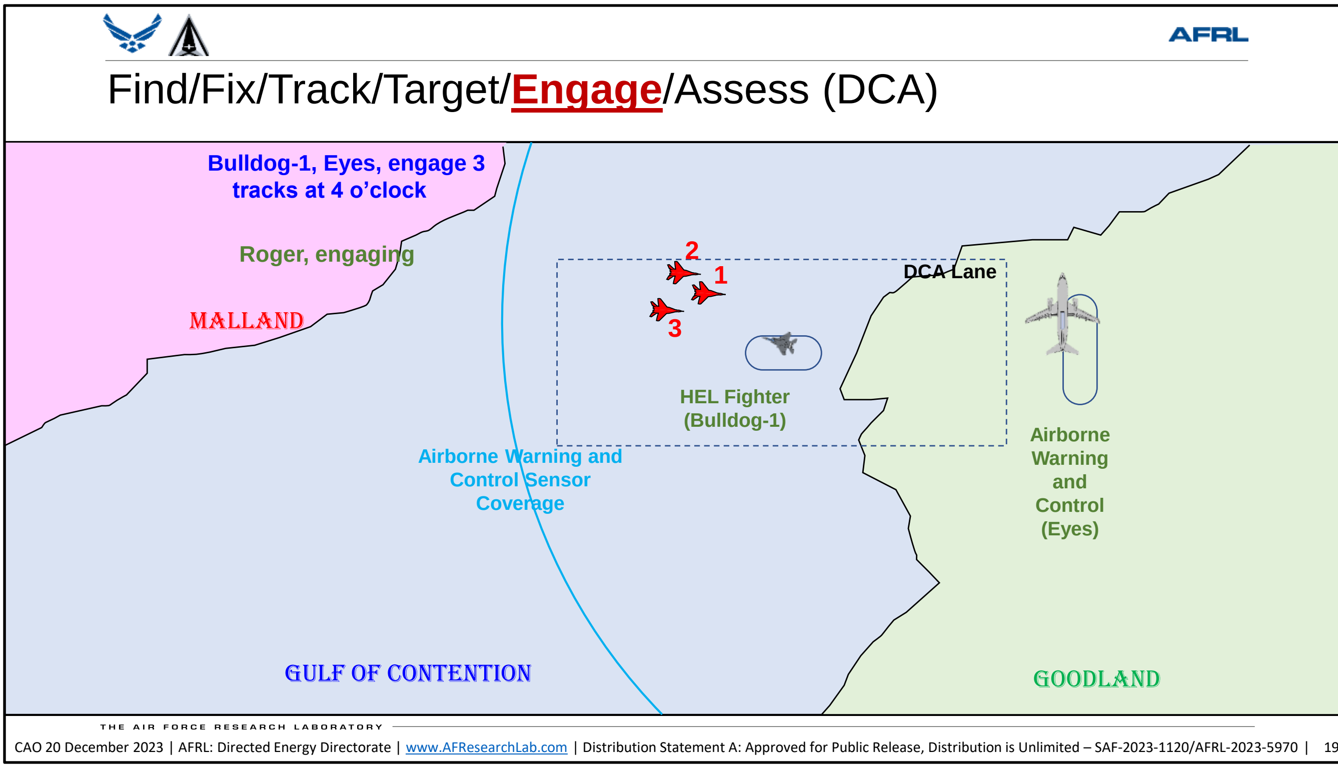
Now begins the process of figuring out what those entities are, and, more importantly, if they are threats to Goodland. Note, this is a process, bounded by the Rules of Engagement (ROE) that Goodland has in place. It is often a process of elimination to determine what the contact is not, before arriving at a decision of what it is (not friendly or neutral). Eyes determines that the entities are flying too high to be helicopters and too fast to be a private airplane or jet. They could be Malland fighters and warrant further checking.



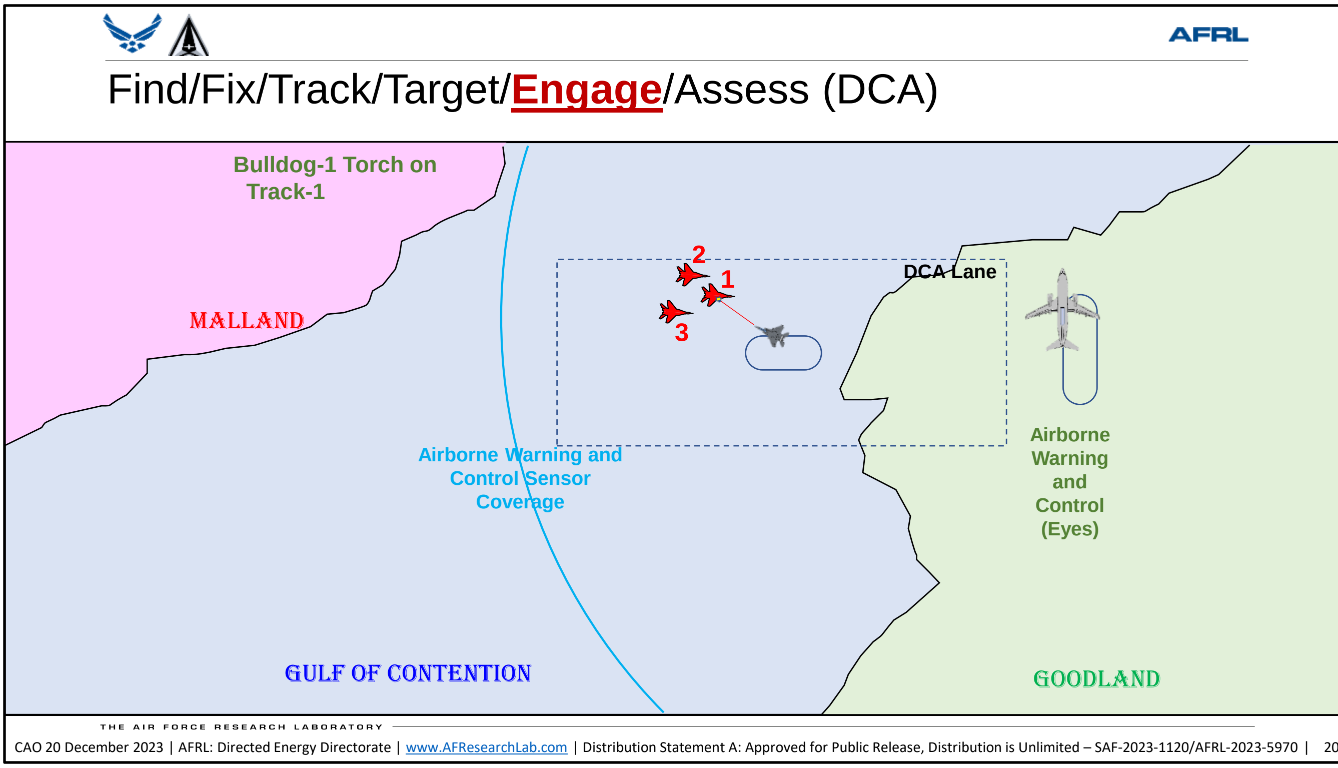
Once Eyes has several detections on the entities, it develops tracks for each entity. Eyes assigns a unique track number to each and continues to gather information to update the tracks as well as to complete the Fix role of determining whether the entities are hostile. At this state, the three entities are flying into a defended airspace. Eyes attempts an identify friend or foe (IFF) interrogation, which does not get any replies. Eyes attempts comms and does not get any reply. Based on the altitude and speed of the tracks, no flight plans, and no IFF, and no comms, the entities are determined to not be private planes or airliners. Add all of that up and the fact that they're heading toward Goodland from Malland at a high rate of speed, Eyes declares them "Hostile" tracks that may be targetable In Accordance With (IAW) the relevant Rules of Engagement (ROEs) and situational factual circumstances.



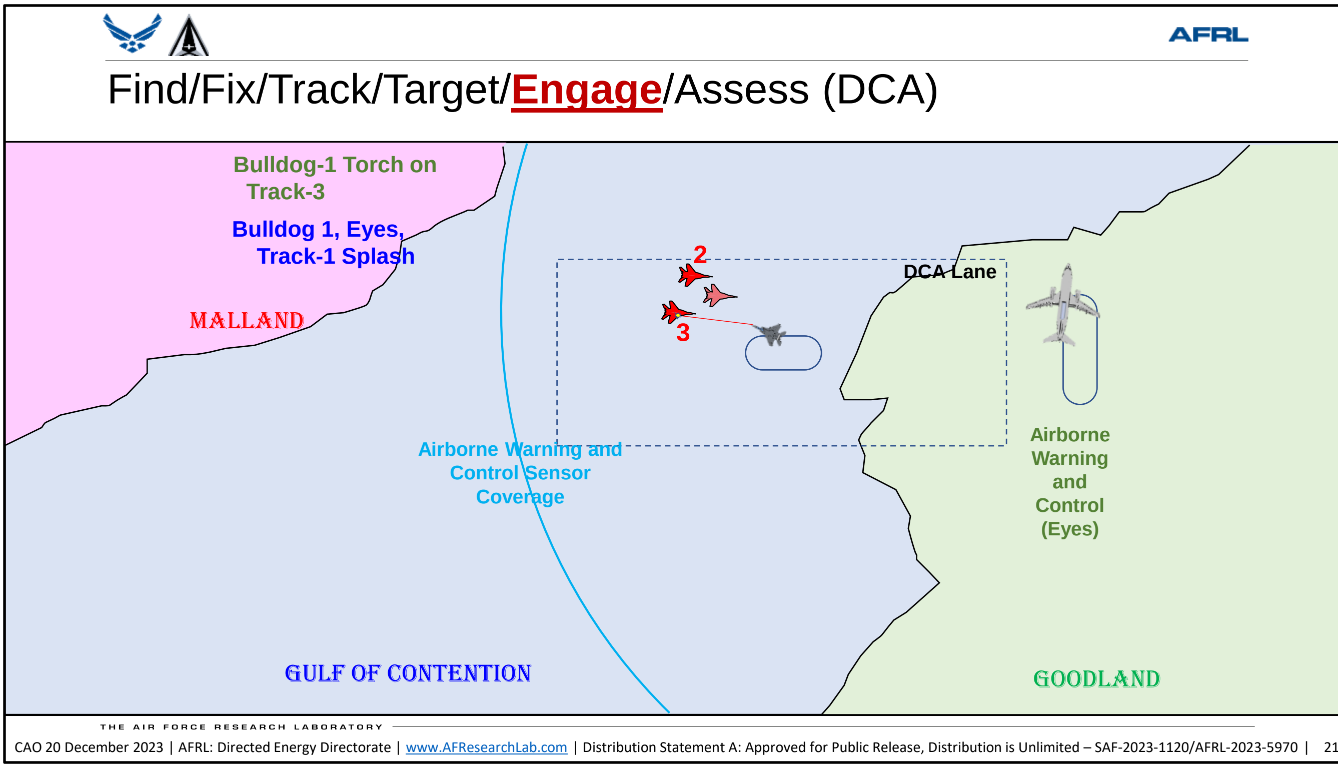
Eyes now determines which weapon to bring to bear against the tracks. There's only one choice in this example since there is only one HEL fighter, Bulldog-1. More fighting assets would create a more complicated scenario with more sophisticated weapon assignments.



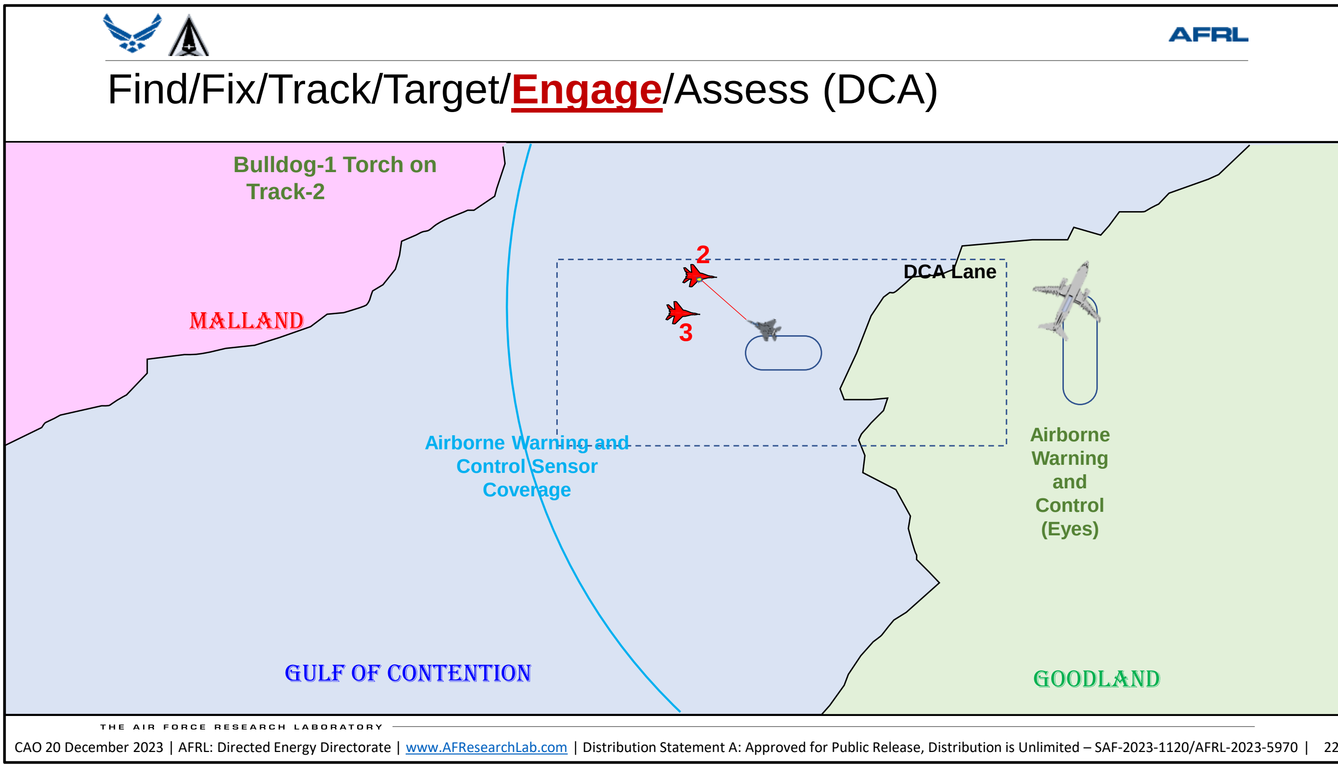
Because there are 3 threats and only 1 asset to engage them, the engagement phase for this scenario will have Bulldog-1 attempt to deal with all 3 threats. Engagement begins when Eyes passes the tracks to Bulldog-1. Bulldog-1 confirms acceptance of the assignment and moves off orbit to engage the Malland fighters. Bulldog-1's sensor are limited, so Eyes will continue to update Bulldog-1 on the greater situation. Bulldog-1 will engage the threat using the only weapon available, i.e., a HEL.



Bulldog-1 engages Track-1 with its HEL. The HEL engages the aimpoint on Track-1 until its logic tells it the aimpoint should have been destroyed as determined by the dwell time. If sufficient dwell has been achieved, the target is considered destroyed. This sufficient dwell time is known as lethal dwell time.

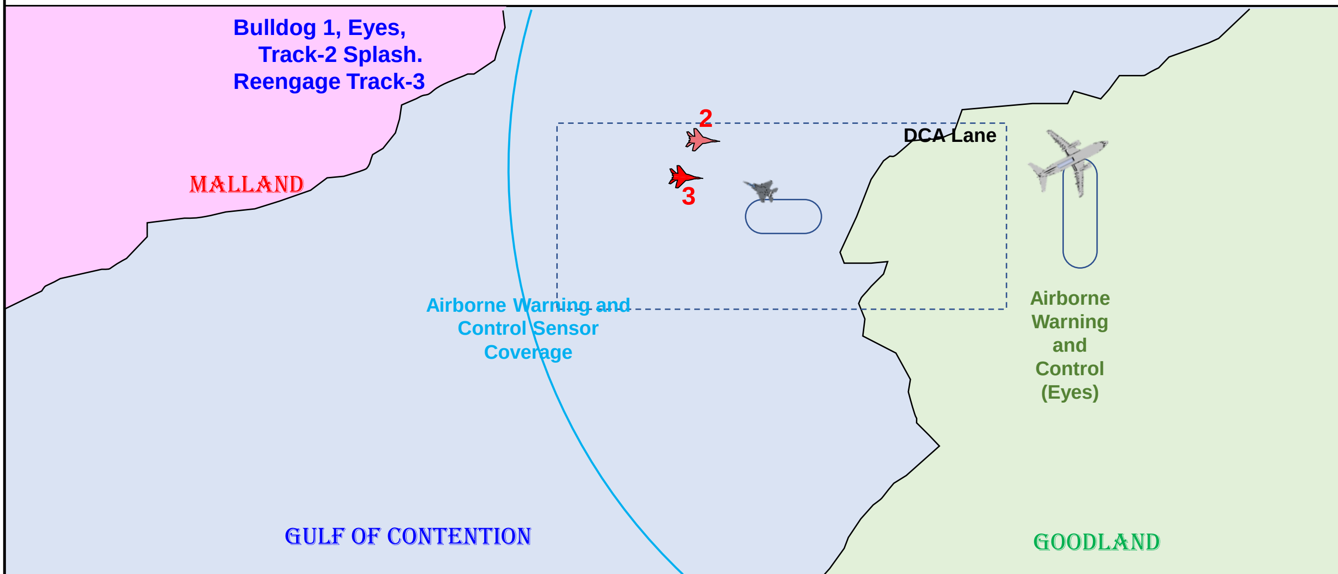


Bulldog-1 moves on to engage Track-3. Bulldog-1's HEL maintains dwell on Track-3 until the expected lethal dwell is achieved. The sensors for Bulldog1 and Eyes are both used to track and confirm effect.



Bulldog-1 moves on to engage Track-2. Note that neither Bulldog-1, nor Eyes get indications that Track-3 was defeated.

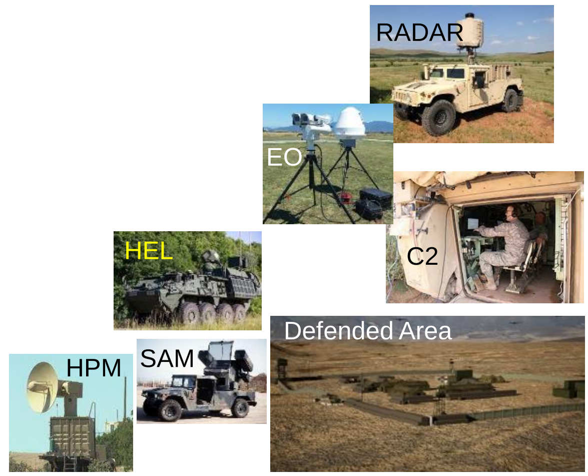
Find/Fix/Track/Target/Engage/Assess (DCA)



Between Bulldog-1's and Eyes' assessment of the situation, Tracks-1 and -2 were defeated; but Track-3 is still alive and well. As no further tracks are in sight, Eyes directs Bulldog-1 to reengage Track-3. At this point, the cycle picks up, again, at the Engage Step of the Kill Chain.

This concludes the description of an air-defense scenario.

Setting the Stage: Base Defense (BD) Scenario



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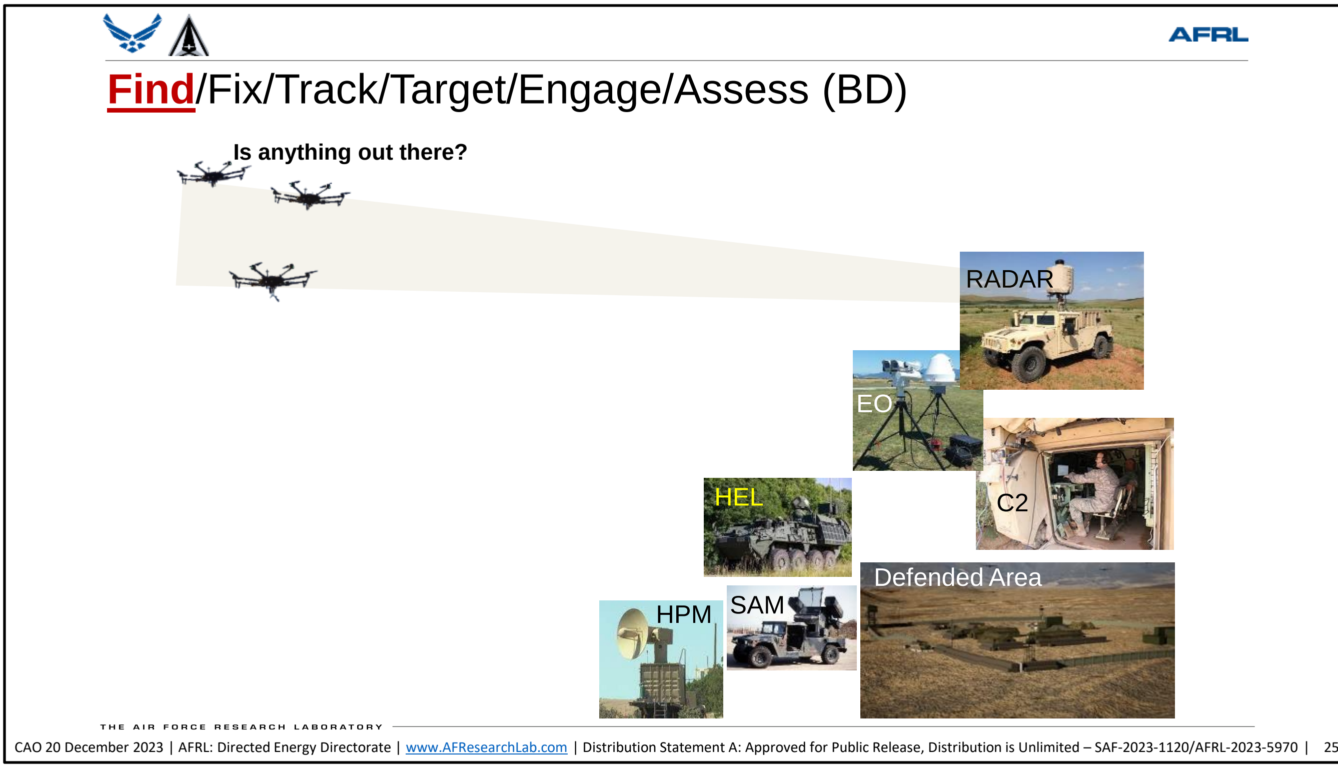
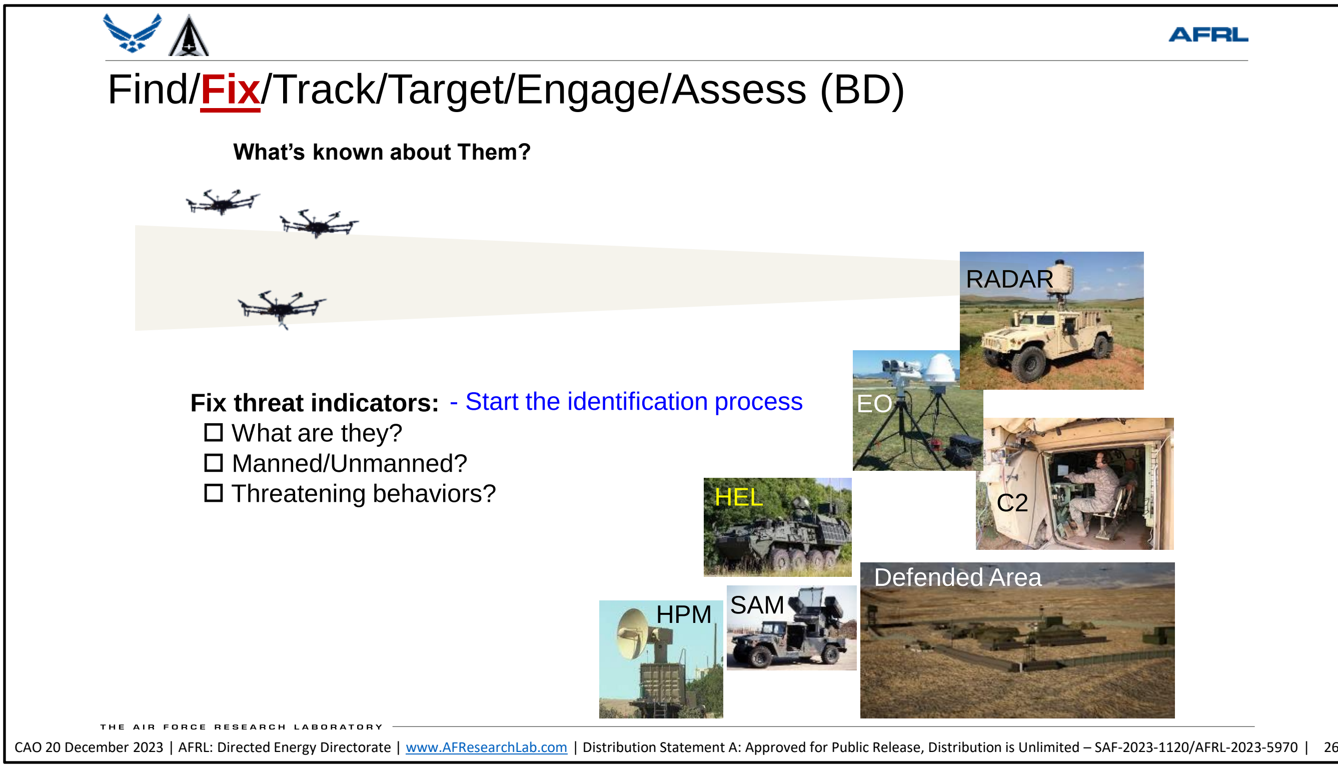
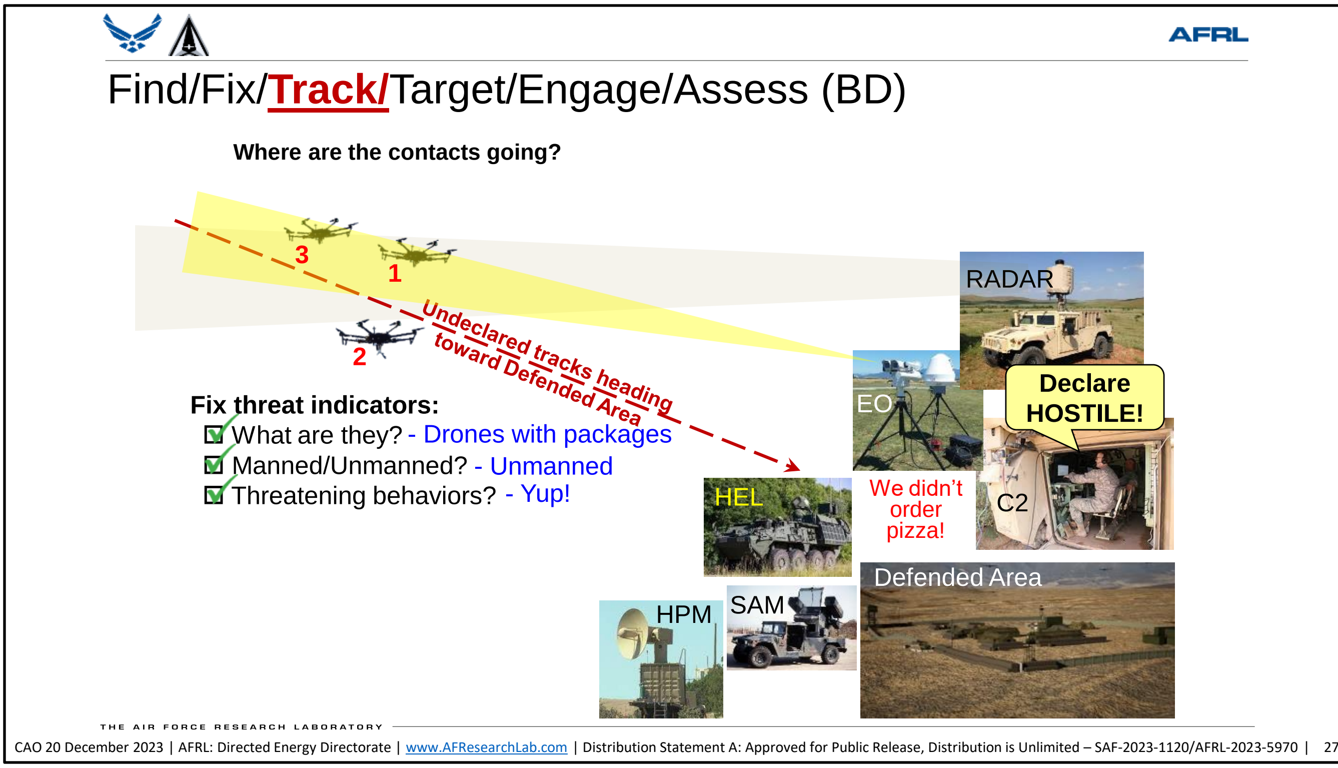
Welcome to the Base Defense (BD) scenario. The mission is to defend Camp Swampy from airborne attack which is under the control of a Command and Control (C2) element. Intel says the Barefoot Ones have been preparing a drone attack against Camp Swampy. Fortunately, Camp Swampy has some defenses, besides it formidable walls, gates and machine gun emplacements. Its sensors include a RADAR system capable of drone surveillance. It would provide the initial detection and track capability. They also have an Electro-optical (EO) system, that can receive radar tracks for more precise tracking and track identification. Its weapons include a Stinger (a surface-to-air missile system), a counter small-Unmanned Aerial System (C-sUAS) HEL weapon system, and a C-sUAS High Power Microwave (HPM) weapon system. The sensors and weapons are all under the authority of the C2 function of the Base Command Post. The C2 will make the decision of whether tracks are hostile – or threats – and make track assignments to the weapon systems for prosecution. At this base, the C2 controls the Radar and EO/IR sensors.



