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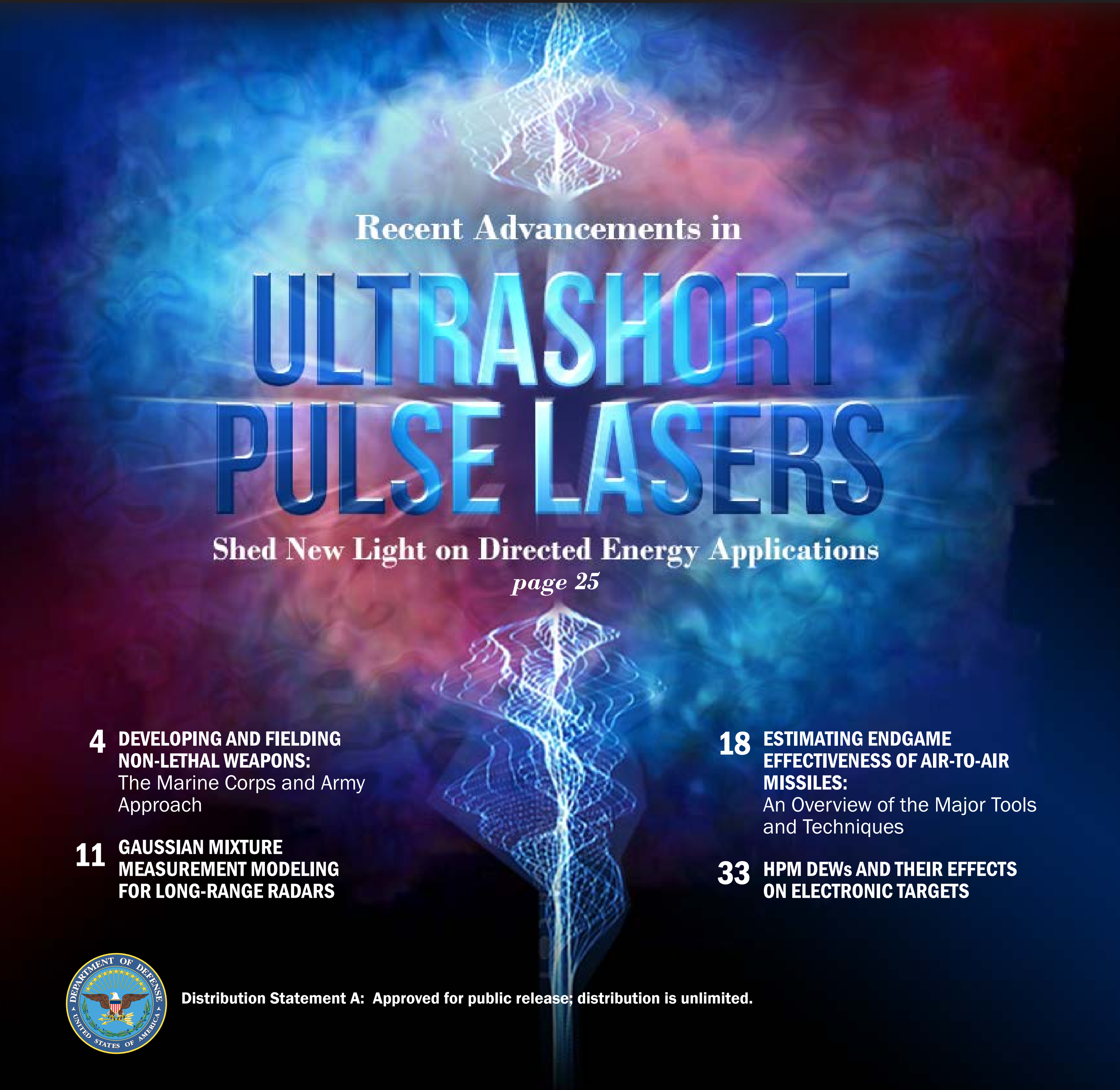

Recent Advancements in ULTRASHORT PULSE LASERS Shed New Light on Directed Energy Applications

page 25

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On the Cover:
Computer-enhanced image of ultrashort pulse laser simulation.

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MESSAGE FROM THE EDITOR

BRIAN BENESCH

As a relatively new member of the DSIAC team, I have been struck by a prominent theme throughout the organization—its focus on being a catalyst for collaboration, to foster a cooperative network in the defense systems community. The articles in this summer issue demonstrate DSIAC's unique value in being the DoD's hub for defense system information and analysis.