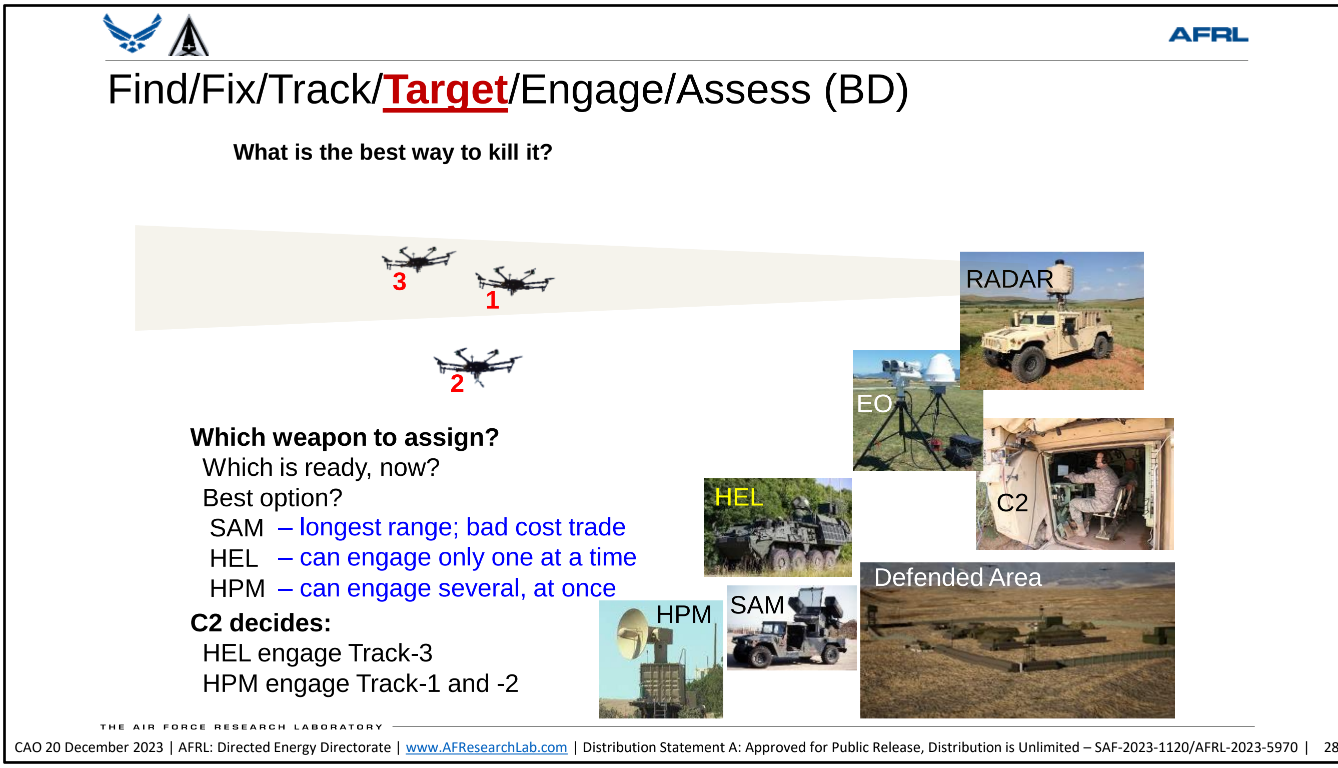
In the Find step, the radar, in its surveillance role, detects three entities. The detections are relayed to the C2.



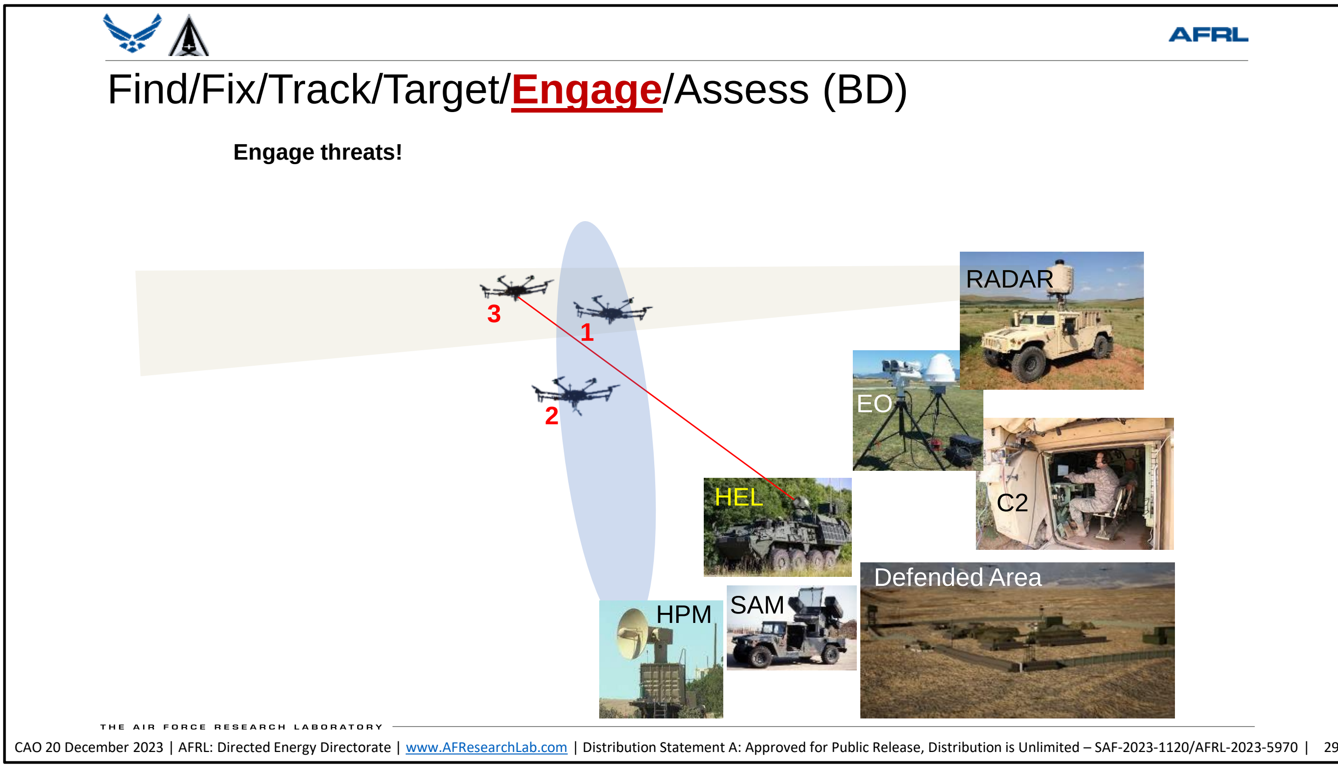
In the Fix step, C2 monitors the RADAR's progress toward forming tracks on the contacts. The C2 has the responsibility of determining what the entities are and if they are threats to the camp. Again, this is a process, bounded by the Rules of Engagement (ROE) put in place for the Defended Area's defense. This is often a process of elimination, to determine what the entity is not, before arriving at a decision of what it is (not friendly or neutral). For example, it's too low and slow to be an airplane, or not following a ballistic path – so not a mortar or artillery round.



As the RADAR continues detecting the entities, it automatically forms tracks, assigning unique track numbers to each and gathers any further identification information on each track, in the completion of the Fix step. It is determined that they are flying in, low and slow, toward our defended area. At this point, C2 directs the EO sensor from either the HEL or HPEM (or both) to use the track data from RADAR to get an image of the incoming tracks. The EO looks and determines they are drones carrying packages. The EO sensor's imagery is good enough to see the drones are unmanned. This matters because destroying an unmanned drone is a low regret outcome and carries much less consequences than destroying a manned aircraft and killing its crew. With the RADAR track showing the tracks are coming into a defended area, C2 declares the tracks as hostile.



In the Target step, C2 determines which weapon(s) to bring to bear against the tracks. In our example C2 has three choices. The first check is which are available, right now. All three are showing availability. C2 assesses each weapon for the task. The SAM typically has a longer range, but Stingers are not made to engage small drones, and using a $100,000 missile to take out an $800 drone is not a good cost tradeoff. The HEL can usually reach farther than the HPM but can only engage one track at a time. The HPM can engage multiple tracks at a time (if they are in the HPM's beam) but has the shortest range of the three weapons. C2 decides that HEL engage Track-3 because it's the furthest away. If the HEL is unsuccessful, it can reengage, or the HPM can jump in. HPM engage Track-1 and -2.

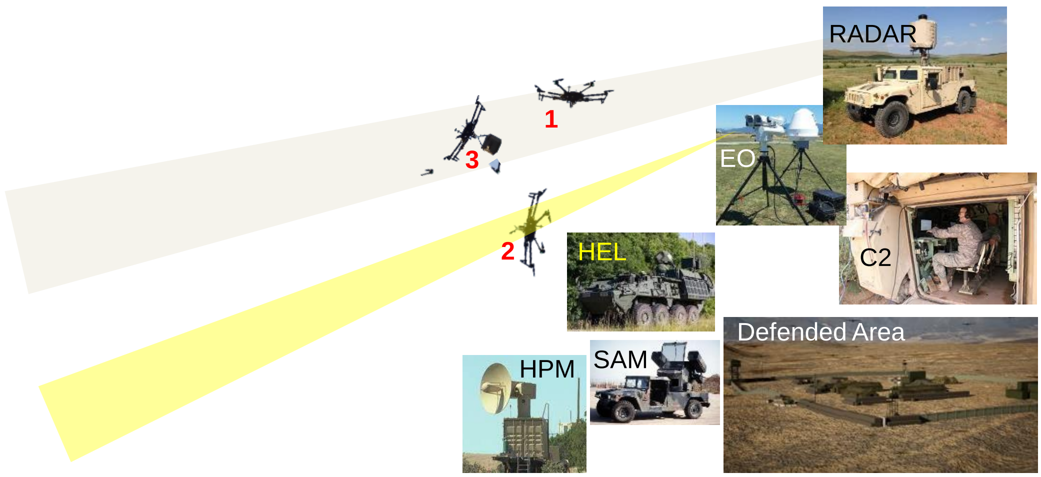


C2 assigns HEL to engage Track-1 by sending the track data thus clearing the HEL to engage. HEL engages.

C2 assigns HPM to engage Track-1 and -2 by sending their track data and clears the HPM to engage. HPM engages.

Find/Fix/Track/Target/Engage/**Assess** (BD)

Were they killed or should we reengage?



Based on the sensor inputs from RADAR, EO, HEL and/or HPM EO, and any engagement observations from the HEL and HPM operators, C2 assesses the outcome of the engagements.

Tracks 2 and 3 were defeated, Track 1 is still incoming.

As no further tracks are in sight, C2 can direct HEL, HPM, or both, to reengage Track-1.

At this point, the cycle picks up, again, at the Engage Step of the Kill Chain.

Military Utility (MU) – A KE/DE Example

- Military worth of a system (including versatility, or potential)
  - Performing its mission
  - In a competitive environment
- Measured against
  - Operational concept
  - Operational effectiveness
  - Safety
  - Security
  - Cost/worth

Mission: Protect Flight Line from Drone Attack

		Suitability Factors	
	Effectiveness	Safety	Cost/Shot
Net Gun	Within 50 ft	Debris	$50
Chain Gun	Within 2000 ft	debris (round impact zone)	$$$
HPEM	Some distance	No debris, electronic hazard	¢¢
HEL	Farther	No debris, ocular hazard	¢¢

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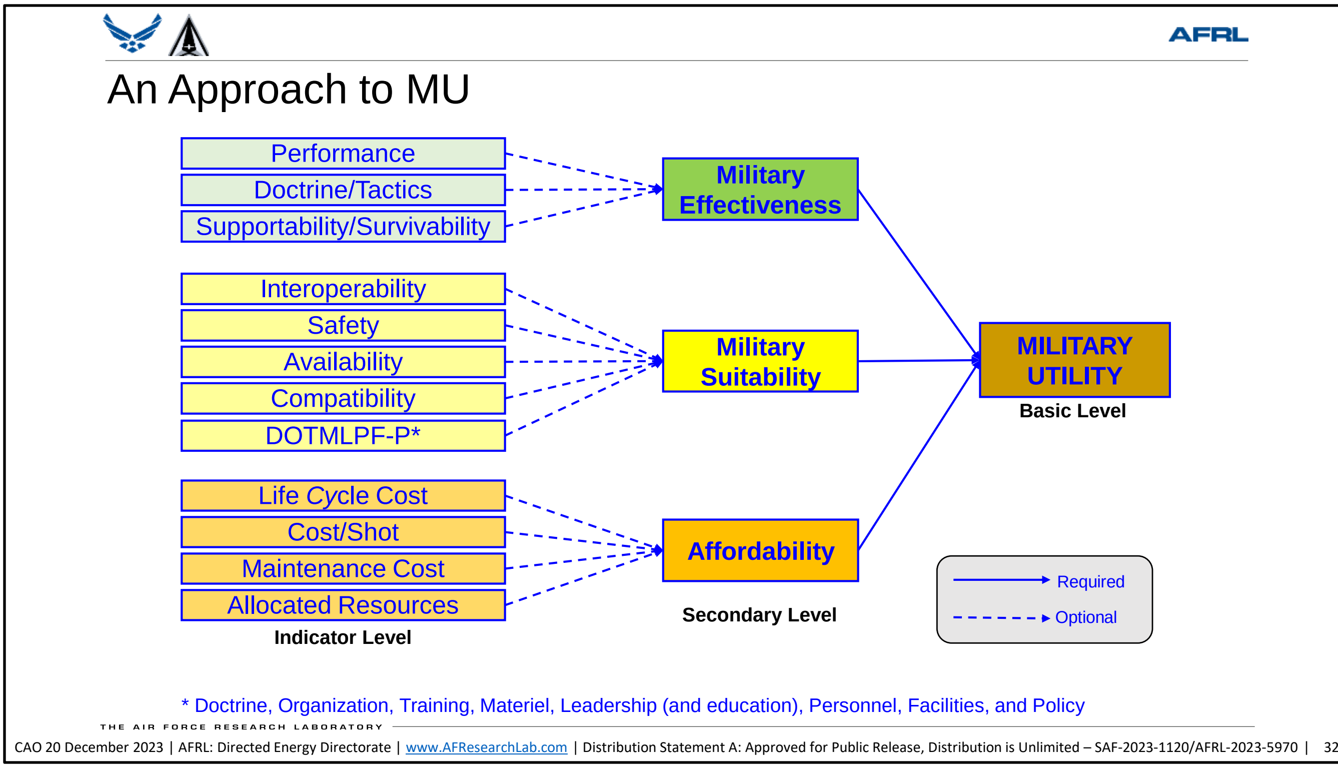
Military utility is a complex topic with varying opinions. This course attempts to glean information from several sources to present the basic concepts. According to Air Force Instruction 99-103, Capabilities-Based Test and Evaluation, Military Utility is “the military worth of a system performing its mission in a competitive environment including versatility (or potential) of the system. It is measured against the operational concept, operational effectiveness, safety, security, and cost/worth. Military utility estimates form a rational basis for making management decisions.”

An example of a military utility assessment of counter-drone systems might use lethal range as the measure of effectiveness, and suitability factors of safety and cost per shot. Net guns have a very short range, requiring the operator to be in the path of the incoming drone, they leave debris for each missed shot, and cost about $50/per round. Chain guns have a longer range but the $100+ rounds may hit the ground and leave unexploded ordnance. HPEM systems leave no debris and can disrupt electronics (friend, foe, or civilians). HEL systems have a longer range than HPEM systems, leave no debris but require eye protection. The best military solution for counter drone mission depends on the specifics of the mission, what kinds, numbers, and spreads of attacks are expected.



AFRL/RDMW is attempting to develop an approach to assessing military utility. This method includes breaking tasks down into components and assigning them to general categories of Military Effectiveness, Military Suitability, and Affordability. Military effectiveness focuses on the performance of the weapon and how it fits within the battlefield doctrine. Military suitability evaluates the practicality of the weapon for the battle. Affordability assesses the value of the weapon based not only on cost, but also life cycle and maintenance. *Andersson et al.

Resources

- *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition*, Robert E. Ball, American Institute of Aeronautics and Astronautics, Inc., 2003
- *Introduction to Laser Weapon Systems*, Glen p. Perram, Salvatore J. Cusumano, Robert L. Hengehold, and Steven T. Fiorino, Directed Energy Professional Society, 2010
- *Air Force Doctrine Publication 3-60: Joint Targeting*, Joint Force Development, 28 September 2018
- *Military Utility: A Proposed Concept To Support Decision-Making,* Kent Erik Andersson, Martin Bang, Carina Marcus, Bjorn Persson, November 2015
- www.deps.org: Directed Energy Professional Society (DEPS) short courses

Here are some resources useful for further study of DE.

Next Training Course

- ☑ Directed Energy Weapon: Introduction (DEW: Intro)
- ☐ Directed Energy Weapon: High Energy Laser (DEW: HEL)
- ☐ Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM)

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Once the Directed Energy Weapon – Introduction Course has been completed, AFRL/RDMW's Directed Energy Weapons: High Energy Laser (DEW: HEL) and Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM) courses are recommended.

Acronyms

Acronym	Definition
AFRL	Air Force Research Laboratory
BD	Base Defense
C2	Command and Control
C-sUAS	Counter Small-Unmanned Aerial System
DCA	Defensive Counter-Air
DE	Directed Energy
DEW	Directed Energy Weapon
EO/IR	Electro-Optical/Infrared
EW	Electronic Warfare
F2T2EA	Find, Fix, Track, Target, Engage, Assess
HEL	High Energy Laser
HPEM	High Power ElectroMagnetic
HPM	High Power Microwave

Acronym	Definition
IFF	Identification Friend-or-Foe
KE	Kinetic Energy
KEW	Kinetic Energy Weapon
LOS	Line-of-Sight
LWIR	Long-Wave Infrared
MU	Military Utility
MWIR	Mid-Wave Infrared
NIR	Near Infrared
ROE	Rules of Engagement
SAM	Surface-to-Air Missile
SWIR	Short-Wave Infrared
UAV	Unmanned Aerial Vehicle
W	Watt

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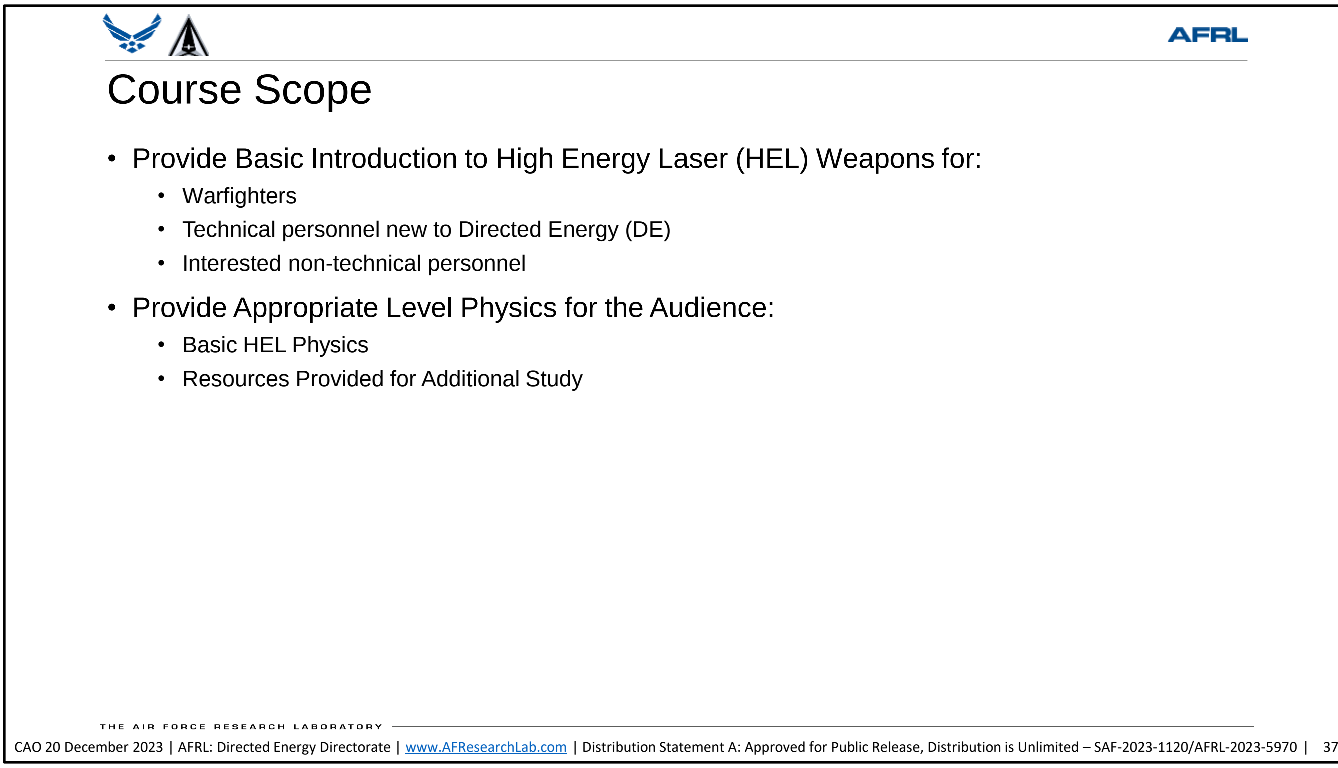
We recommend that you read this presentation in Note Page View for optimal formatting.

Welcome to AFRL/RDMW's Directed Energy Weapon: High Energy Laser training course. This is a publicly-releasable presentation developed to familiarize people with HEL weapons.



The science of HELs is a very technical area of knowledge where one can spend an entire career developing specialized expertise in just a few HEL phenomena.

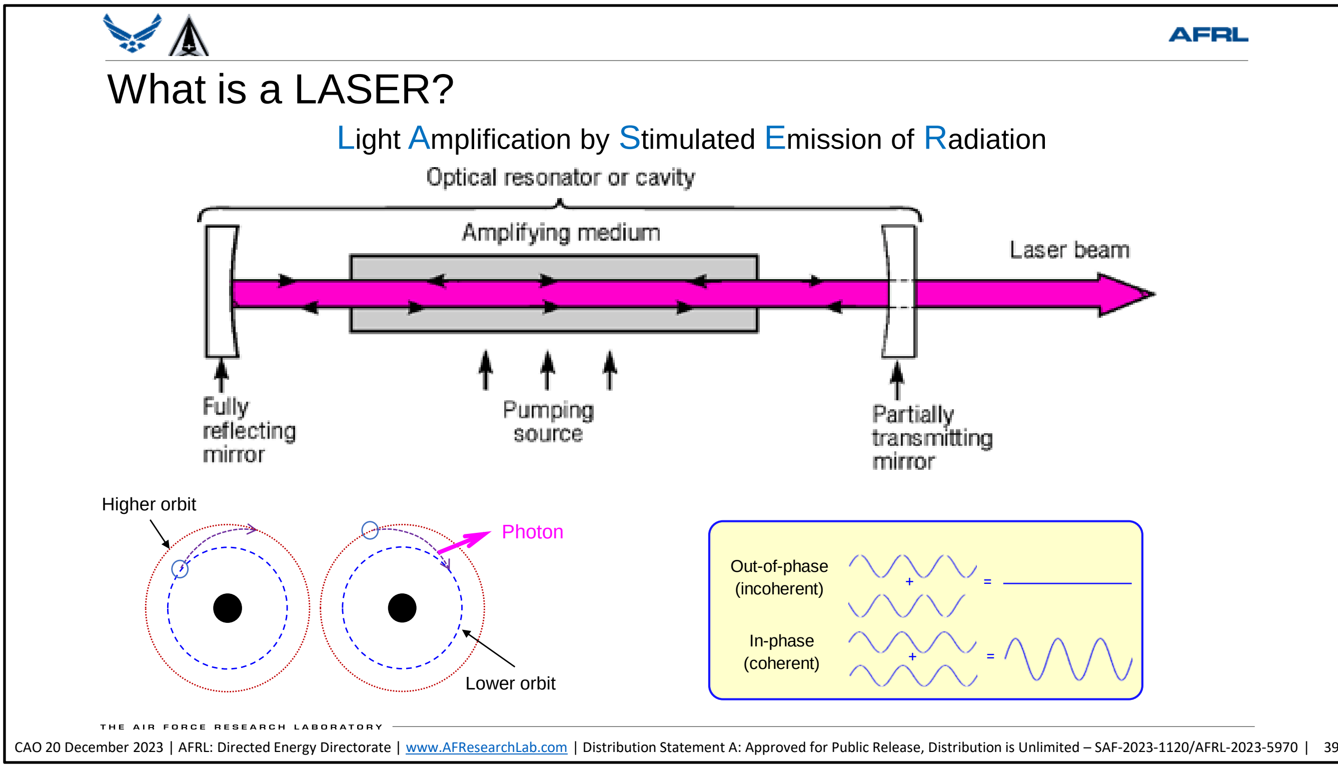
The scope of this course is a basic introduction to Directed Energy Weapons (DEW) and associated technologies. The focus is on high energy laser weapons as applied to the battlefield.

If you wish to further advance your understanding of the complex topics presented, we provide some suggested resources for additional study.

Introduction to HEL Weapon Systems

- What is a LASER?
- History of HEL Weapons
- Components of LWS
- Laser Weapon System (LWS) Effects on Targets
- Military Utility of LWS
- Modeling and Simulation

In this training course, some laser physics concepts are introduced first. A quick overview of the history of HEL weapons and a glimpse of some systems currently in development and fielded will be given. A ground-based laser system has been chosen to further explain some important components of a laser weapon system (LWS) as well as the various ways lasers can affect targets. A brief discussion has been provided of a LWS and its unique contributions to military utility in a battlespace. The final topic explains the Modeling and Simulation (M&S) efforts for HELs.

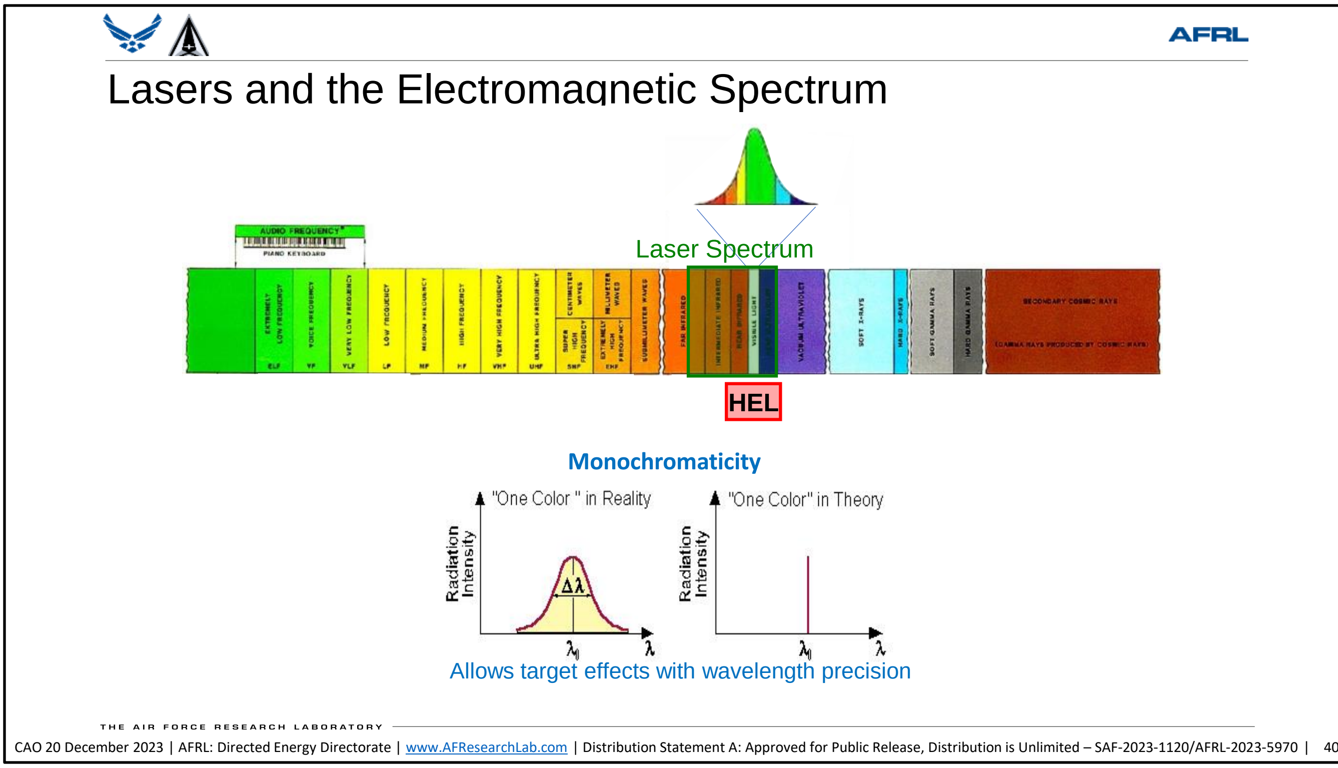


Laser is an abbreviation for "Light Amplification by Stimulated Emission of Radiation." Operation of a laser can be explained by describing, in simple terms, how electromagnetic radiation, specifically light energy, can be stimulated and how that light can be amplified to produce different levels of laser power. Shown here is a simple representation of a laser resonator cavity consisting of two mirrors, the amplification medium and a pumping source.

Light particles are called photons and produce light energy. Photons are generated by stimulating or exciting electrons that surround an atom into a higher orbit and then allowing them to return to a lower orbit. This action of moving from higher to lower orbit produces streams of photons. The energy that provides the stimulation can be electrical or chemical.

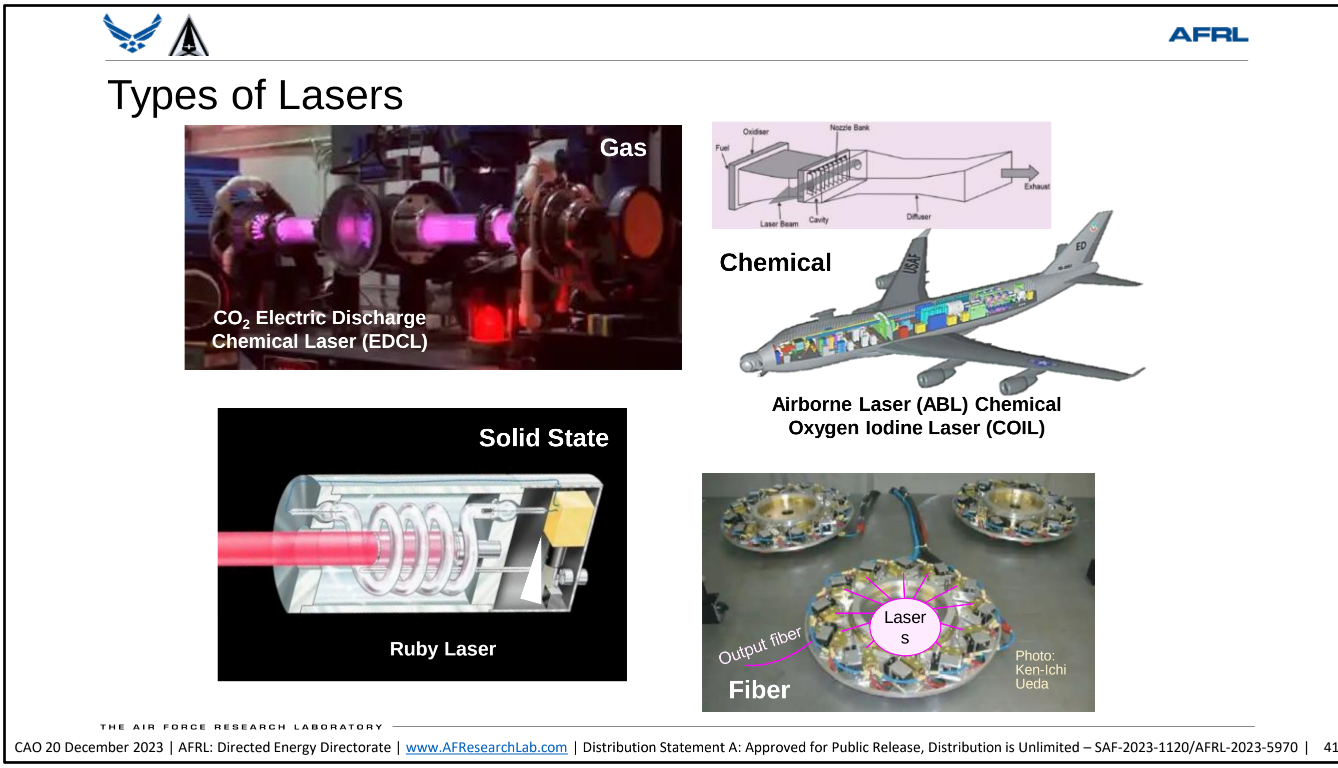
In the simple diagram in the center, the photons being pumped bounce between two mirrors within an amplifying medium. This amplifying medium can be a gas, a chemical reaction or a solid. Solid amplifying medium are generally rods or fiber-optic filaments made of various rare-earth elements, like those used in laser pointers.

One of the two mirrors in the simplified laser diagram fully reflects the light while the other allows partial transmission of the light. Eventually, due to this pumping and reflecting process, the photons will reach the same resonating frequency and be in phase. Being in phase means that the peaks and valleys of the light waves coincide with one another. When this happens, coherent light is created with a higher magnitude than the individual waves. What comes out of the resonating cavity is concentrated light energy, in the form of a coherent laser beam.

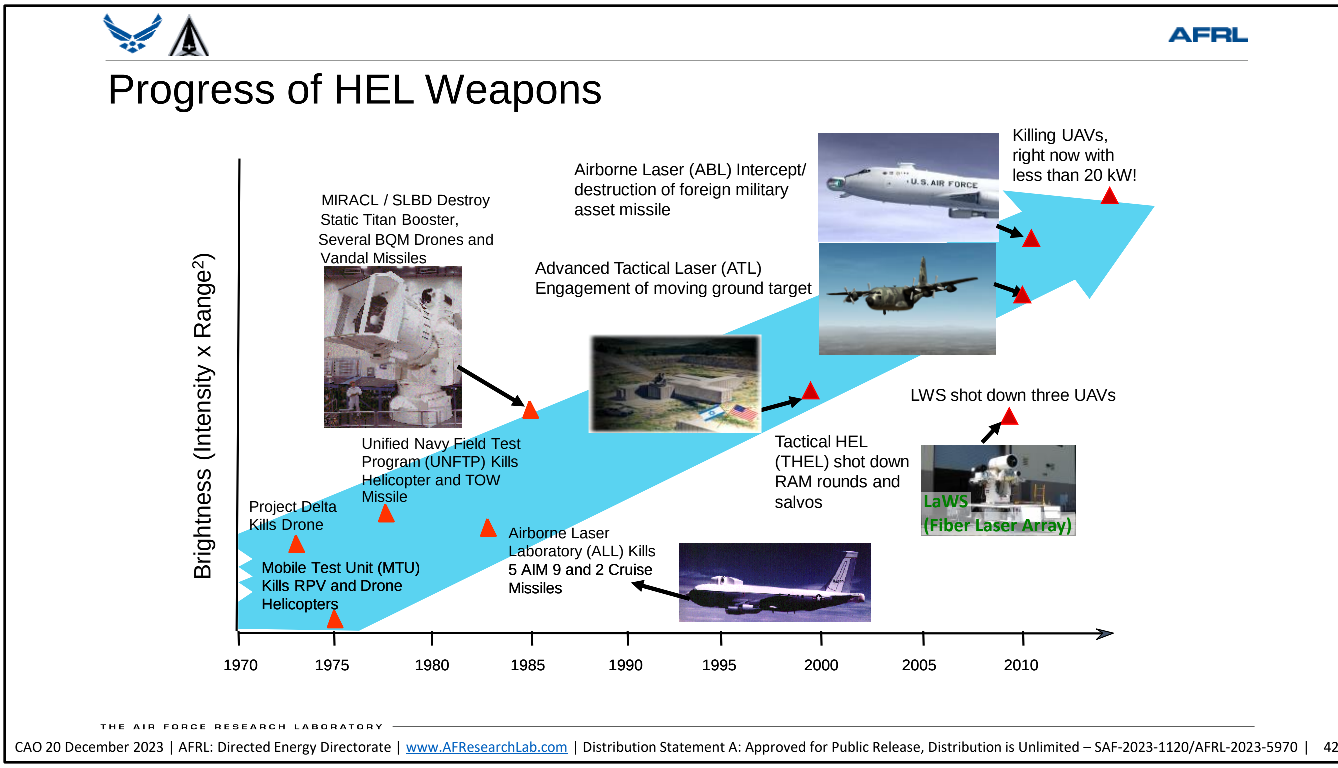


Coherent light is in phase, implying that it is monochromatic which means it functions at a particular wavelength in the electromagnetic spectrum. Recall from Directed Energy Weapon: Introduction, the waveband for lasers includes the visible and infrared bands. A laser is described by its single wavelength, but realistically, the laser wavelength is normally distributed around a particular wavelength and spread over a small range. The wavelength of a laser is important because it allows us to precisely achieve a target effect. Target effects will be discussed in more details later in this training.

Because a laser's energy is light energy, it can travel long distance at the speed of light in a specific direction. This directionality allows the energy to precisely reach a target that can be quite far away. Both monochromaticity and directionality are important features that make lasers useful as a weapon system.



Types of high energy lasers are typically identified by their amplifying mediums and/or pumps. There are four major categories: Gas, Chemical, Solid State, and Fiber Optics. This topic won't be discussed too much except to state that currently the most recent efforts are focused on solid state and related fiber optic technologies. In addition to different mediums and pump sources, various lasers also generate different power levels with varying qualities in the laser beam. Each laser type has its own technology challenges as well. These challenges include thermal management, power vs weight, and range for effect. We will not dive into the details of designing laser systems, but instead will show some progression in laser development and their application to the battlefield. There will also be explanation of some common terms used in laser weapon systems.



HEL has had some impressive history through the years. HEL has been used to engage drones with lasers as far back as the 1970s. In the early 1980's, the Airborne Laser Lab downed airborne AIM-9 air-to-air missiles and cruise missiles while in flight. In subsequent slides, more current laser weapon systems such as the Tactical High Energy Laser (THEL), and the Airborne Laser (ABL) will be shown.

Impressive feats with higher-power HELS as well as laser weapon systems and drones with power levels of less than 20kW have been demonstrated. The current technology direction is seeking laser systems with higher power along with lower weight or volume. Systems that readily integrate into existing platforms are also areas of research and design.

Tactical High Energy Laser (THEL)

- Shot down 28 Katyusha rockets, 5 artillery shells (2000 and 2001)
- Shot down an incoming artillery round (2002)
- Mobile version shot down multiple mortar rounds (single and salvo, 2004)

The Tactical High Energy Laser (THEL) was considered, but not selected, as a component of Israel's "Iron Dome" defense system. In the early 2000's, this mobile system destroyed 28 Katyusha rockets, 5 artillery rounds, and mortar rounds, including multiple mortar rounds, simultaneously airborne, from different locations.

Airborne Laser (ABL)

- July 2002 – Flight testing begins
- Nov 2004 – Chemical Oxygen Iodine Laser (COIL) successfully fired (ground test)
- Sep 2008 – First Light (first firing of COIL)
- Jan 2010 – High-energy COIL used to intercept an instrumented missile
- Feb 2010 – First destruction of a test rocket
- Feb 2010 – Lethal Demo – first intercept and destruction of threat-representative ballistic missile

The Airborne Laser (ABL) employed a Megawatt (MW) class Chemical Oxygen Iodine Laser (COIL). It was an example of a HEL fully integrated into the Boeing 747 airframe. This MW-Class HEL began flight tests in 2002, first fired, in flight in 2008, and engaged three ballistic targets in 2010, culminating in the destruction of a foreign military asset missile.

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Airborne HEL Platforms and Missions

Airborne Laser (ABL)
Platform: Boeing 747
Mission: Counter-Ballistic Missile

Self-Protect HEL Demonstrator (SHiELD)
Platform: F-15E
Mission: Aircraft Self-Protect

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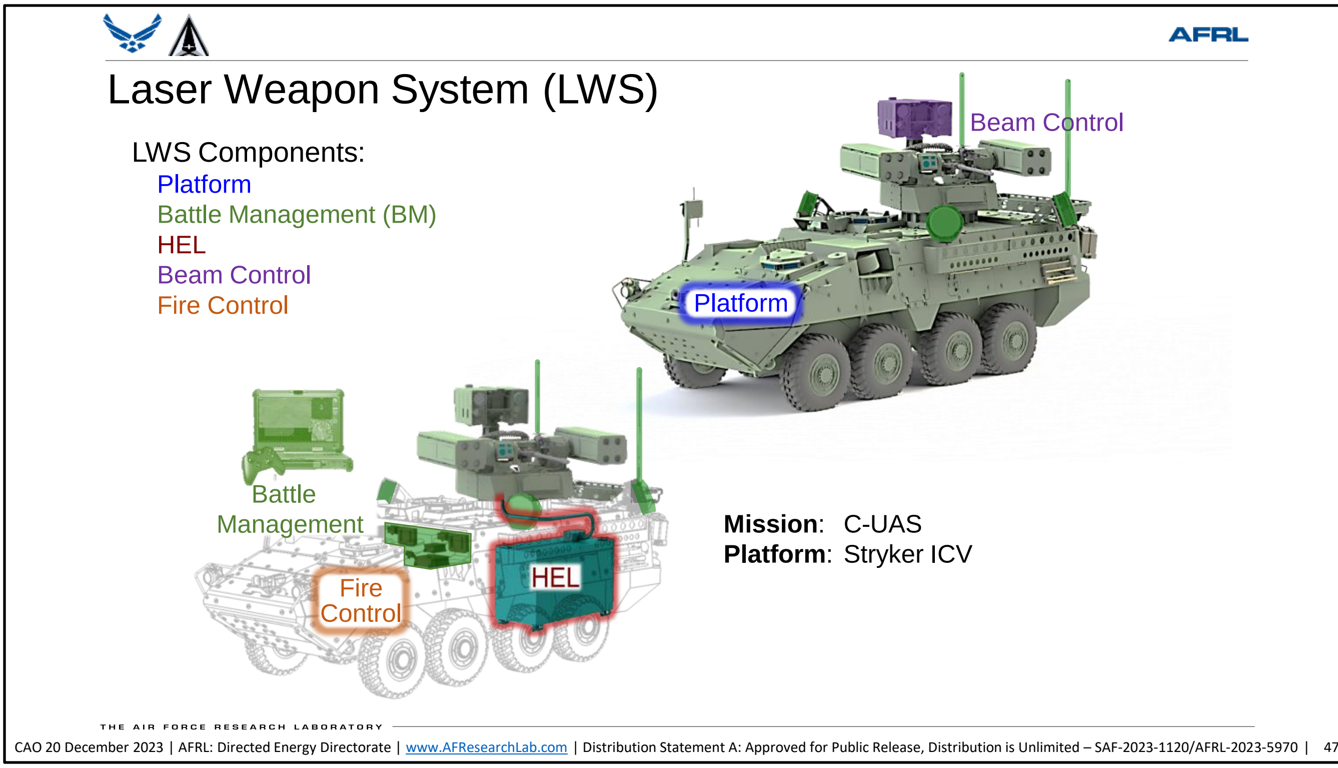
Depending on mission needs, HELs can be placed on different platforms to perform different roles. The ABL was an example of a Megawatt-Class laser engineered for integration inside a Boeing 747. The ABL's mission was to defeat ballistic missiles in flight.

Recent HEL technologies are no longer focused on integrating lasers into existing aircraft, but as attachments to the aircraft exterior. HELs are being designed to be mounted on external pod systems as opposed to being fully integrated within an aircraft design. An example of a pod-mounted system is the Self-Protect High Energy Laser Demonstrator (SHiELD) program. SHiELD is a demonstrator for the use of a HEL as an aircraft self-protection weapon.

Countering Unmanned Aircraft Systems (UAS) is also an important mission. There has been an explosion of kW class systems under development to defeat attacks from single or swarms of UAS. The Navy's Laser Weapon System (LWS) is an example of a counter UAS (c-UAS) HEL system that is surface-based. LWS was installed on the USS Ponce, an amphibious transport dock. In addition to counter-UAS capabilities, the Navy found that the LWS optics allows excellent contact identification capability.