It is in the vein of collaboration that DSIAC is proud to present the feature article on ultrashort pulse laser (USPL) research, representing a truly collaborative research effort. Like many DoD research topics, USPL research faces limited funding and resources. So scientists and engineers across different DoD and academic laboratories have formed a community to jointly enhance research efforts. USPLs offer a unique benefit compared to traditional speed-of-light laser technologies due to USPLs' short pulses and the ability to achieve high energy with low loss over a distance. The article, which is jointly authored by researchers with the Air Force, Army, and Navy, includes references to research contributions from numerous U.S. universities that participate in the collaborative USPL research efforts. This article demonstrates how joining forces to share information among various organizations from the DoD and academia can greatly enrich scientific research.

Continuing with the theme of collaboration and speed-of-light technologies is our article on high-power microwave (HPM) directed energy weapons (DEWs). This article educates the reader on HPM DEWs as an alternative to laser-based DEWs. The fundamental principles of HPM DEWs, along with references to various Joint DoD applications, are described. One such application is in the field of non-lethal weapons (NLWs), which nicely complements our article on developing and fielding NLWs.

The NLW article once again exhibits the power of collaboration, a primary DSIAC focus. The article describes the Joint (DoD-wide), Army, and Marine programs aimed at developing and fielding NLWs. The fundamentals of NLWs are explained, followed by a survey of the current and future NLW programs. These programs include technologies such as the aforementioned DEWs, as well as acoustics, electricity, flashbangs, kinetics, and more. As with USPL research, NLW developers must work with limited resources; so joint programs are imperative to enhancing NLW technologies.

Relative to collaboration, DSIAC maintains ongoing partnerships with universities to provide an extended network of experts for the defense system community. One such academic partner is the Georgia Tech Research Institute, which has provided an article on modeling long-range radars. Long-range radar systems must be precise. Unfortunately, there are instances where data are degraded when converting the measurements to the systems that need the data. This article discusses one modeling methodology to address the problem. DoD technologists can learn much from this academic research being conducted to enable greater radar precision.

Finally, our article on estimating endgame effectiveness of air-to-air missiles highlights DSIAC's continued interest in promoting an awareness and sharing of tools for the benefit of the greater DoD. This article presents the methodology behind widely used DoD vulnerability and lethality models (many of which are distributed by DSIAC) to show how air-to-air missiles are evaluated. Significant advancements in computational capabilities have given way to comparable advancements in tools for evaluating air-to-air missiles. As these tools continue to evolve, it is essential that the defense community maintain an understanding of the available tools described.

In summary, this journal issue captures DSIAC's core value of collaboration within the defense community. The five articles demonstrate the nature of collaboration encouraged by DSIAC as well as the breadth of DSIAC's network of experts. All of this is done while communicating quality technical information, thus continuing to promote a culture of increased education and awareness. ■

DEVELOPING AND FIELDING NON-LETHAL WEAPONS:

THE MARINE CORPS AND ARMY APPROACH

By Nathan Rush and Ross Miller

Introduction

Changes in modern warfare have included a remarkable shift in the international security mosaic. While threats from traditional state actors still exist, threats from nonstate actors have emerged in ways that have added to the complexity of national security challenges. As the world's population continues to migrate to urban areas, adversaries are increasingly adapting their tactics to conduct operations in and among noncombatant populations to counter U.S. forces' abilities to maneuver and engage with lethal capabilities to defeat them. Therefore, developing capabilities that enable our forces to achieve our campaign objectives, while simultaneously minimizing the adverse effects of military operations on civil populations, is essential to our success as a military. Our capabilities must be flexible, effective, affordable, and robust enough to allow us to effectively and efficiently organize, train, and equip our force for a wide range of operational contingencies—hence the need for non-lethal weapons (NLW).

This article outlines the U.S. Marine Corps and U.S. Army approach to developing and fielding NLWs and comprises information provided by the Joint Non-Lethal Weapons Program (JNLWP) Support Officers for those organizations.

(Source: U.S. Marine Corps photo by Lance Cpl. Victoria Ross)

WHAT ARE NLWs?

As defined in DoD Directive 3000.03E, "DoD Executive Agent for NLW and NLW Policy," NLWs are "weapons, devices and munitions that are explicitly designed and primarily employed to incapacitate targeted personnel or materiel immediately, while minimizing fatalities, permanent injury to personnel, and undesired damage to property in the targeted area or environment. NLWs are intended to have reversible effects on personnel or materiel [1]." NLW capabilities are further categorized into counter-personnel (CP) or counter-materiel (CM) core capability areas.