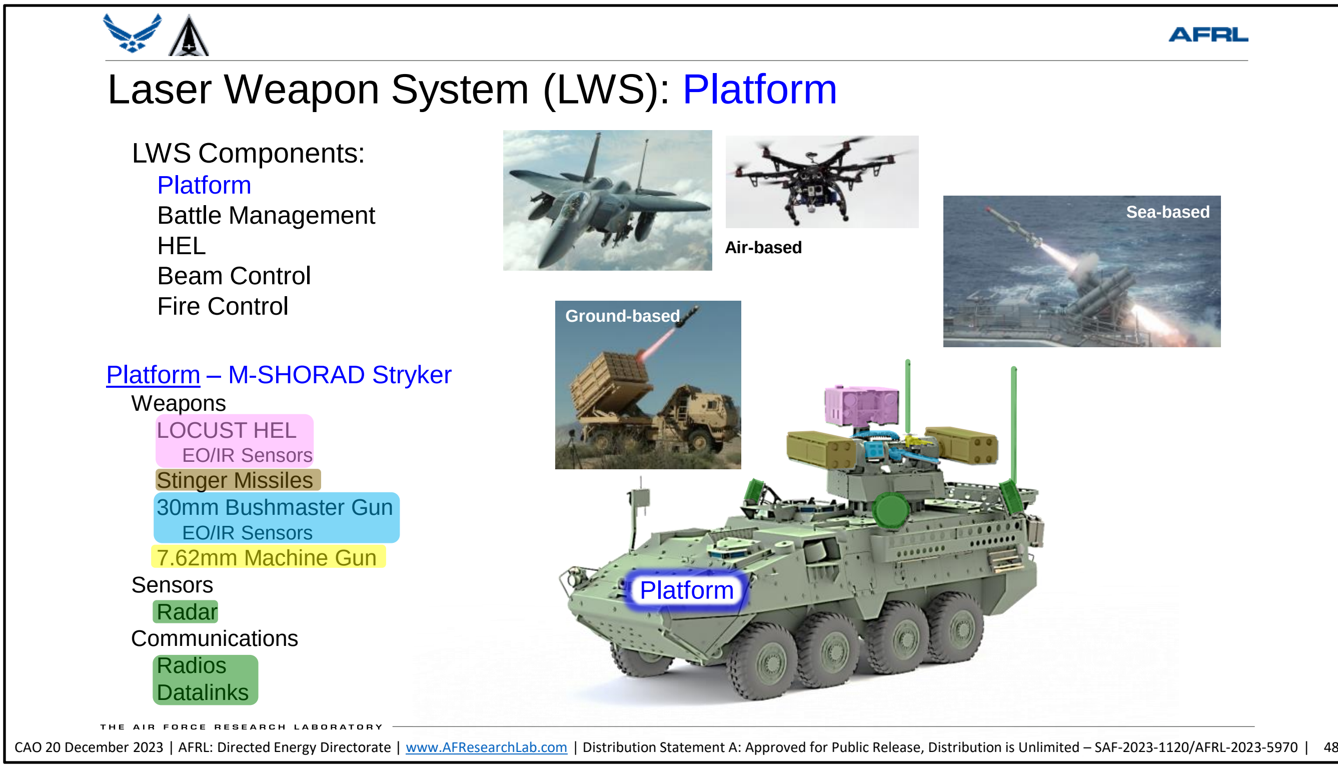
The HEL Weapon System, or HELWS, is another example of a c-UAS HEL. HELWS was installed on a Polaris all-terrain vehicle. As shown, there are a wide range of platforms being engineered for c-UAS mission from the bed of a pickup or trailer to larger military transports and armored vehicles to naval ships.



When a laser is placed on a platform to perform a military mission, it becomes a Laser Weapon System (LWS). To be effective for this purpose, the system needs to encompass more functions than simply generating photons.

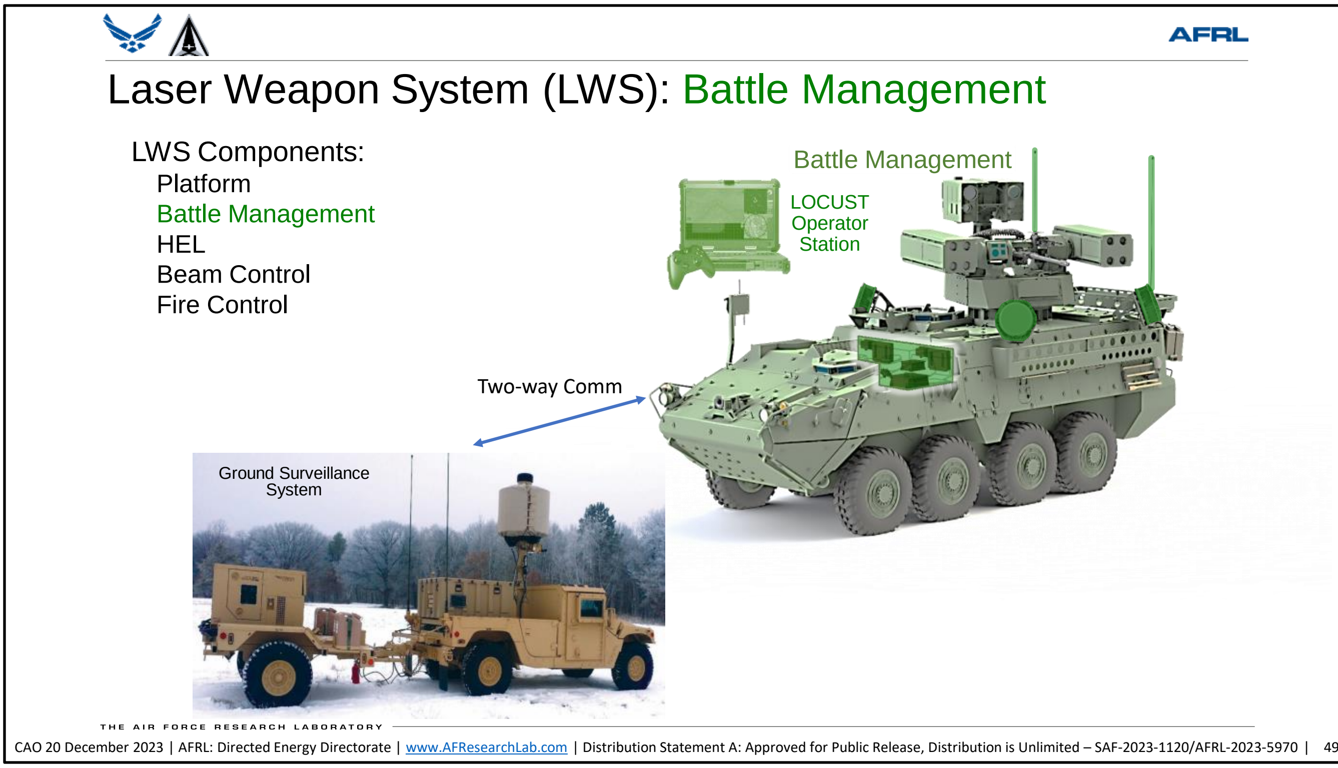
We present some important functions of the LWS by looking at the Army's Maneuver Short-Range Air Defense (M-SHORAD) program to investigate the Low-Cost Counter-Unmanned Aerial System for Targeting (LOCUST) implementation on the Stryker Infantry Carrier Vehicle. This setup offers many functions for multi-mission. The M-SHORAD has several weapon systems and sensors that are integrated on a Stryker. LOCUST is also a good example of an integrated laser system. The combinations in this LWS can be tied into the larger Command and Control (C2) net to receive external track information as well as to share their internal sensor data. Increased fidelity and robustness can be achieved to provide a more complete depiction of the battlespace.

There are several possible missions of interest for the HEL, but the mission shown in this example is protecting maneuvering Brigade Combat Teams from unmanned aerial systems (UAS) attack, i.e., C-UAS defense. The next slides will look more closely at the five components of LWS – platform, battle manager, HEL, beam control, and fire control.



The LWS is mounted on a platform that allows the laser weapon to be moved and/or pointed to its desired and most effective position. Ground platforms can be fixed or mobile. Airborne platforms can be manned or unmanned. There are also sea-based platforms.

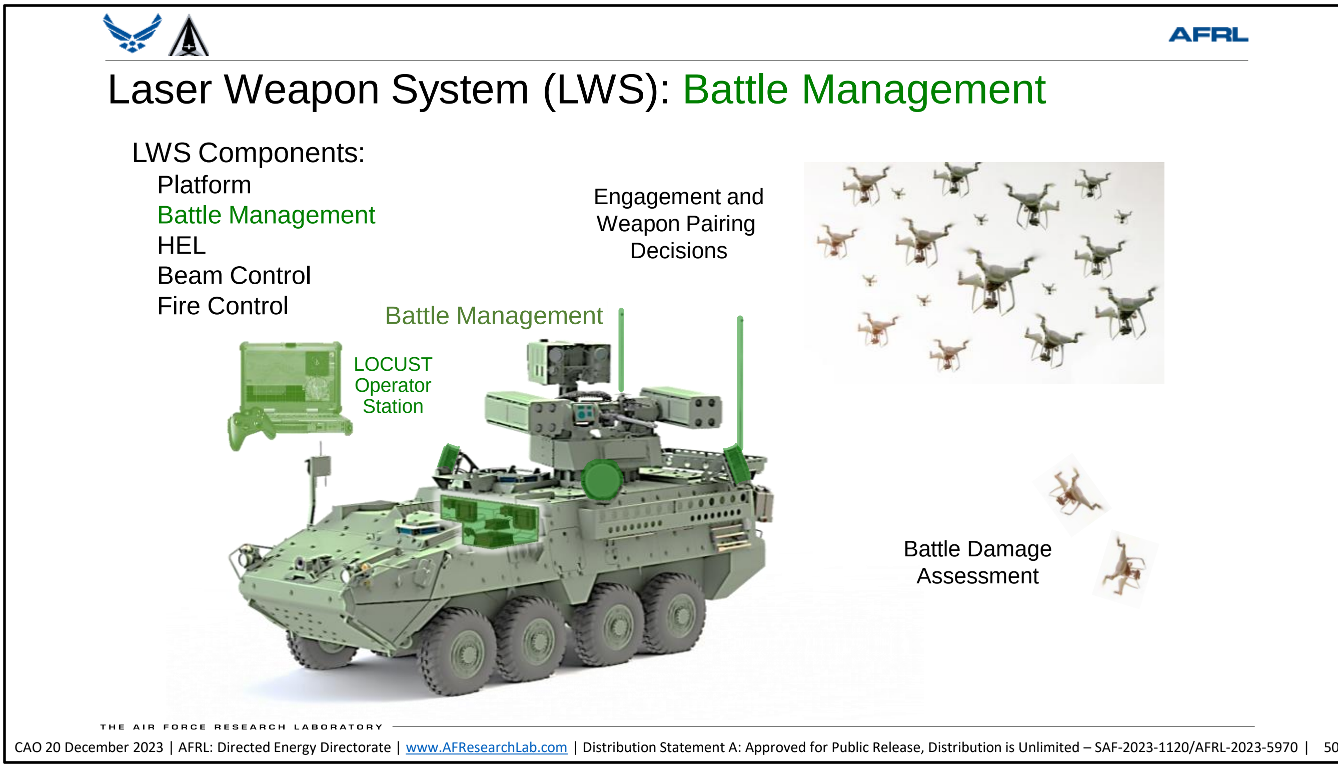
For this example, the platform is the ground-based Stryker armored vehicle whose mobility allows for added flexibility and effectiveness in ground-to-air engagements. This platform also provides electrical power, cooling systems and protective armor. The M-SHORAD system contains four separate weapon systems along with its own sensors and communication systems.



BM provides the C2 that handles the entire weapon system and decision-making steps of the Find-Fix-Track-Target-Engage-Assess (F2T2EA) Kill Chain. Battle management can be completely automated or include human interaction via a live or remote operator.

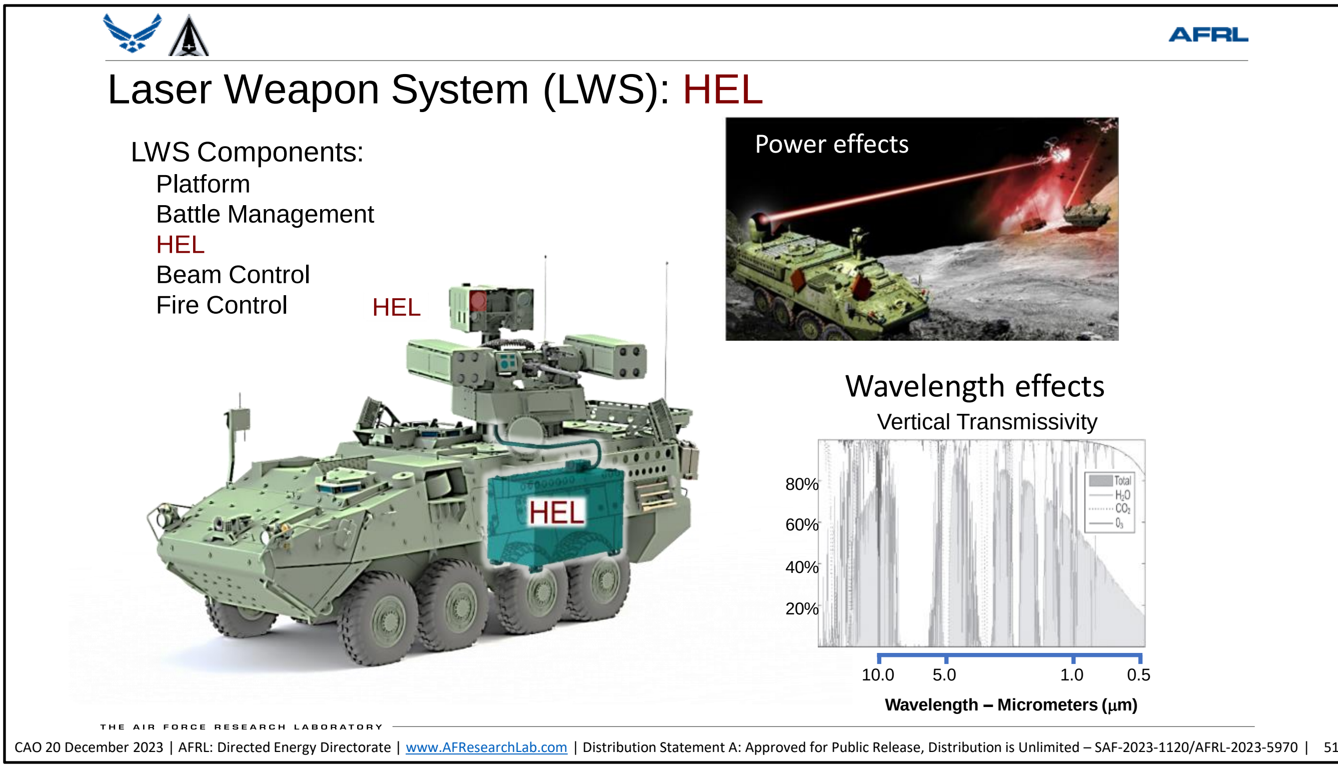
BM C2 function includes receiving the communications from a higher authority and transmitting that information to the correct recipients. The BM needs to confirm the receipt of tracks. It initiates its own tracks to make weapon pairing assignments and maintain awareness of the status of the battlefield. This includes continuing to track any existing or new detections that it receives.

BM controls the sensors on the platform. The platform sensors use the feed from surveillance sensors to provide track information to its own radar and EO/IR sensors. For this example, the LOCUST system includes both radar and EO/IR sensors and can make use of both to augment the cueing received from the surveillance sensors. Once the platform sensors determines their own tracks, the LWS BM can provide additional track data to the higher communication network.



BM also maintains the list of tracks provided by sensors to prioritize when they should be engaged and by which weapon. Engagement decisions can be based on Rules of Engagement (ROE), closure time to a threat or most effective opportunity against a threat. Weapon pairing decisions can be based on availability, sufficient magazine and probability of kill. The probability of kill for HEL weapons includes a variety of factors such as threat type, range, engagement geometry and aimpoint.

The goal is to successfully engage as many threats as possible with the available weapons on the platform. Hence, BM needs to not only maintain threat tracks and status of its weapons (i.e., the laser magazine), but it also needs to be aware of the large battlefield picture. The LWS sensors participate in Battle Damage Assessment (BDA) by providing reports of threat damage to the higher authority. These reports confirm engagement success and can include seeing the threat tumble, fall or blow apart.

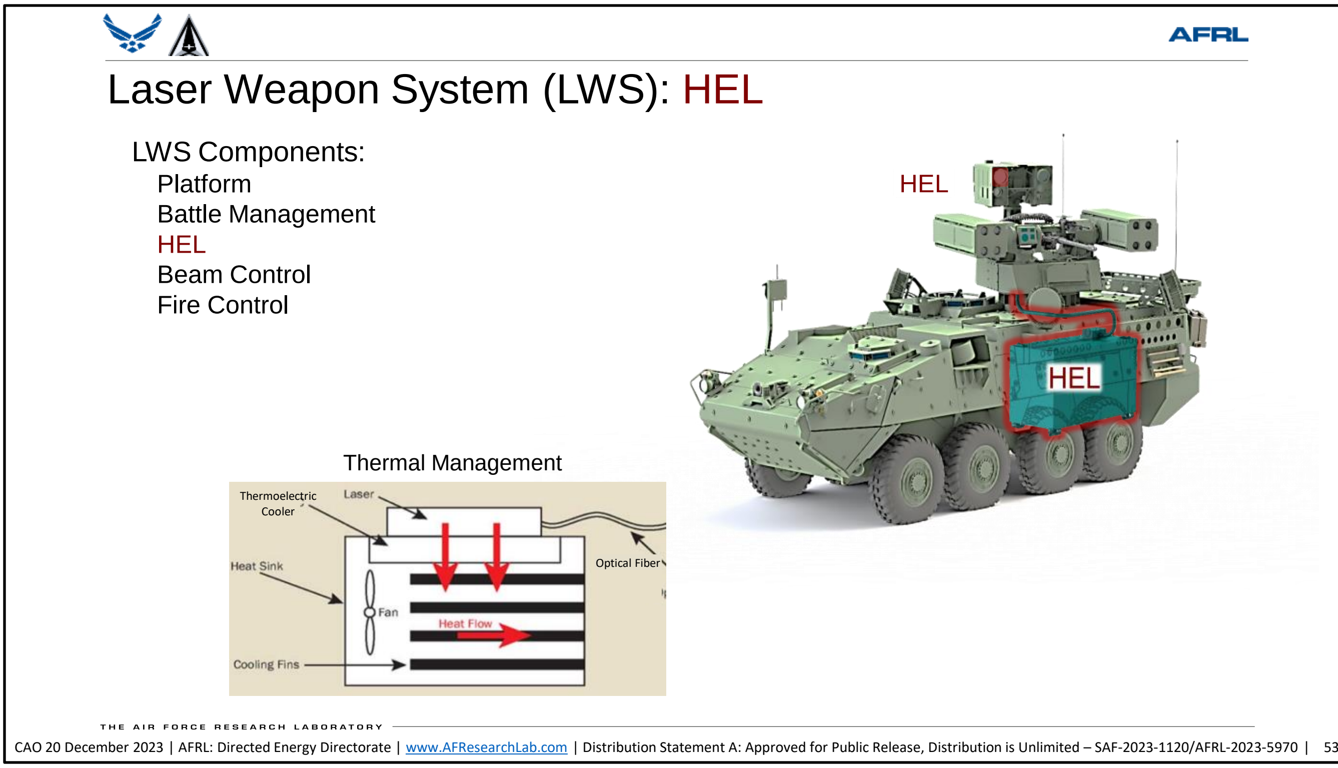


In this example, the HEL is a combination of laser modules available on LOCUST. Below are several laser parameters important to understand when using a laser as a weapon system. These parameters are highlighted below.

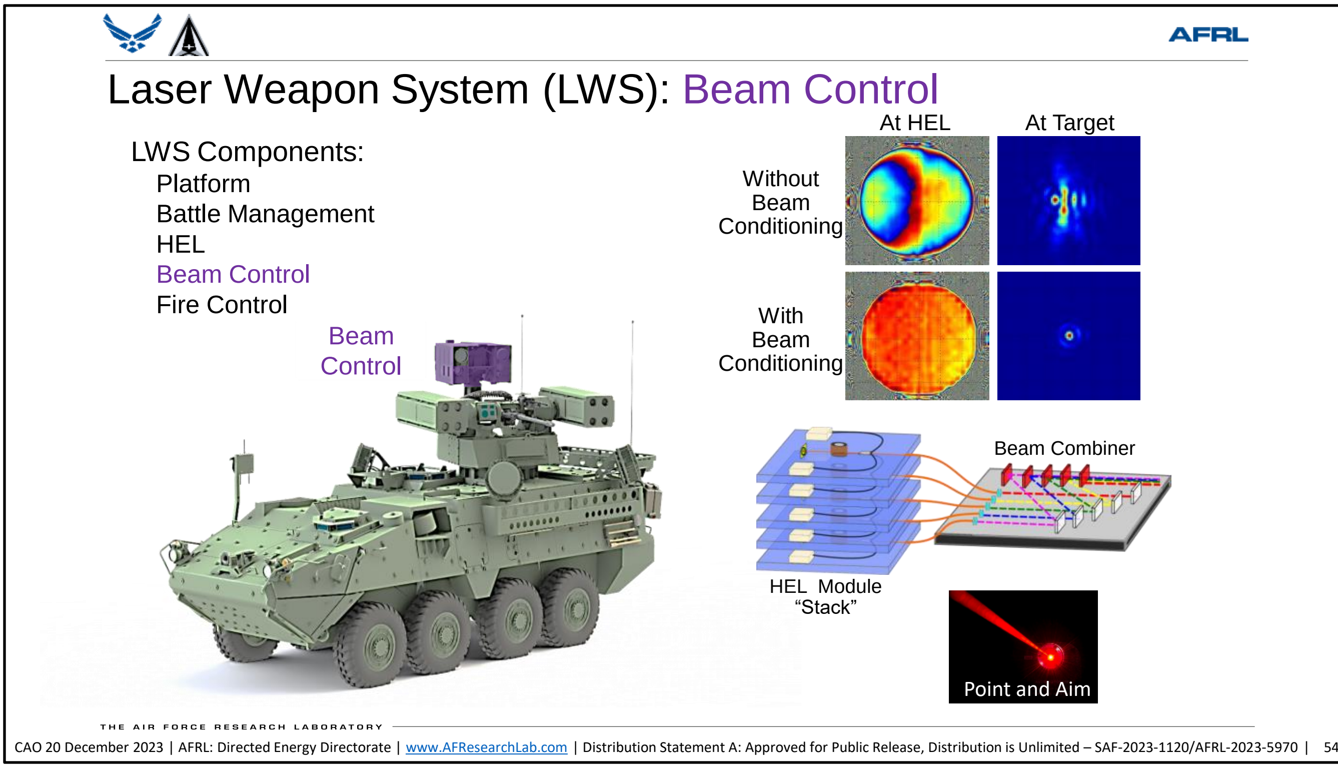
The wavelength determines the effect the laser will have on a target. As a laser beam passes thru atmosphere, the wavelength also determines how much energy gets transmitted.

The power of a laser is typically measured in watts, kilowatts or megawatts. In general, the higher the power, the larger the laser system. While the desire may be to bring the most power to bear on a difficult target to minimize dwell times, the platform often limits the size of the best LWS. The power of a HEL system can be scalable. LOCUST's HEL achieves its scalability with a multi-module design. Synergistically related to power, the laser's magazine characterizes its firing capacity. As the LWS is focusing energy on a target, it is expending the magazine. At the same time, though, the laser can be recharged if designed to do so and thus restore its magazine.

The aperture is the diameter of laser exit from the LWS. The aperture of the laser system determines the ability to focus and the amount of light scatter. In general, the larger the aperture, the farther the beam can be focused to deliver lethal levels of irradiance. Irradiance is the power per area. If the laser produces a certain amount of power that power can be pin-pointed over a small area or a larger area on the target. That area is called the spot size. For a given power, the larger the spot size, the smaller the irradiance and either less damage is done, or it will take longer to achieve the desired damage effect. Spot size also depends on distance traveled because of beam divergence, i.e., the laser beams gets wider with distance. The degree of damage is related to the irradiance over time, called dwell time.

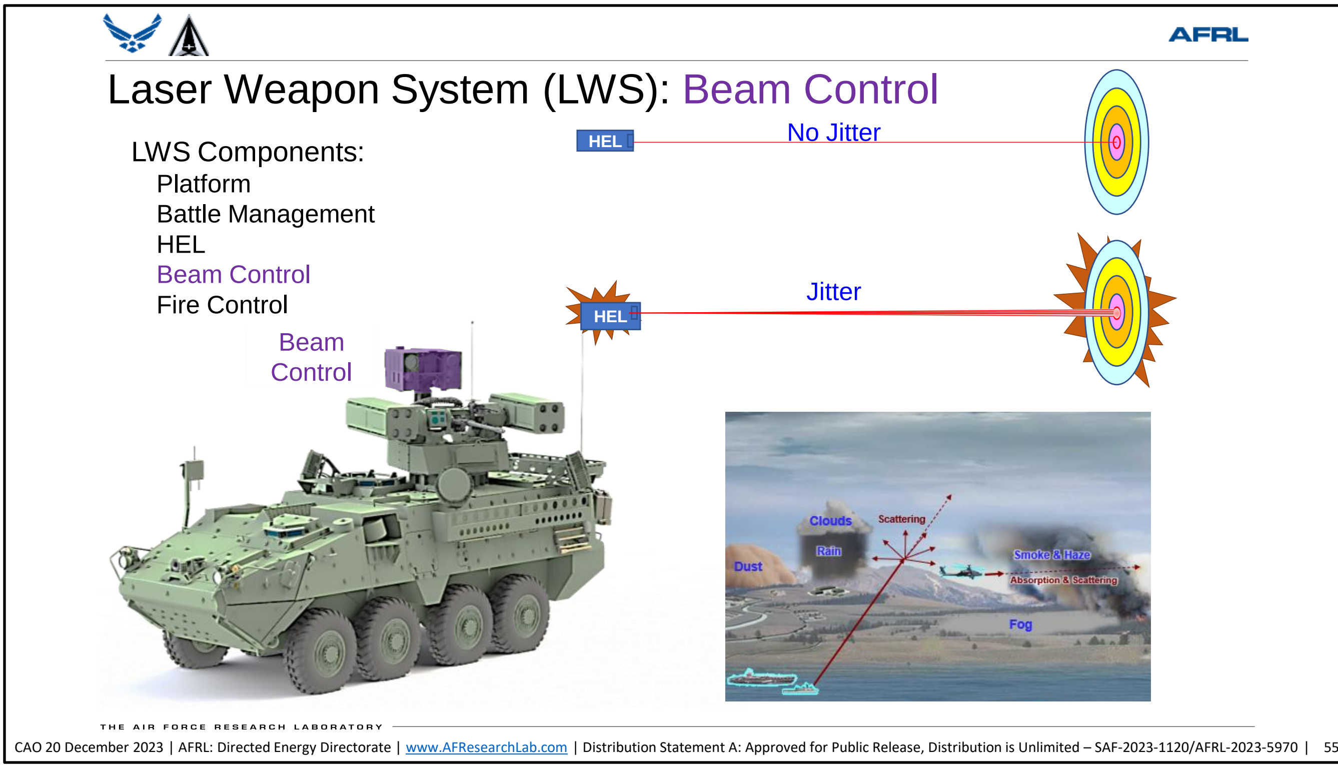


LWS efficiency is the ratio of the actual power generated to power exiting the laser cavity. Some chemical lasers can achieve around 90% efficiency, while solid state lasers are currently approaching 50% efficiency. The system inefficiency is manifested as waste heat. For example, a HEL with a 45% efficiency would take 100kW to generate a 45kW beam. The other 55kW becomes waste heat. Thermal management then becomes an important subsystem for the LWS. To keep the beam control optics within operational temperature limits, the thermal management system uses a variety of cooling methods, i.e., heat exchangers, air conditioners, heat sinks, depending on the platform. A fixed platform has an advantage over mobile systems because they can afford the larger size and weight required for thermal management.



The beam that is produced from the laser cavity is only useful as a weapon system if the beam is of good quality and it can be controlled to point and aim at the target. Achieving a high beam quality is a complex and specialized field which will not be covered in this training course. It is possible to condition the beam to focus it more effectively while reducing beam variability.

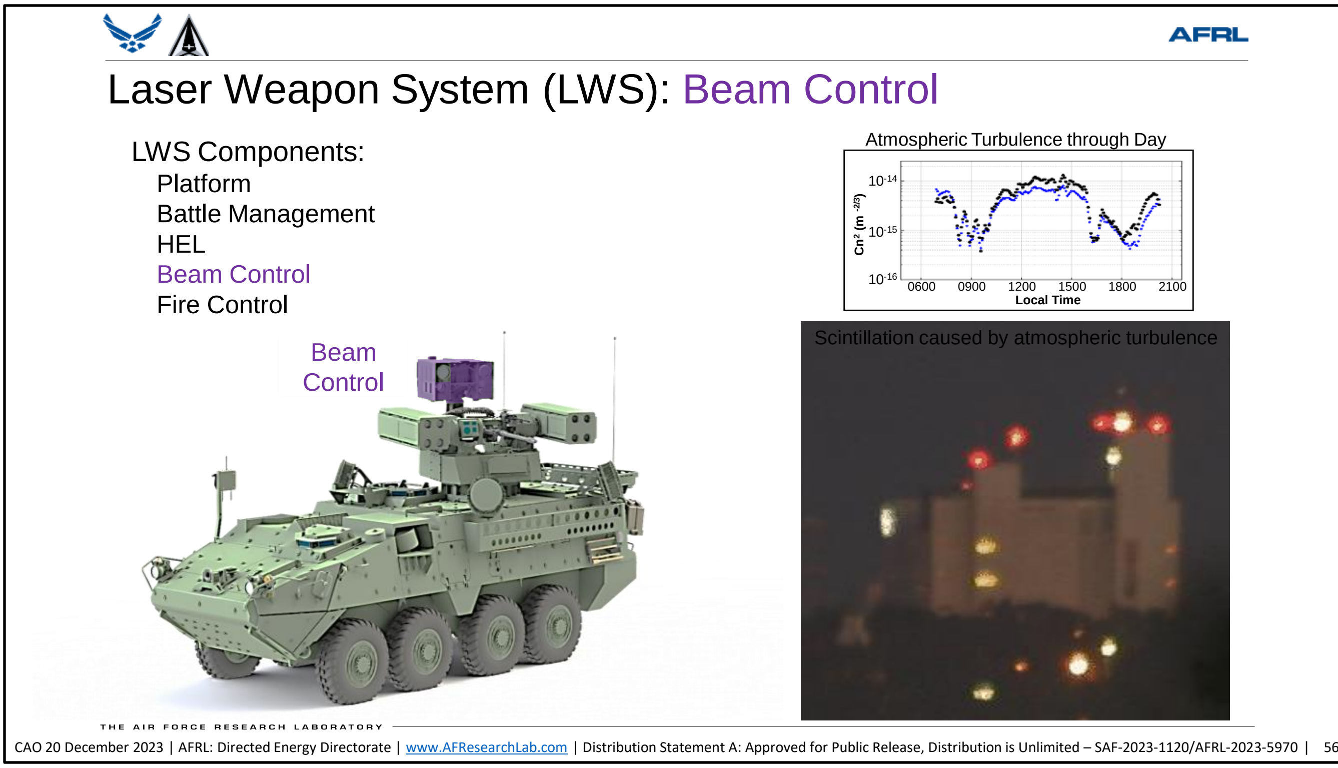
LOCUST has multiple laser modules which may require the beam control to combine the beams before performing the pointing task. The pointing capability for the LOCUST beam control resides on the M-SHORAD turret for azimuth control and a separate gimbal for elevation control. The azimuth and elevation controls support the electro-optical sensors during the HEL engagement phase of the kill chain. This will be explained in more detail later in the training. For now, the turret/gimbal combination allows the beam to be maneuvered to the target as well as settling on an aimpoint and maintaining the aimpoint until the desired target effect is achieved.



There are several factors that can interfere with the beam's ability to effectively point and aim. One is jitter, which is the vibration the LWS experiences due to the platform, the laser and other components. All platforms on the ground or the airspace experience jitter. Jitter effects can be understood by thinking about aiming a laser pointer out of a moving car. For LWS, jitter is measured in microradians or less, meaning, minimizing jitter effects is an important part of designing the laser weapon system.

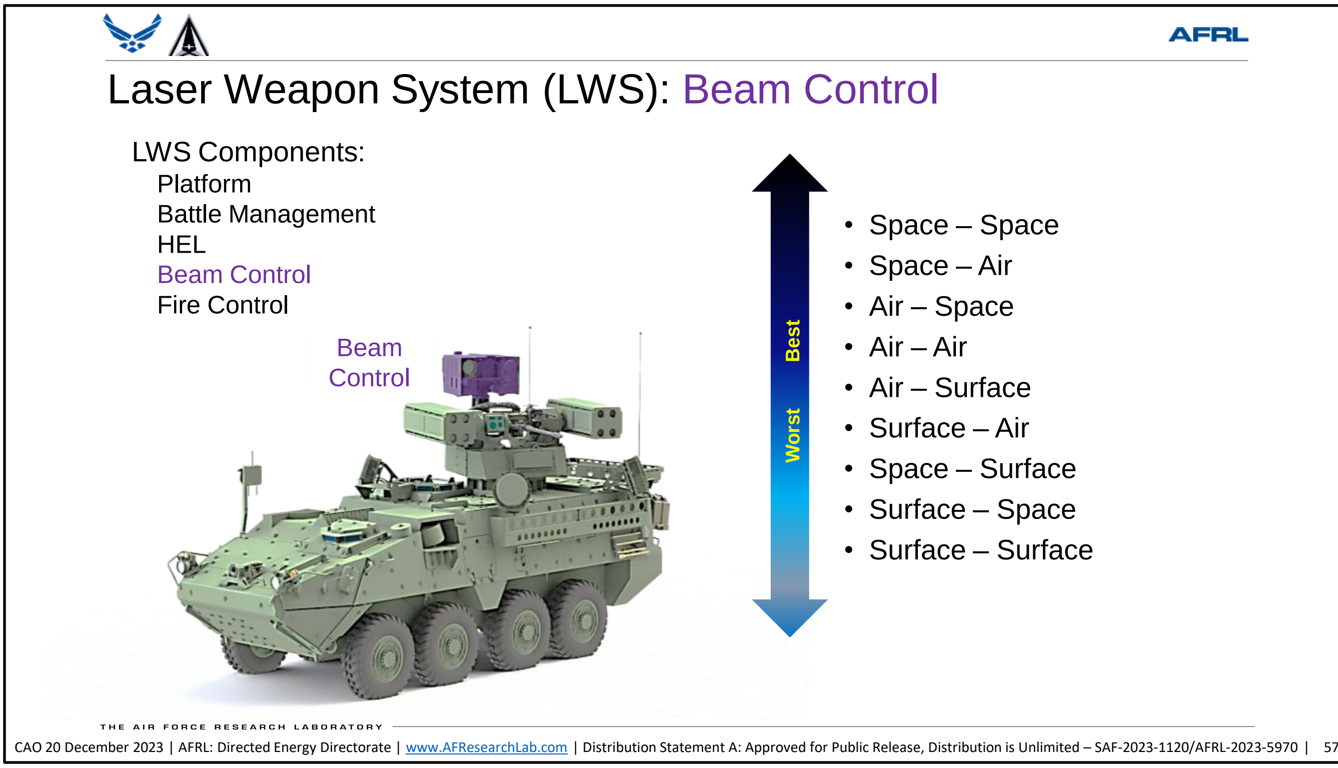
Weather and atmosphere can also interfere with pointing and aiming a beam as it is propagated from the source to the target. By propagation, we mean moving photons through the atmosphere and accounting for the effects that reduce beam power on the target. The primary effects are scattering, absorption and turbulence.

Scattering occurs when light hits an object and is reflected, causing it to not reach the target. Absorption occurs when a photon hits an object and imbeds itself so it can't reach the target. When the atmosphere is foggy, rainy, cloudy, dusty, smokey or hazy, the propagation of a laser beam is negatively impacted. The photons are being scattered and absorbed, thus reducing how much energy can get to the target.

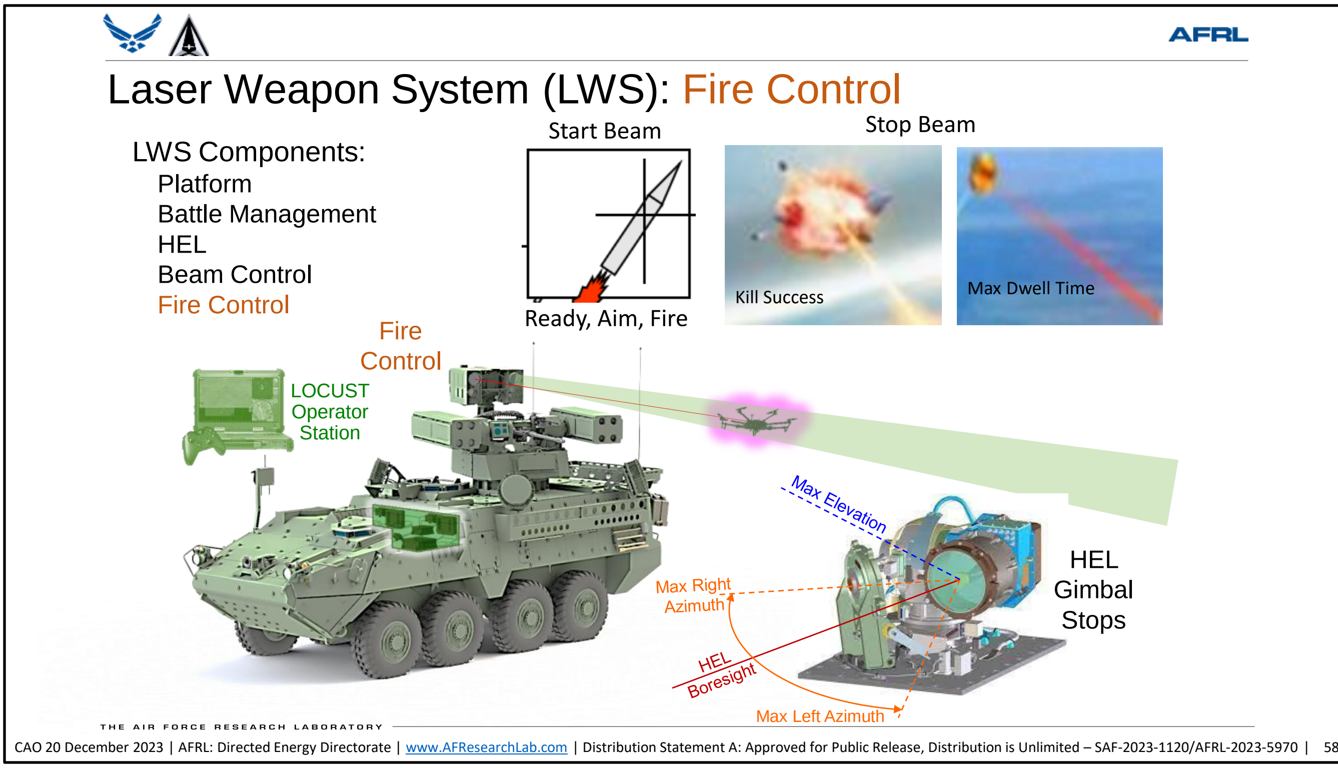


Atmospheric turbulence is ever present in varying degrees due to temperature fluctuations in the atmosphere. Turbulence impacts the laser beam by randomly modifying the phase of the beam, making it less coherent. We discussed the importance of a coherent beam earlier, so a less coherent beam will also reduce the power at the target. Note that even on a clear, non-windy day, turbulence will affect a laser beam because of localized temperature variations. In general, atmospheric turbulence is lowest after sunrise and after sunset because the natural heating cycle of the sun on the earth produces the best match of the earth surface temperature to the atmospheric temperature at those times. After a rainfall, turbulence can be lower because particulates have been washed away and the cooling effect of the rain moderates the temperature fluctuations.

Aerodynamic turbulence is due to wind or movement of air around a platform. This has a significant effect on propagation of the beam on the target depending on the look angle. Aerodynamic turbulence can be mitigated with adaptive optics.



The impact of weather and atmosphere changes with altitude. The atmosphere closer to the earth is denser and can contain more particulates. There will be more scattering and absorption near the earth because of light bouncing off particulates and being absorbed by those particulates. Temperature fluctuations tend to be worse near the ground, so turbulence becomes more of a problem at lower altitudes. The atmosphere as you approach outer space will be thinner and less likely to hold onto those particulates, making atmospheric issues less of a problem. Given this, laser propagation through space would give the best beam quality and laser propagation would be most troublesome near the earth. Also, lasers generally work better shooting up then shooting down

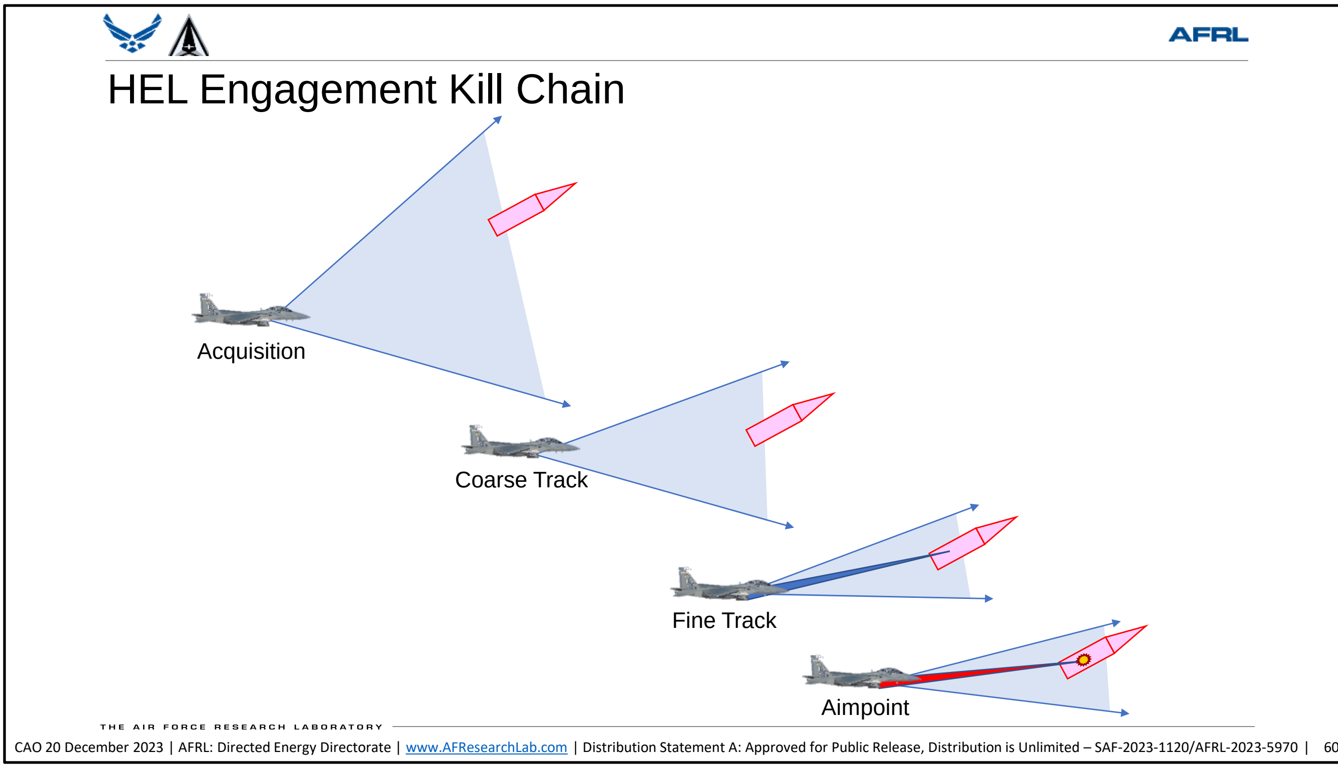


Fire Control is weapon-specific and controls all the steps up to a successful firing. After BM has made the decision to engage the threat, the fire control determines when the beam is turned on or off. This can be a manual or an automatic process. The laser beam is only turned on when it is tracking on the target aimpoint and able to dwell for sufficient time to achieve a successful effect. A future slide covers the steps in the engagement phase of the kill chain that need to occur before aimpoint tracking and firing can begin.

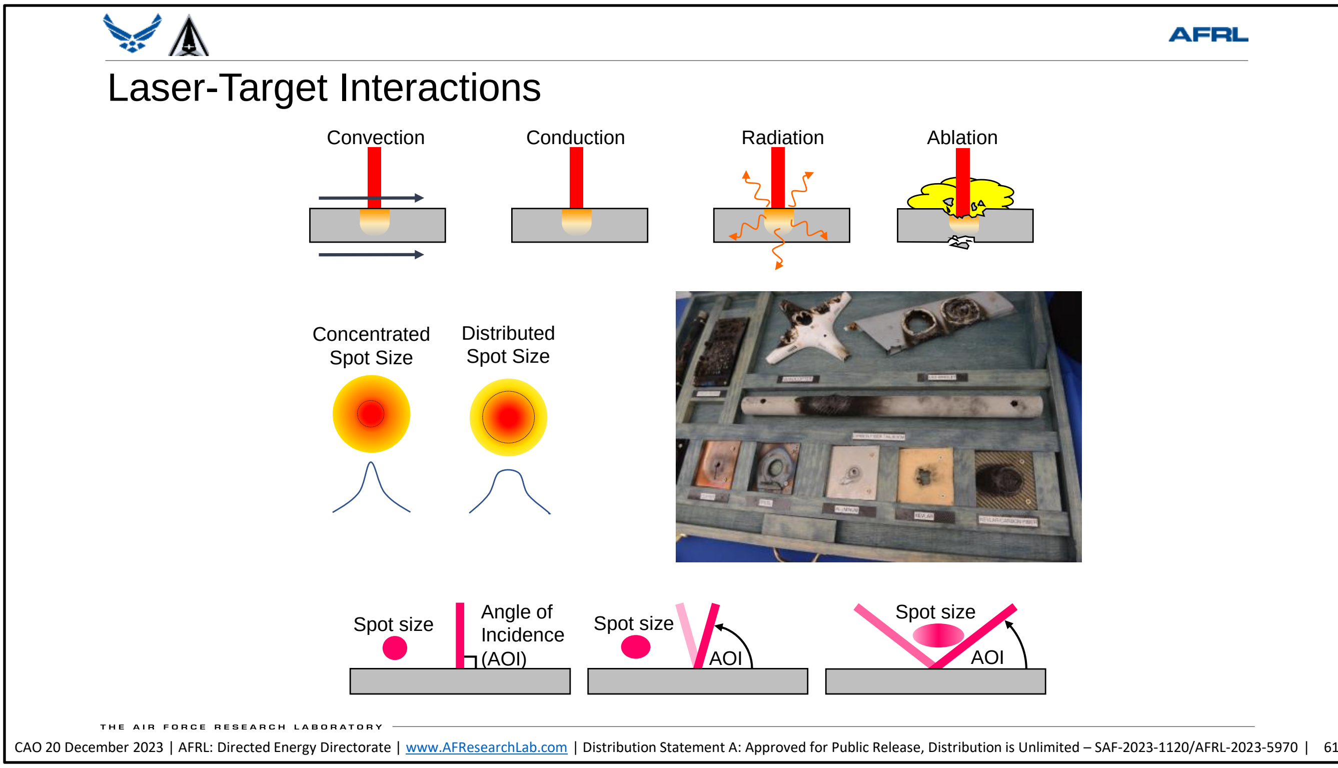
Fire Control also controls when to turn off the beam. One reason for stopping the shot would be kill success. Safety reason can also interrupt the laser beam. This might include exceeding the maximum dwell time which could cause an overheating situation. Tracking a threat until a gimbal stop is reached will also stop the firing to avoid damaging the system.

A deconfliction signal can also cause a safety interruption. Deconfliction occurs when the HEL beam might inadvertently interact with an entity that is not the intended threat. Since HELs can travel long distances and even beyond where the threat is, deconfliction is of concern not just to nearby entities, but those beyond the threat that could be in the line of sight. Entities that should not experience the HEL energy include ‘friendlies’ such as personnel, equipment, and weapons on the ground, in the air or space. Accidentally exposing neutral entities to the laser beam could create an incident.

The term Predictive Avoidance (PA) is the method employed by the Laser ClearingHouse (LCH) to prevent laser beams from inadvertently damaging satellites. It is predominantly a deterministic method for allowing when a laser can be on. PA is being replaced by Probability Risk Assessment (PRA) which includes probabilistic concepts, such as the likelihood of damage, in determining when to turn a laser off. PRA theoretically allows more use of HEL weapons.



In the engagement phase of the kill chain, there are steps that must be in place before a HEL can be fired. These steps are implemented with electro-optical infrared (EOIR) sensors. The first step is acquisition where the EOIR sensor receive the track cues from a surveillance sensor and develops its own tracks for the threat within its field of view (FOV). It then moves to coarse track to get the laser beam centered to the target. The next step is fine track where the resolution becomes more refined, and the beam is centered on the target. In aimpoint phase, the beam moves to the assigned aimpoint. When tracking on the aimpoint is stable, the laser beam can be fired at the aimpoint and maintained for the duration of the dwell time. During this process, some system may measure the atmosphere and compensate accordingly to improve the beam quality. If for any reason, the aimpoint cannot be maintained, these steps in the engagement phase will need to restart.



Laser-Target interactions are the various effects the photon energy produces as it contacts the target and the surrounding environment. This energy is deposited on the target material as intense heat.