Note that the definition specifically states weapons that are "explicitly designed," which precludes lethal weapons used in a "non-lethal manner." The definition also uses the term "immediately" to scope out more deliberate non-lethal means, such as information or psychological operations. Although there may be some overlap, NLWs generally do not include "electronic warfare."

The "reversible effects" of NLW refer to the ability to return a target to its pre-engagement functionality. Characterization of the human effects of NLW use must be conducted during the materiel development process to assess the likelihood of achieving the desired effect(s) and identify potential risk of significant injury (RSI) for CP systems, as well as the RSI for collateral damage to humans from CM systems [2]. RSI is a metric intended to evaluate the risk of a NLW causing significant or permanent injury. It should be noted that while NLWs are defined with the design of "minimizing injuries," they are not required to have a zero probability of producing fatalities or permanent injuries.

Policy

The previously mentioned DoD Directive 3000.03E establishes policy and assigns responsibilities for the management of the DoD NLW program. Policy directs that NLW doctrine and concepts of operation be designed to reinforce deterrence and expand the range of options available to commanders, enhancing the ability of U.S. forces to accomplish the following objectives:

- Deter, discourage, delay, or prevent hostile actions.
- De-escalate situations to preclude lethal force.
- Adapt and tailor options to the operational environment.
- Better protect the force.

That said, NLWs shall not limit a commander's inherent authority and obligation to use all necessary means available and to take appropriate actions in self-defense. In all cases, the United States retains the option for immediate use of lethal weapons, when appropriate, consistent with international law.

BACKGROUND AND ORGANIZATION

The JNLWP

The JNLWP was established to "stimulate and coordinate NLW requirements" and today is focused on fielding fully supported and integrated systems designed to give commanders non-lethal options. The Commandant of the Marine Corps serves as Executive Agent (EA). To support the EA, the Joint Non-Lethal Weapons Directorate (JNLWD) was established to manage the day-to-day activities of the JNLWP and oversee the joint research and development funding lines dedicated to developing the DoD's suite of NLWs. The U.S. Marine Corps, U.S Army, U.S. Navy, U.S. Air Force, U.S. Coast Guard, and U.S. Special Operations Command are responsible for NLW procurement and sustainment.

Marine Corps NLW Program

Combat Development & Integration (CD&I) integrates Marine Corps non-lethal concepts and requirements-based warfighting capabilities, including doctrine, organization, training, materiel, leadership and education, personnel, and facilities, to ensure the Marine Corps is properly organized, trained, and equipped with NLW capabilities. NLW systems that supplement lethal systems will provide increased force application options to meet the Marine Air Ground Task Force's (MAGTF) dynamic requirements for future operations across the full range of military operations. The Marine Corps Systems Command (MARCORSYSCOM) and Marine Corps Operational Test and Evaluation Agency (MCOTEA) execute the development, acquisition, and operational test and evaluation requirements for fielding NLW capabilities. The endstate is to produce Marines trained and equipped to seamlessly integrate non-lethal capabilities in operations in which

> While NLWs are defined with the design of "minimizing injuries," they are not required to have a zero probability of producing fatalities or permanent injuries.

civilian casualties and collateral damage are limited.

Army NLW Program

The Army's NLW Program develops NLW capabilities, training materials, and support for the procurement and fielding of NLW systems. To support these tasks, the Army established the Army Non-lethal Scalable Effects Center (ANSEC) at Fort Leonard Wood, Missouri. This organization is under the Commander, Maneuver Support Center of Excellence, and Army proponent for NLWs. The ANSEC Chief reports to the Assistant Commandant, U.S. Army Military Police School. The materiel development of NLWs is completed by the Armament Research, Development and Engineering Center and either the Program Executive Office (PEO) for Ammunition or PEO Soldier at Picatinny Arsenal, New Jersey. Their mission is to develop and field NLWs. The entire process is overseen by the Army Capabilities Integration Center (ARCIC) at Fort Eustis, Virginia. In ARCIC, the Director, Capabilities Development Directorate, reviews all NLW requirements documents and forwards them to the Headquarters, Department of the Army (HQDA), Deputy Chief of Staff (DCS) G-8 for approval and resourcing.

REQUIREMENTS GENERATION

JNLWP

The JNLWP produced a Capabilities Based Assessment (CBA) and two Initial Capability Documents (ICD) to assist in the preparation of Joint and Service NLW requirements. The capability area tasks, shown in Table 1, resulted from the 2008 Joint Non-Lethal Effects (JNLE) CBA. The associated CP and CM ICDs are dated April 2009. The capability area tasks provide a broad foundation for the development of Joint and Service-unique NLW requirements and science and technology objectives.