There are three heat transfer mechanisms – convection, conduction and radiation. Convection is the transfer of heat via the movement of fluids, such as the flow of air around the target. Conduction is the transfer of heat through the body. The lased side of the material is hotter and will conduct that heat to the colder side of the material. Thermal radiation is the energy that is emitted from a heated surface and can travel in all directions. If sufficient heat energy is applied to the target, the material can be ablated, that is, removed, thus reducing the integrity of the target structure.

The laser's spot size is related to the intensity of the beam. A very focused beam can produce a high peak intensity. A spot size that is more spread out will have lower peak intensity. The angle at which the laser beam hits the target is called the angle of incidence (AOI).

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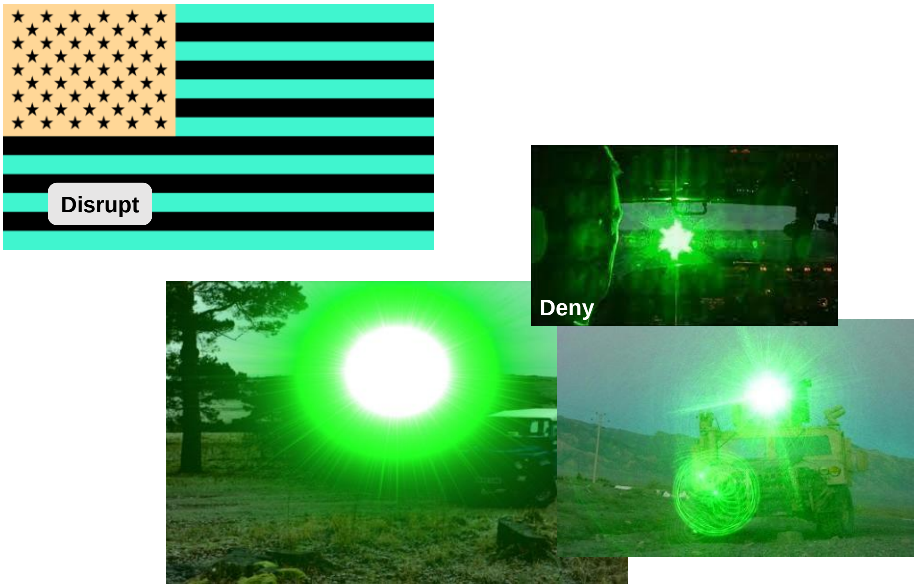
Target Effects: Temporary Effects



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HELs can produce various effects on the target based on the wavelength, power of the laser, and dwell time. The choice of the effect is intended to support a military objective. These objectives are often identified as temporary and permanent effects. For each effect, there is an associated minimum irradiance level and dwell time.

Some temporary effects occur while the laser is applied. Saturation of the sensor (dazzling) is an example of this type of temporary effect. Other temporary effect continues even after the laser is turned off. This type of disruption causes a delay that requires a time for action thus temporarily removing the threat from the battle. An after-image that can disrupt a sensor's ability to clearly identify an image is an example of a temporary effect occurring after the lasing stops.

Target Effects: Permanent Effects

Mission Kills

Catastrophic Kills

There are essentially two types of permanent kill effects – Mission kills and Catastrophic kills. Mission Kill prevents a threat from performing its mission for today's battle, but the threat could be repaired for future battles. The HELs energy might overheat a component and cause it to not function properly. This component could then be replaced for future missions.

HELs can be used to focus permanent destructive energy on a critical component. This can result in catastrophic or mobility kills. Catastrophic Kill (K-Kill) is permanent loss of the system. Mobility Kill (M-Kill) prevents the threat from moving.

What HELs Bring to the Battlespace

	HEL	KE	EW	Cyber
Effect	Temporary and Permanent	Permanent	Temporary	Temporary and Permanent
Clandestine	Yes	No	Yes	Yes
Non-weapon functionality	High Precision Sensors	Minimal	Yes	Yes
Magazine	Rechargeable	Manual reload	N/A	N/A
Debris	Smaller	Larger	N/A	N/A

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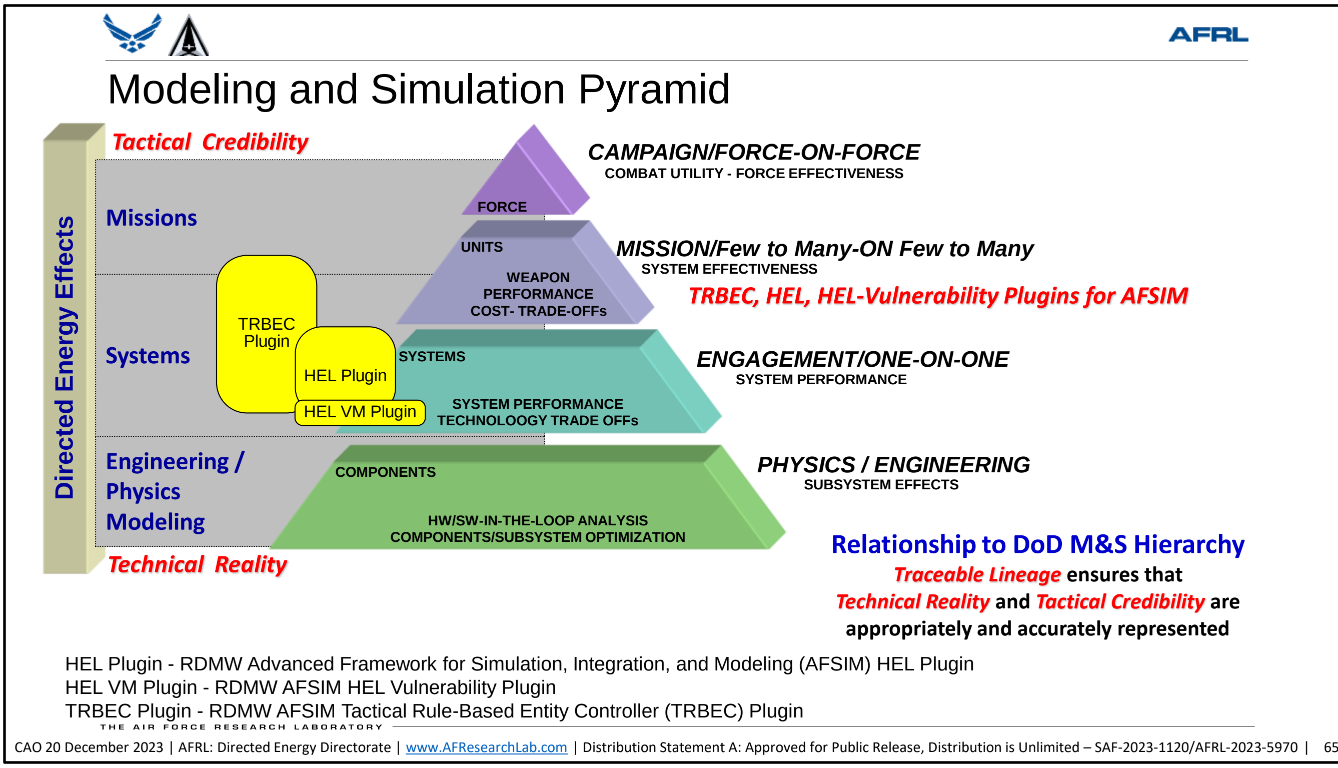
While laser weapons systems would not be the single approach to delivering battle success, they provide military utility with complementary warfighting tactics to other weapon systems such as kinetic, electronic and cyber. LWS are uniquely situated to augment where engagements can take place as well as the types of target effects.

A laser's ability to deliver intense, pin-point energy at the speed of light provides the benefit of precise and clandestine engagements that leave little trace. When not engaging, the sensors on-board the LWS can provided track data supporting other phases of the kill chain. The term 'deep magazine' applies to the LWS because of its recharge capability. Recharging and thermal management can occur while in the battle, thus preparing the LWS to either reengage the same threat or take on another assignment.

Besides unique benefits, LWS also have unique limitations. Because lasers induce damage based on generated heat, they are effective only against threats with heat-vulnerable aimpoints. The laser beam effectiveness is susceptible to atmospheric conditions.



The Air Force Research Laboratory (AFRL) M&S approach is hierarchical. At the base are physics & engineering methods for research, modeling and analysis. The physics/engineering constructs move into Engagement Level M&S where detailed analysis of one-on-one (1x1) engagement phenomenology is studied. The results from the Engagement phase is fed into a Mission Level M&S. At the Mission level, systems are modeled with M-on-N scenarios (MxN). They are played out to answer specific weapon system effectiveness questions. Results from the Mission level can then be moved up to Campaign Level M&S where high level force effectiveness questions are addressed.

AFRL/RDMW develops and manages high energy laser (HEL) software developed for Advanced Framework for Simulation, Integration, and Modeling (AFSIM), the mission level modeling tool.

Resources

- HEL
  - *An Introduction to Laser Weapon Systems*, Glen P. Perram, Salvatore J. Cusumano, Robert L. Hengehold, and Steven T. Fiorino, Directed Energy Professional Society, 2010
  - www.deps.org: Directed Energy Professional Society (DEPS) short courses

Here are some resources useful for further study of DE.

Next Training Course

- ☑ Directed Energy Weapon: Introduction (DEW: Intro)
- ☑ Directed Energy Weapon: High Energy Laser (DEW: HEL)
- ☐ Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM)

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Once the Directed Energy Weapons: High Energy Laser (DEW: HEL) course has been completed, the AFRL/RDMW Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM) course is recommended if not already completed.

Acronyms

Acronym	Definition
ABL	Airborne Laser
AFRL	Air Force Research Laboratory
AFSIM	Advanced Framework for Simulation, Integration, and Modeling
ALL	Airborne Laser Laboratory
ATL	Advanced Tactical Laser
BM	Battle Manager
C2	Command and Control
COIL	Chemical Oxygen Iodine Laser
c-UAS	Counter-Unmanned Aerial System
DE	Directed Energy
DEW	Directed Energy Weapon
EO/IR	Electro-Optical/Infrared
F2T2EA	Find, Fix, Track, Target, Engage, Assess
FOV	Field of View
HEL	High Energy Laser

Acronym	Definition
HPEM	High Power Electromagnetic
HPM	High Power Microwave
LCH	Laser Clearing House
LOCUST	Low-Cost Counter-unmanned Arial System for Targeting
LWS	Laser Weapon System
M&S	Manufacturing and Simulation
M-SHORAD	Maneuver Short-Range Air Defense
MTU	Mobile Test Unit
MW	Mega-watts
PA	Predicative Avoidance
PRA	Probability Risk Assessment
ROE	Rules of Engagement
SHiELD	Self-Protect HEL Demonstrator
THEL	Tactical High Energy Laser
UAV	Unmanned Aerial Vehicle

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We recommend that you read this presentation in Note Page View for optimal formatting.

Welcome to AFRL/RDMW's Directed Energy Weapons: High Power Electromagnetic training course. This is a publicly-releasable presentation developed to familiarize people with HPEM weapons.

Course Scope

- Provide Basic Introduction to High Power Electromagnetic (HPEM) Weapons for:
  - Warfighters
  - Technical personnel new to Directed Energy (DE)
  - Interested non-technical personnel
- Provide Appropriate Level Physics for the Audience:
  - Basic-Level Physics
  - Resources Provided for Additional Study

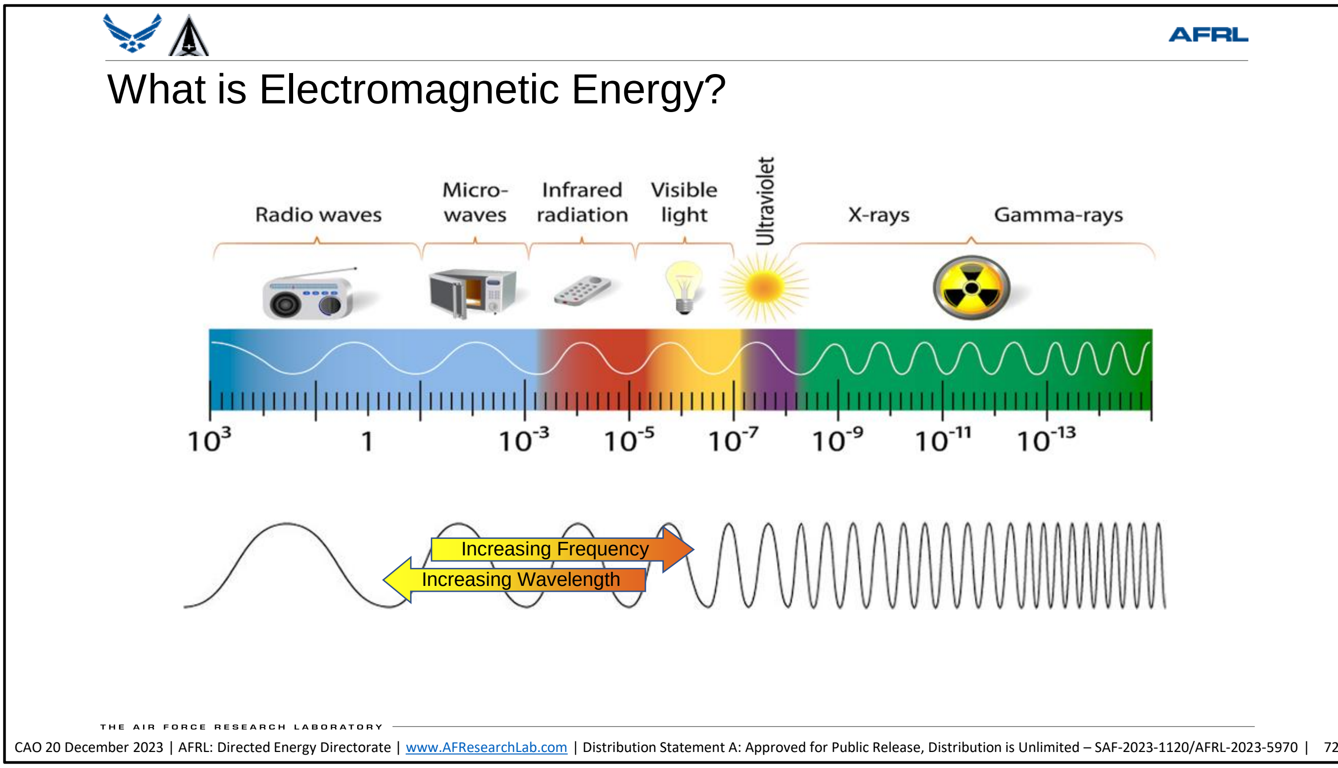
The science of HPEMs is a very technical area of knowledge where one can spend an entire career developing specialized expertise in just a few HPEM phenomena.

The scope of this course is a basic introduction to HPEM weapons and associated technologies. The focus is on high power electromagnetic weapons as applied to the battlefield. Some suggested resources have been provided for additional study to further advance understanding of the complex topics presented.

Introduction to HPEM

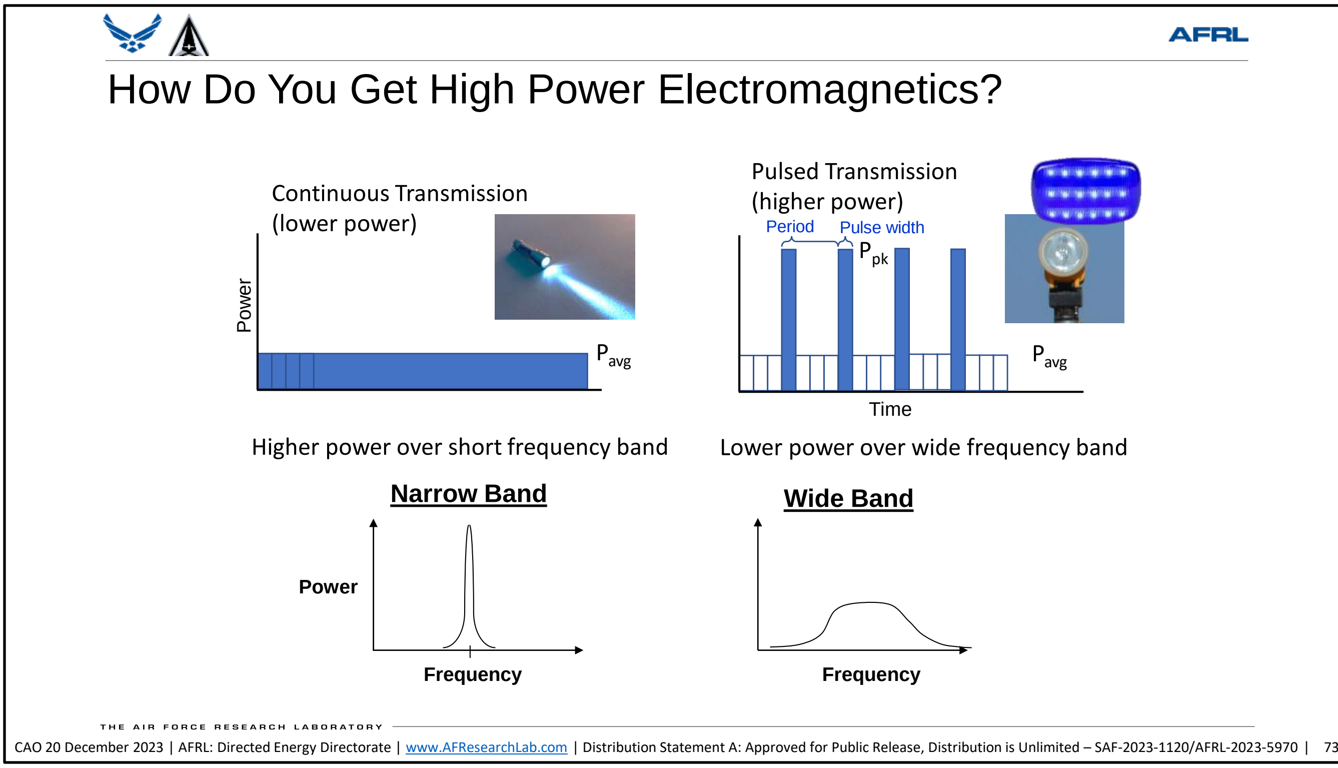
- What is HPEM?
- History of HPEM Weapons
- The HPEM Weapon System
- HPEM Effects
- Military Utility (MU) of HPEM Weapon Systems
- Modeling and Simulation

In this training course, some basic HPEM concepts are introduced first. Then, an overview of the history of High Power Electromagnetic (HPEM) weapons and a glimpse of some systems currently in development will be given. HPEM weapons and their unique contributions to effectiveness in a battlespace will be discussed. An example of an HPEM weapon system will be used to describe the necessary components. Next, aspects of HPEM weapon military utility and effectiveness will be covered. The final topic is information on HPEM modeling and simulation.



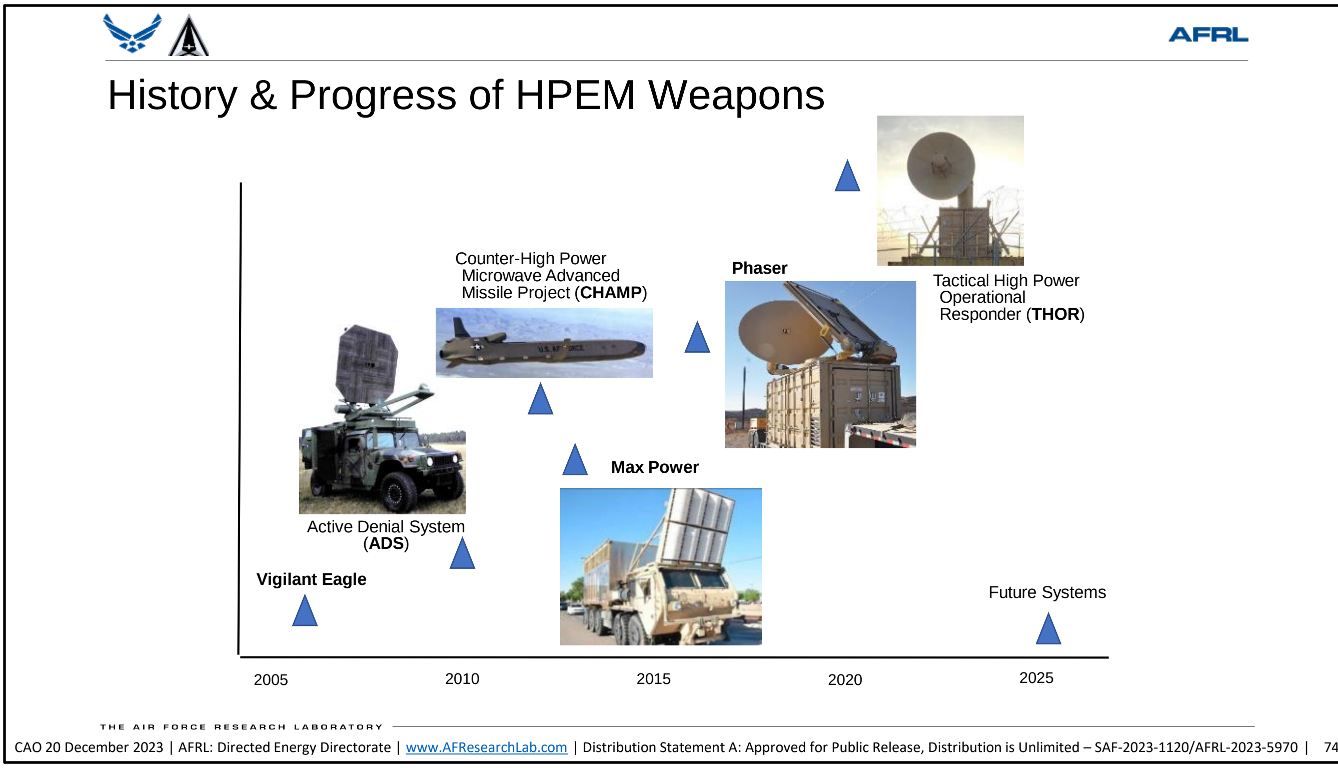
Electromagnetic (EM) energy is a fundamental force of nature that travels as waves through space at the speed of light. EM doesn't have mass or charge, but instead, produces light energy in bundles called photons. EM energy can also be described by frequency or wavelength. If you recall from previous DE training charts, frequency and wavelength are inversely proportional to each other. As frequency increases, wavelength decreases. The range of EM frequencies is broad and includes very low radio waves to very high gamma rays.

HPEM is commonly considered to be mainly in the radio frequency band (3Hz to 3000GHz). However, HPEM can be generated for any frequency in the electromagnetic spectrum. The selection of the frequency determines how the system can perform.



Electromagnetic energy can be transmitted continuously or in pulses. Continuous energy streams are steady with some average power level, like the light from a flashlight. Continuous power generally is low, on the order of watts. Pulsed energy puts out short bursts of high power, then nothing and repeats this pattern, like a strobe light. The power from a single pulse can be very high, well over megawatts.

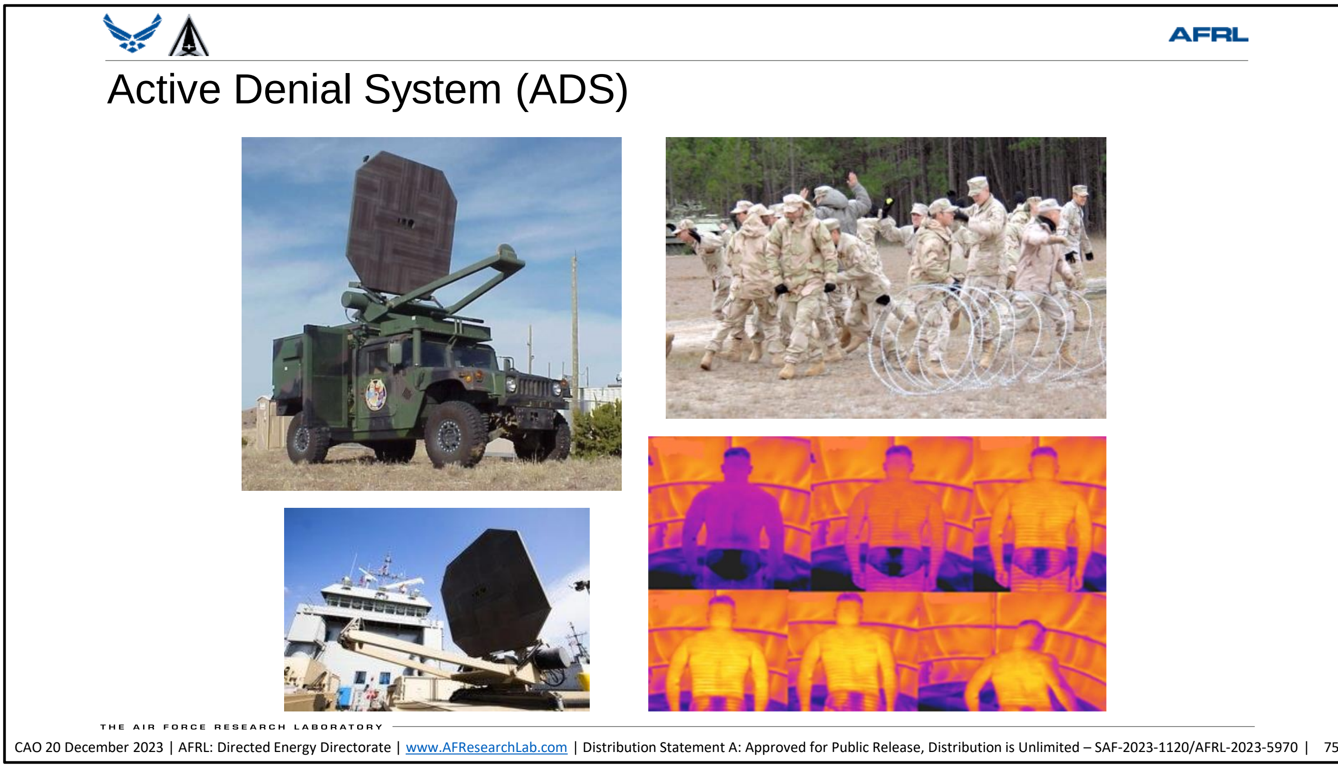
HPEM energy systems are typically pulsed power systems because higher power is produced from pulsed systems. To achieve high power, the pulse times for HPEM are very short, in the nanosecond range. In addition to pulsing, HPEM also produces high power by operating within a narrow frequency band. This combination of very short pulses within a narrow bandwidth creates the high-power performance that is sought on the battlefield.