Marine Corps

Formal requirements for NL capabilities have been identified and validated at the joint and Marine Corps service level. The origins of requirements are diverse. Requirements can be prompted by Combatant Command Integrated Priority Lists, lessons learned, need statements submitted by the operating forces, joint requirements, and other sources. These sources, along with joint and Marine Corps CBAs focusing specifically on non-lethal effects lead to the development and validation of formalized requirements. In addition, the annual Marine CBA process translates future-focused Service strategic guidance into an enterprise-wide plan by specifying a prioritization of desired future capabilities based on operational priorities, guidance, planning documents, critical capability gaps, and desired future direction for MAGTF Combat Development. During this annual Marine CBA process NL capability gaps and solutions are identified and prioritized against other Marine Corps enterprise gaps and solutions.

Army

The Training and Doctrine Command's ARCIC performs a Capabilities Needs Analysis (CNA) to support current and future capabilities development efforts. The CNA uses DoD and Army Strategic guidance and approved Army concepts to identify and order required capabilities and associated tasks, conditions, and standards. It identifies and prioritizes Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities and Policy (DOTMPLF-P) fielded and programmed solutions. It also assesses operational risk to identify and prioritize capability gaps and identifies gap solution strategies and developmental priorities. The assessment produces

Table 1: CP and CM Tasks

Counter-Personnel (CP) Tasks	Counter-Materiel (CM) Tasks
• Deny access into/out of an area to individuals (open/confined) (single/few/many) • Disable individuals (open/confined) (single/few/many) • Move individuals through an area (open/confined) (single/few/many) • Suppress individuals (open/confined) (single/few/many)	• Stop small vehicles • Stop medium vehicles • Stop large vehicles • Disable vehicle/many vehicles • Stop small vessels • Stop large vessels • Disable vessel/many vessels • Stop fixed-wing aircraft on the ground • Divert aircraft in the air • Deny access to facility (i.e., block points of entry)

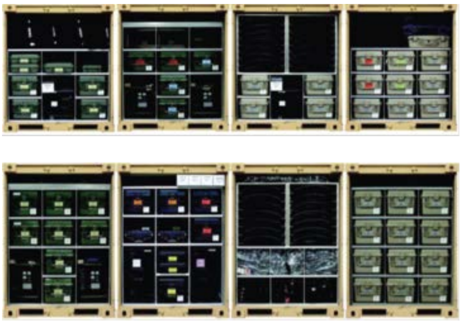
the Army's single list of prioritized programmed DOTMLPF-P solutions and prioritized gaps, informing Army Program Objective Memorandum (POM) resourcing and long-range procurement requirements through the Strategic Portfolio Assessment Review (SPAR).

The SPAR, is managed by the HQDA, DCS G-8 resource managers, reviewing Army capabilities by portfolio over a 30-year period. It provides portfolio priorities and cross-portfolio options aligning efforts for soldiers to receive the right capabilities. The focus is on decisions affecting both the upcoming POM build and mid-range portfolio strategies, and long-term strategic equipping needs informing science and technology investments.

CURRENT AND FUTURE PROGRAMS

The following program summaries provide examples of current and future Marine Corps and Army NLW programs.

Marine Corps - Current



Courtesy: JNLWD

The Escalation of Force-Mission Module (EoF-MM) consists of multi-functional NLW systems and force protection equipment needed during escalation of force situations. Each EoF-MM is designed by capability module for expedited deployment and consists of 10 modules, providing commanders with an improved ability to tailor and scale responses to fit various missions, such as crowd control or vehicle check points. The complete EoF-MM is contained in four quadcons and assigned primarily to Marine Expeditionary Units (MEU), Marine Expeditionary Brigades (MEB), and Law Enforcement Battalions.

Courtesy: JNLWD

The Ocular Interruption (OI) device provides a non-lethal capability to safely engage individuals with a visible laser light that delivers a glare effect to warn and/or suppress targeted personnel. OI will replace legacy dazzling lasers in the Marine Corps inventory (LA-9/P and the 532P-M GLARE MOUT). Using the latest technology, OI integrates a range finder and incorporates engineering controls to regulate energy levels below maximum permissible exposure limits.