While deployed HPEM weapons are more recent, HPEM systems have a long history with initial development dating back to World War II.

Vigilant Eagle, which was the earliest significant system, was meant to be an airport defense system which used microwaves to defeat missiles fired at aircraft. It consisted of missile detection and tracking systems, a Command and Control (C2) element, and a scanning array High Power Microwave (HPM) weapon. The C2 would determine the missile's launch point and the scanning array emitted microwave energy pulses to disrupt the missile's guidance systems.

The remaining systems in this HPEM weapon timeline will be discussed in the next few charts with some demonstration movies.



The Active Denial System (ADS) was a nonlethal counter-personnel weapon. It was intended to induce a painful heating sensation on an adversary's skin without injury.

ADS was compliant with all U.S. treaties and legal obligations (i.e., the Geneva Conventions) and tested to show minimal health risks. Although deployed to Afghanistan, it was withdrawn from use because of potential concern about public opposition.

The Army explored the development of a Solid-State Active Denial Technology (SS-ADT) for such missions as crowd dispersal, checkpoint security, perimeter security, and port protection both in fixed and mobile modes

The Counter-High Power Microwave Advanced Missile Project, or CHAMP, is an unmanned HPM weapon on an Air-to-Ground (AGM)-86 Air Launched Cruise Missile. It is a counter-electronic system, capable of flying into a contested area to disable several threats in its flight path. It was tested against operationally relevant targets in 2012. In 2019, twenty CHAMP cruise missiles were deployed to the field.

CHAMP offers a proven capability to defeat electronic systems in an enemy structure without employing kinetic weapons like bullets or explosives. As such, CHAMP completely avoids damage to infrastructure and danger to life. The CHAMP system is highly adaptable and can be deployed from a variety of platforms, depending on mission needs.

Max Power

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Max Power is a counter-Improvised Explosive Device (IED) HPEM weapon on a heavy truck chassis with a mission of defeating IEDs before they detonate and destroy a convoy.

Max Power emits an electromagnetic pulse a billion times stronger than the average household microwave oven.

A Max Power prototype was deployed to Afghanistan in 2012 where it was on point for 19 combat missions with convoys across IED-infested roads and highways.

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Phaser


UAS Group	Maximum Weight (lb)	Operating Altitude (ft)	Speed (kts)
1	0 - 20	< 1,200	100
2	21 - 55	< 3,500	< 250




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The Phaser is a counter – Unmanned Aerial System (UAS) HPEM weapon housed in a transport container, it can operate on a trailer or on the ground. It has been successfully tested against both Group 1 and Group 2 UAS – Note the group definitions in the table on the upper right of the slide. Phaser is a counter-swarm weapon because it can affect all UAS within its beam. This capability was demonstrated at Ft Sill, Oklahoma in 2013. It has become the predecessor for newer counter-swarm systems.

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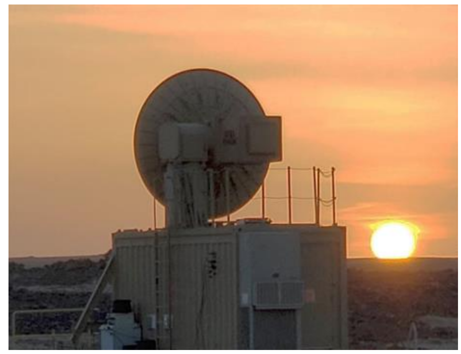
Tactical High Power Operational Responder (THOR)



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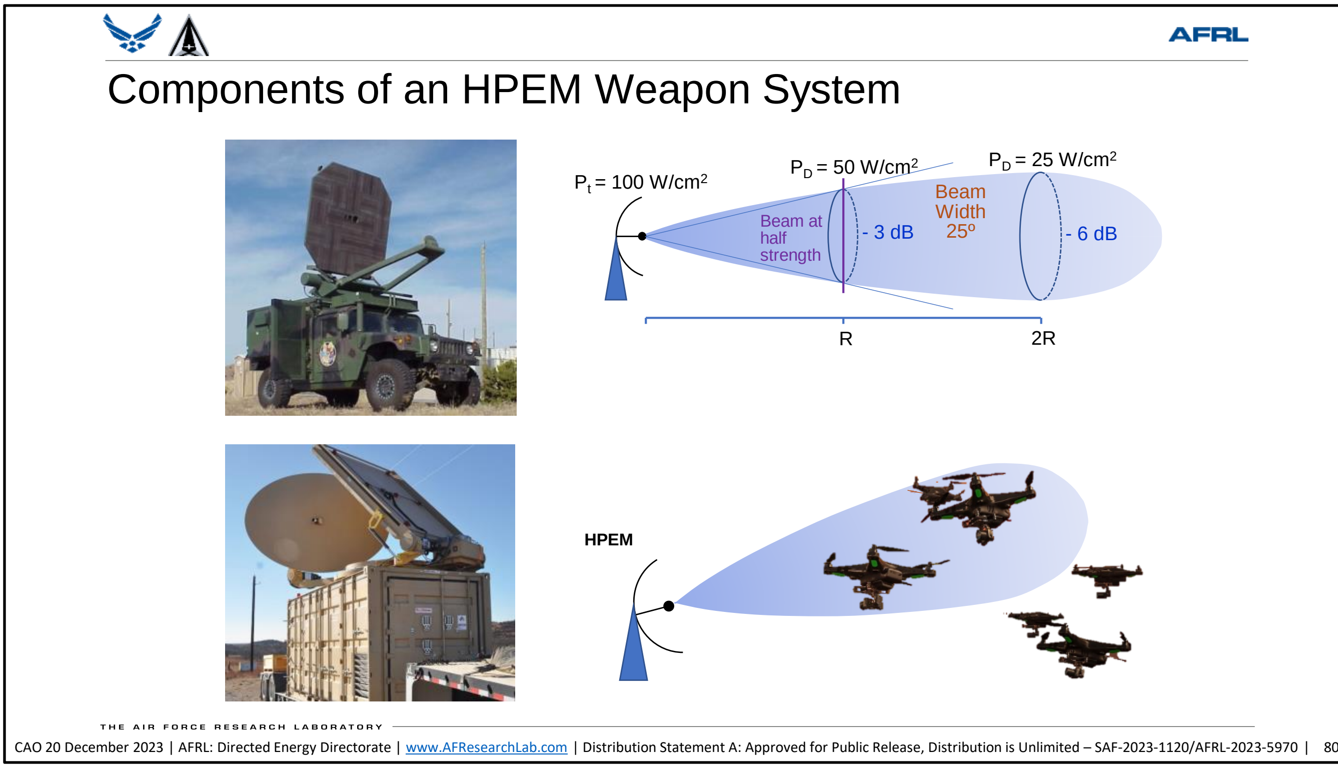
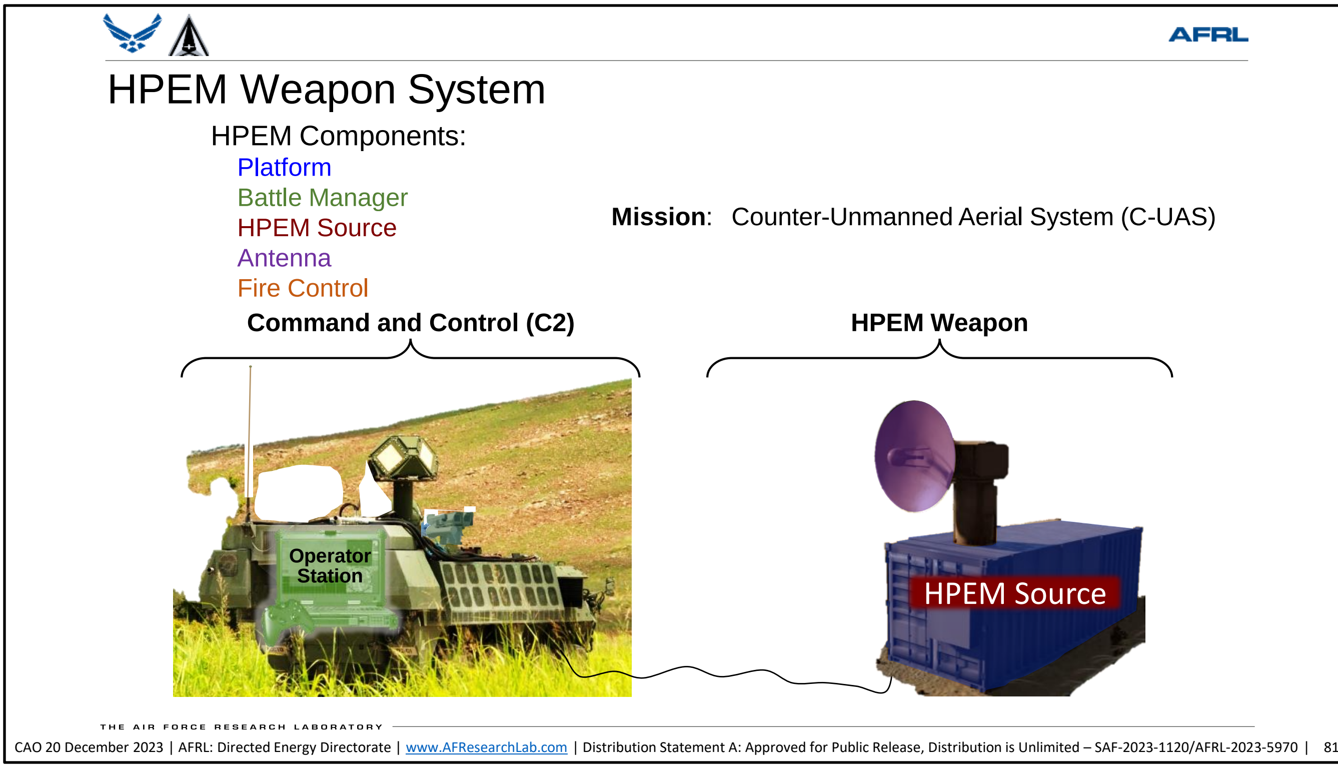
The Tactical High Power Operational Responder (THOR) system is a counter-swarm UAS HPEM weapon designed to defend air bases. It was deployed for field testing in 2021. The technology was installed in a 20ft-long shipping container that could be transported in a military cargo aircraft such as C-130.



When a HPEM is placed on a platform to perform a military mission, it becomes a HPEM weapon system. Before discussing the various components of a HPEM weapon system, it is important to understand how a HPEM weapon engages threats. Kinetic and high energy laser weapons focus the system on a single target to cause an effect. The effect that HPEM has on the battlefield is based on a volumetric cone of electromagnetic energy. Any threat within this volume will experience the HPEM energy. This allows the weapon to engage multiple targets simultaneously. Those threats directly in the centerline of the cone will experience higher power than those on the edge of the cone, but all threats in the volume will be illuminated.

The power of a HPEM system is measured in terms of power density with units of W/cm2. This power is highest near the source. As the energy transmits away from the source, it’s power decreases. The distance from the energy source and power at that range are inversely proportional to each other.



We will now go through the components of a HPEM weapon performing a counter UAS mission. The weapon system has five components:

The platform

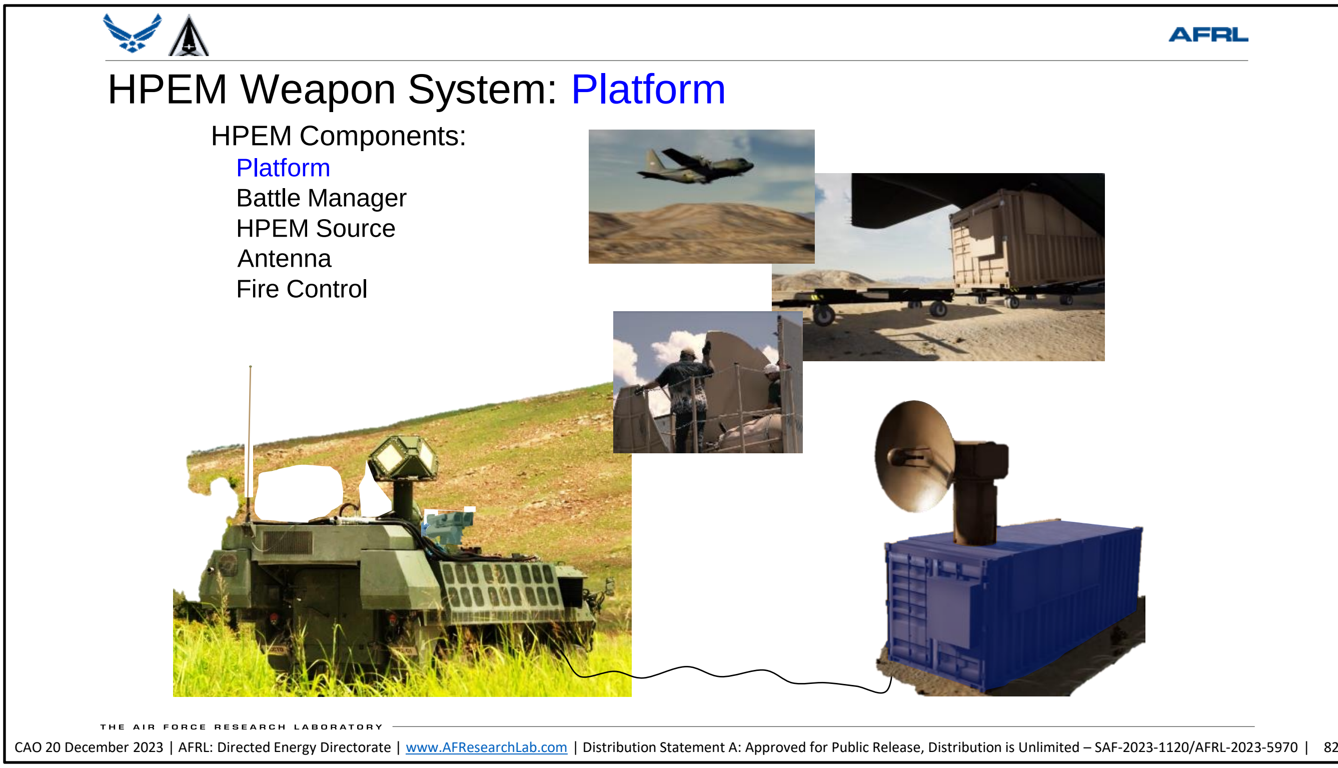
The battle manager

The HPEM source

The antenna

The fire control

The next few charts show details of these components.



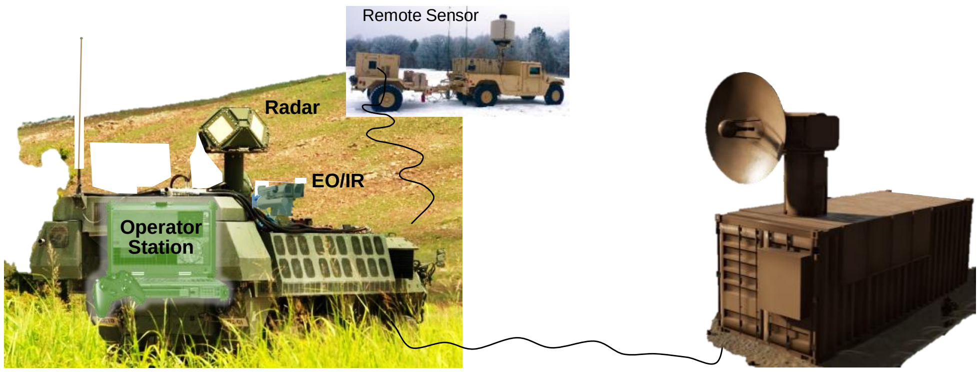
The HPEM platform can be transportable or stationary. When in operation, though, it is in a fixed position. The platform houses the HPEM source, the electrical power generator, the thermal control system and the transmit antenna. The systems can operate from generators or external power source.

Sensors, communication networks, the operator station and other components that may be damaged by the HPEM beam are placed away from the platform.

HPEM Weapon System: Battle Manager

HPEM Components:

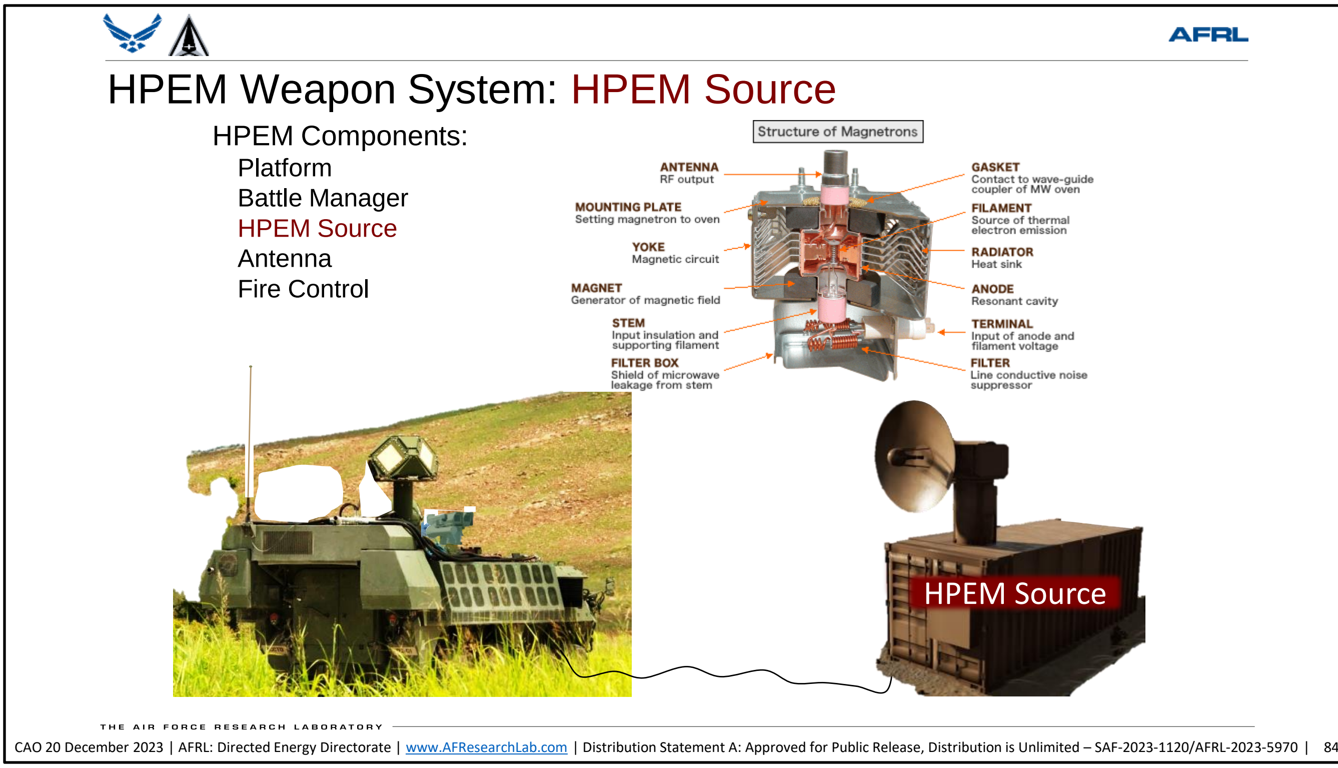
- Platform
- Battle Manager
- HPEM Source
- Antenna
- Fire Control



The Battle Manager (BM), provides the Command and Control (C2) functions. The responsibilities include receipt of tracks, assignments, and other commands from a higher authority, as well as the transmission of the weapon status, current situation, and any detection or track data that should be fed to a higher-level air picture.

BM controls the sensors on the weapon system. The sensors use the feed from surveillance radars to provide track information to its own sensor systems. The HPEM weapon system includes both phased array radar and Electro-Optical/Infrared (EO/IR) sensors that are not co-located with the HPEM weapon. Once the platform sensors determine their own tracks, the weapon's BM provides additional track data to the higher communication network.

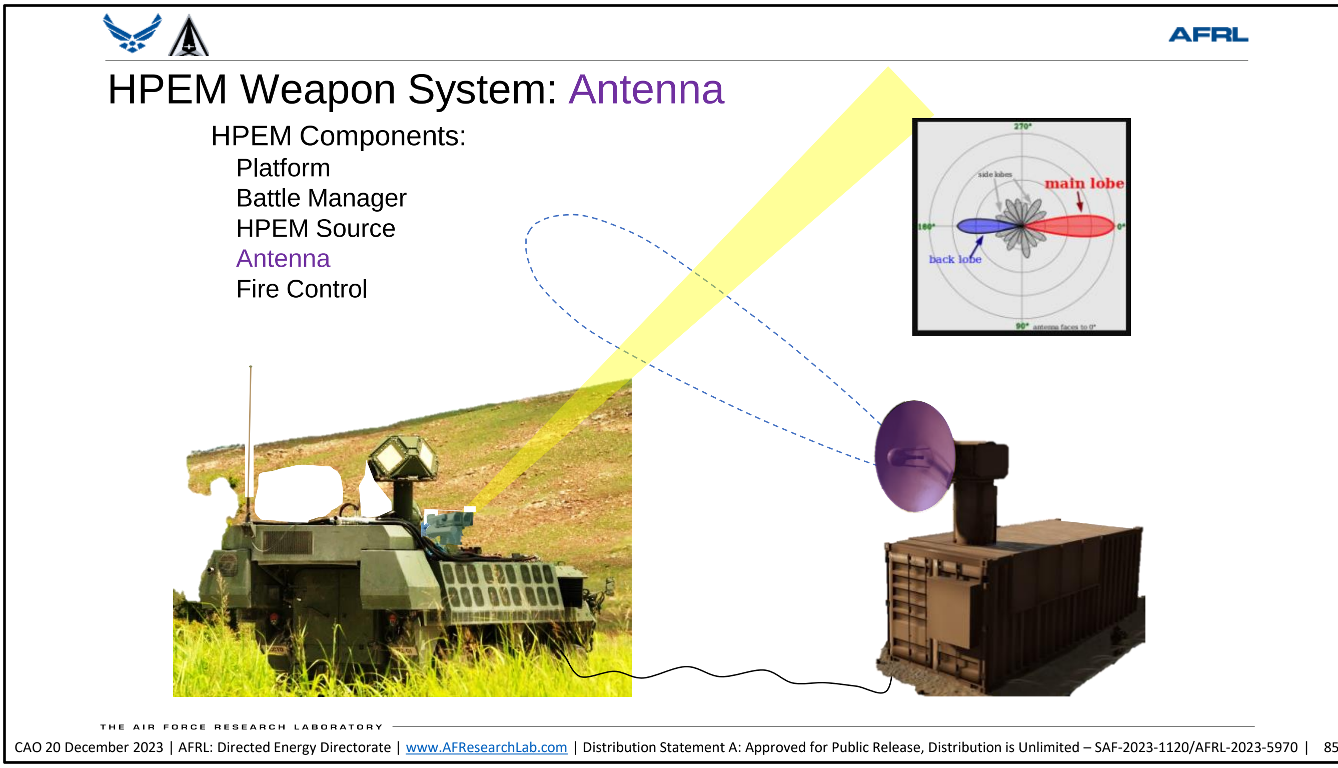
From BM information, the operator makes the final determination to engage in the battle based on track quality. BM also maintains the tracks for the operator to perform Battle Damage Assessment (BDA). The operator reports back the status of the engagement to the BM.



The HPEM source defines the HPEM wavelength, frequency and initial power. These parameters determine the transmission through the atmosphere and the power density that will be deposited on the target. The source also determines the efficiency of the system and the thermal management required to operate the system. HPEM systems all have vacuum systems to improve the efficiency to the antenna.

There are several types of HPEM sources. The one shown in the figure is a magnetron.

HPEM sources can be continuous or pulsed. For example, counter-personnel systems are often continuous. Currently counter electronics and counter UAS system are pulsed.



The antenna controls, directs and tracks the beam to the threats using EO/IR sensors. The transmit antenna is located on the HPEM platform. The EO/IR sensors are externally located to avoid the intensity of the high-power energy near the HPEM source. The beam is directed from the source through the transmit antenna and in the direction of the targeted threat track. The antenna is "slaved" to the EO/IR sensor so both the antenna and EO/IR sensor are pointing in the same direction. The operator uses the EO/IR sensor to identify, select and engage individual threat tracks.

The direction of the HPEM beam is based on the antenna radiation pattern. The main lobe contains the highest power. Side lobes are where residual energy radiate and can even be 180 degrees from the main lobe, i.e., back lobe. In between the lobes are regions of near zero energy called nulls. Sensors are typically placed outside of the range of the side and back lobes.

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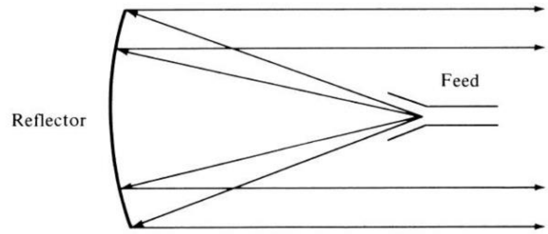
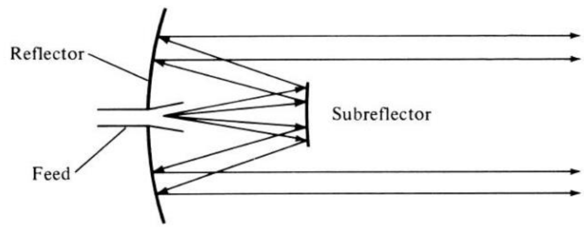
Antenna Designs



(a) Parabolic reflector with front feed



(b) Parabolic reflector with Cassegrain feed

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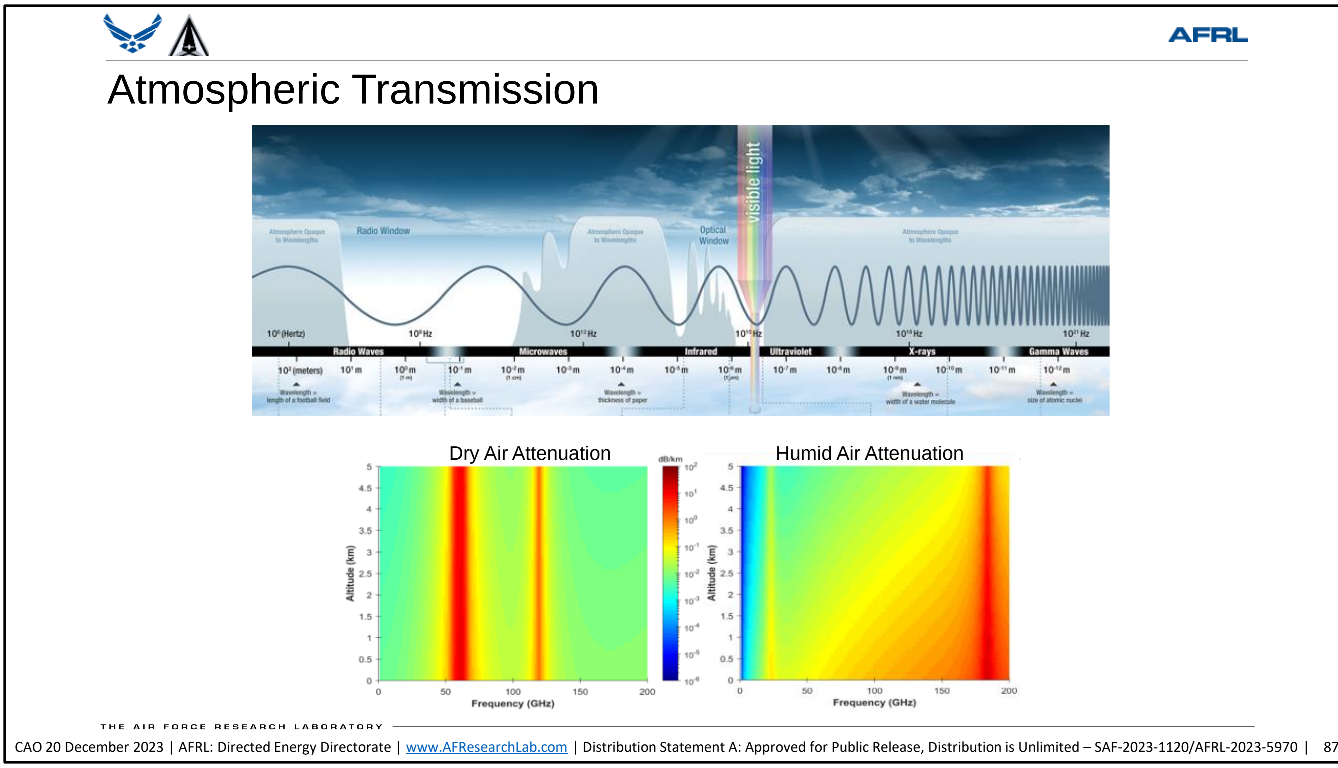
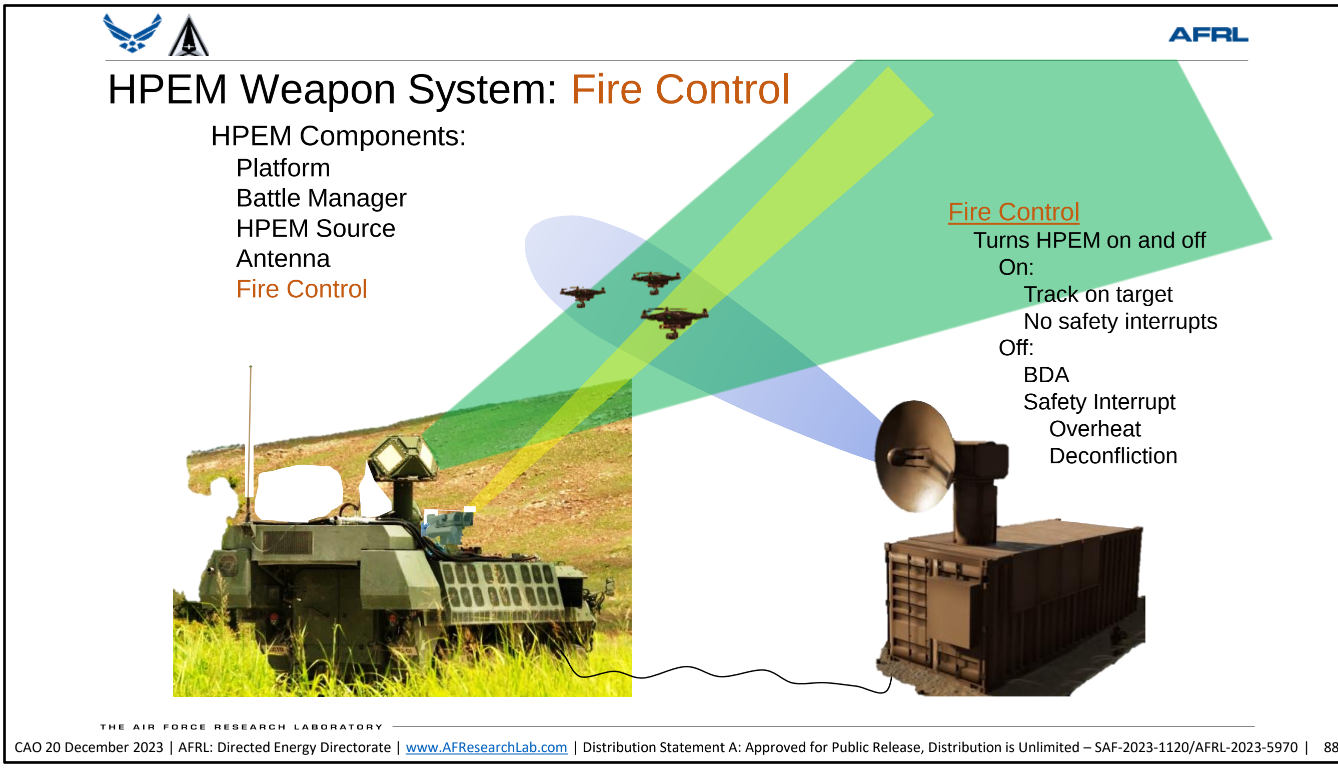
HPEM weapons use antenna designs that focus the electromagnetic energy and increase the power. The amount of increase is called gain. For example, a 100W output system using a 100:1 gain design will produce an Effective Radiated Power (ERP) of 10,000W. THOR uses a Parabolic Dish antenna. ADS has the Flat Parabolic Surface (FLAPS™) antenna.



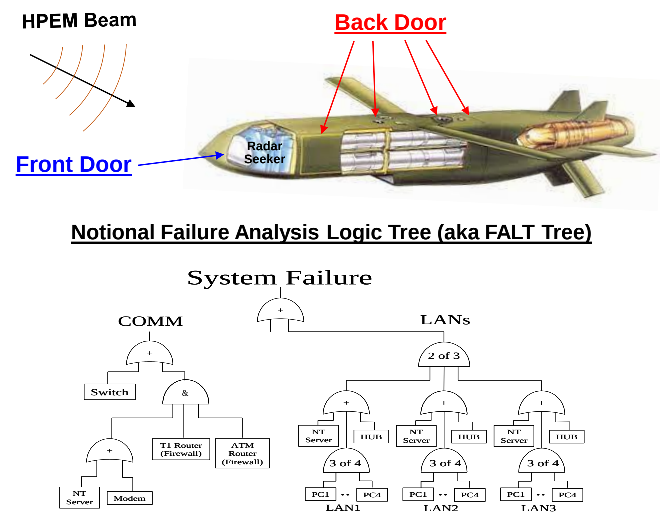
HPEM weapons are subject to the impact of the atmosphere. Certain frequencies will not transmit through the atmosphere. The top plot overlays a typical atmospheric transmission curve with different wavelengths in the electromagnetic spectrum. The peaks correspond to frequencies with good transmissivity and valleys where those frequencies transmit very little energy through the atmosphere.

Humidity also affects the intensity of the HPEM beam as shown in the lower images.



The Fire Control is the on/off controller. It can be automated or controlled by the operator. The fire control system ensures the HPEM weapon is in a fire-ready status, i.e., track established on target, antenna pointed at target and no safety interlock. The fire control operator also has deconfliction responsibilities to ensure no friendly electronics would be affected by the firing of the weapon. Once all safety conditions are met, fire control operator can fire the system until some HPEM effect is achieved.

HPEM Effects and Entries



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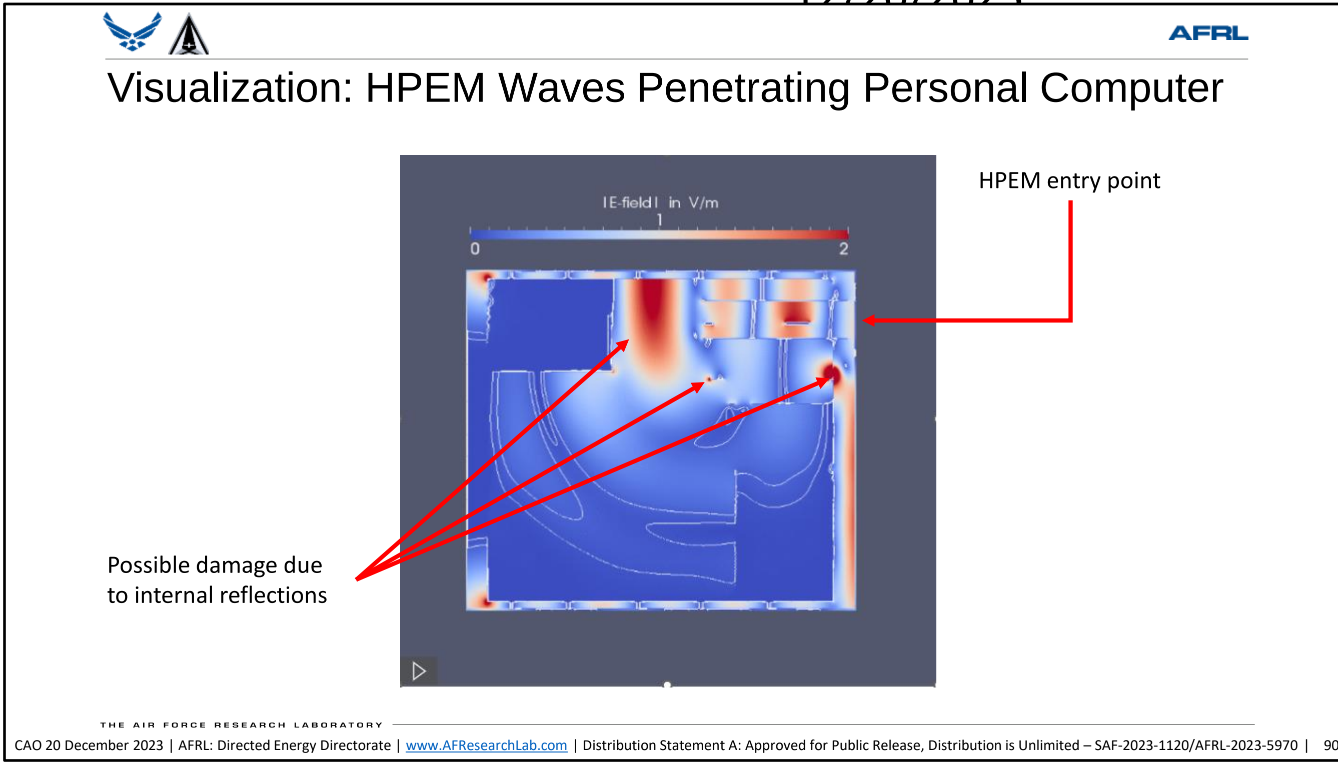
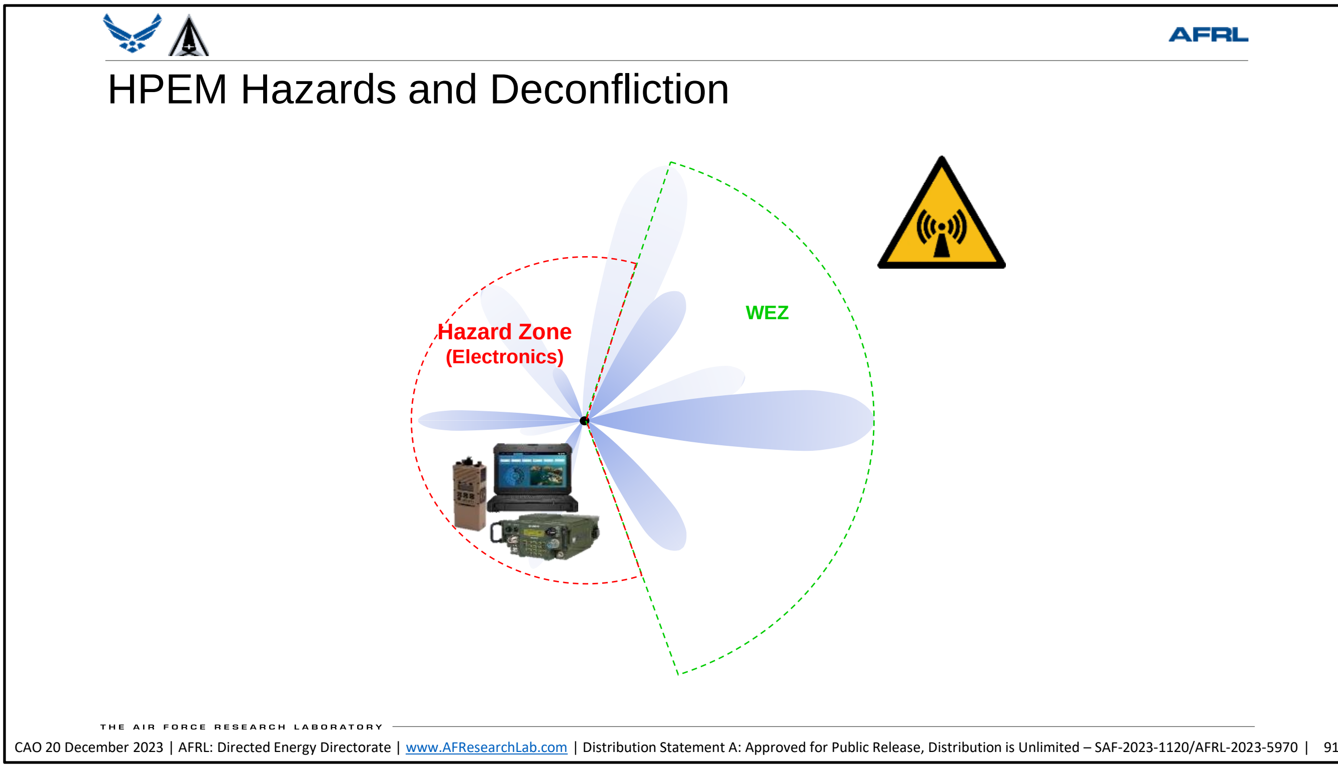
HPEM effects range from temporary disruption to component damage. Disruptions are less than lethal effects and may take the form of a computer reboot or physical discomfort. Damage may be a degraded capability or complete failure of components.

Access to HPEM vulnerable components are called front door and back door. Front door refers to entry that target the receiver antenna at a specific frequency. If the front door entry has been hardened, i.e., additional protections are in place to make the component less vulnerable, more energy will be required to overcome the hardening method. Back door refers to access not at the antenna frequency or via an unintended path such as all openings or cables. These entries are seldom protected and provide an opportunity to couple energy into the system.

The desired effect on the threat platform may require more than one component to be affected. Failure Analysis Logic Trees – or "FALT Trees" is a representation of the total failure mechanism based multiple component level failures.



This is a simulation of radio frequency (RF) propagating into a personal computer. The arrows point to locations that might be damaged as the video progresses.



This chart can be viewed in slide show mode to activate the animation of the antenna lobes.

The intended region of engagement for HPEM is within it's Weapon Engagement Zone (WEZ). The WEZ is assigned for the antenna main beam where the primary energy is directed. Procedures are in place for friendly entities to avoid entering the HPEM WEZ. However, the side and back lobes of the antenna can create hazard zones of lesser power. There are three common hazard zones:

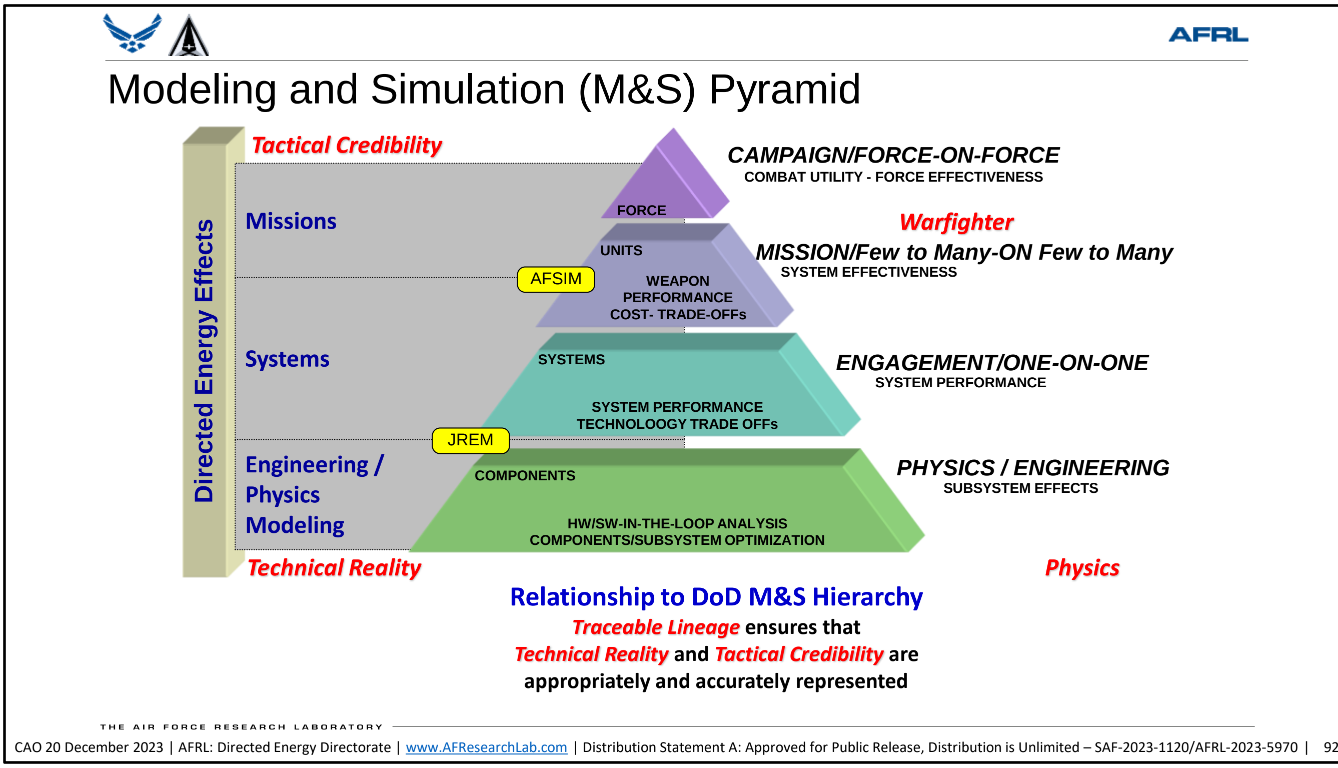
HERO: Hazards of Electronic Radiation to 'Ordinance'

HERP: Hazards of Electronic Radiation to 'Personnel'

HERF: Hazards of Electronic Radiation to 'Fuel'

These hazard zones are also to be avoided by friendly entities.

The HPEM computer components would be placed in a location not susceptible to any energy from antenna lobes.



The Air Force Research Laboratory (AFRL) M&S approach is hierarchical. At the base are physics & engineering methods for research, modeling and analysis. The physics/engineering constructs move into Engagement Level M&S where detailed analysis of one-on-one (1x1) engagement phenomenology is studies. The results from the Engagement phase are fed into a Mission Level M&S. At the Mission level, systems are modeled with M-on-N scenarios (MxN). They are played out to answer specific weapon system effectiveness questions. Results from the Mission level can then be moved up to Campaign Level M&S where high level force effectiveness questions are addressed.

Joint Radio frequency Effectiveness Model (JREM) is an engagement-level simulation for airborne HPEM against ground target.

AFRL/RDMW develops and manages HPEM plugin developed for Advanced Framework for Simulation, Integration and Modeling (AFSIM), the mission level modeling tool.

Resources

- HPEM
  - *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition*, Robert E. Ball, American Institute of Aeronautics and Astronautics, Inc., 2003
  - www.deps.org: Directed Energy Professional Society (DEPS) short courses

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Next Training Course

- ☑ Directed Energy Weapon: Introduction (DEW: Intro)
- ☐ Directed Energy Weapon: High Energy Laser (DEW: HEL)
- ☑ Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM)

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Once the Directed Energy Weapons: High Power Electromagnetic (DEW: HPEM) course has been completed, the AFRL/RDMW Directed Energy Weapons: High Energy Laser (DEW: HEL) course is recommended if not already completed.

Acronyms

Acronym	Definition
ADS	Active Denial System
AFRL	Air Force Research Laboratory
AFSIM	Advanced Framework for Simulation, Integration and Modeling
AGM	Air-to-Ground missile
BDA	Battle Damage Assessment
BM	Battle Manager
C2	Command and Control
CHAMP	Counter-High Power Microwave Advanced Missile Project
cm	centimeter(s)
C-UAS	Counter-Unmanned Aerial System
dB	decibels
DE	Directed Energy
DEW	Directed Energy Weapon
EM	Electromagnetic
EO/IR	Electrooptical/Infrared
ERP	Effective Radiated Power
FALT	Failure Analysis Logic Trees
FLAPS™	Flat Parabolic Surface™
ft	feet
HEL	High Energy Laser
HERF	Hazards Of Electronic Radiation to Fuel
HERO	Hazards Of Electronic Radiation to Ordinance

Acronym	Definition
HERP	Hazards Of Electronic Radiation to Personnel
HPEM	High Power Electromagnetic
HPM	High Power Microwave
IED	Improvised Explosive Device
JREM	Joint Radio frequency Effectiveness Model
kts	knots
lb	pounds
M&S	Modeling and Simulation
MOOTW	Military Operations other than War
P_{avg}	Average Power
P_D	Power Density
P_{pk}	Peak Power
PSO	Peace Support Operations
P_t	Transmitted Power
RDMW	Wargaming and Simulations Branch
RF	Radio Frequency
SS-ADT	Solid-State Active Denial Technology
THOR	Tactical High Power Operational Responder
UAS	Unmanned Aerial System
USSF	United States Space Force
W	Watt
WEZ	Weapon Engagement Zone

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