Marine Corps - Future

Courtesy: JNLWD

The Indirect Fire Munition (IDFM) will provide significant improvements in range, duration of effects, area coverage, and non-lethal effects when compared to current NLW systems. IDFM is an integrated, non-lethal 81-mm mortar munition designed to suppress combatants/noncompliant personnel via auditory and visual degradation at extended ranges. IDFM will deliver a payload consisting of multiple flashbangs, with each individual flashbang producing light, sound, and pressure outputs that will meet or exceed the output of currently fielded flashbangs. At the appropriate distance above the target, the cartridge's nose and tail sections separate, releasing the flashbangs, which disperse and detonate near simultaneously in the target area. A two-parachute design minimizes the falling debris hazard from the nose and tail sections. IDFM will support non-lethal missions to warn, move, distract, deny area, and suppress targeted personnel. Fielding is planned for FY21.

Courtesy: JNLWD

The Disable Point Target (DPT) will provide a non-lethal, untethered, extended-range, precision-point target-disabling effect in EoF situations. Deployable from a safe standoff distance and capable of rapidly re-engaging targets, DPT is uniquely suited for employment in support of urban patrolling, crowd control, entry control point, and perimeter security missions to minimize injury to noncombatants while reducing the risk of injury to operational forces. The analysis of alternatives recommended pursuing electro-muscular incapacitation (EMI) technology to effectively deliver the stimulus, while minimizing blunt impact and the risk of significant injury. The initiative was placed in a programmatic pause in 2014 due to a lack of required funding and will be reinitiated when appropriate funding levels can be resourced.

Army - Current

The Acoustic Hailing Device (AHD) is a long-range communication system used to clearly broadcast critical information, instructions, and warnings at stand-off distances to determine intent and de-escalate potentially dangerous situations. AHD can penetrate walls, windows, and vehicles with directed sound waves. When used in conjunction with other NL response options, the AHD is a solution to enable Warfighters the capability to delay and prevent unauthorized access to protected assets.

Source: TASER Self-Defense

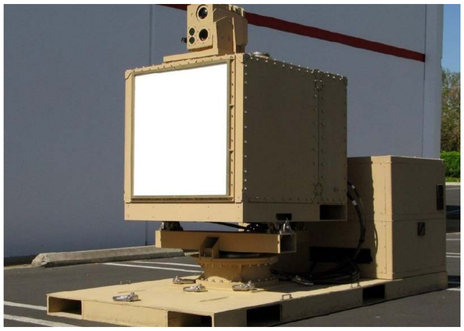
The Launched Electrode Stun Device (LESD) is an electronic control weapon commonly known as the TASER. The LESD fires a two-probe cartridge, providing Warfighters a capability to briefly incapacitate targeted individuals. The LESD uses a measured dose of low amperage electricity to temporarily disable an attacker. The devices gives Warfighters the capability to maintain local security and rule of law.

The Non-Lethal Capability Set (NLCS) is a packaging configuration based on mission modules. NLCS items are designed to temporarily distract, deter, repel, and/or incapacitate personnel/materiel while minimizing fatalities, permanent injury to personnel, and undesired damage to property and environment. The complete NLCS is contained in 10 quadcons and assigned to brigade-size units. The NLCS is a solution enabling Warfighters to execute area, base, route, convoy, and facilities security, as well as host nation police training.

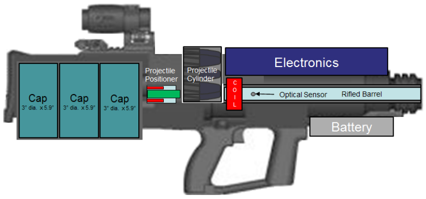
Non-lethal munitions are currently available through normal supply channels. These capabilities deliver kinetic non-lethal force, each with a specifically intended effect. Hand-emplaced and hand-tossed munitions include flash bang and sting-ball grenades and the modular crowd control munition. Rounds for 12-gauge shotguns and 40-mm guns are available for point or area targets, delivering blunt force effects. In addition, vehicle-mounted 66-mm rounds provide blunt force, irritation, or flash bang indirect fire effects.

Army - Future

The Single Net Solution and Remote Deployment Device (SNS/RDD) is a wheeled vehicle-stopping system. The SNS/RDD allows Warfighters to remotely deploy a vehicle-stopping capture device in the path of targeted vehicles. Captured vehicles become temporarily inoperable. SNS/RDD is a solution to give Warfighters the capability to execute vehicle stopping for protected assets, facilities, and bases.



Solid State Active Denial Technology (SS-ADT) is a CP, directed-energy system that projects a focused beam of millimeter waves at 95 GHz to induce an intolerable heating sensation just below the surface of the skin. This non-lethal effect produces a repelling effect against an individual or group with reversible effects, providing the ability to stop, suppress, and repel an advancing adversary as an alternative to lethal force.



The Individual Non-lethal System (INS) is a CP weapon for the dismounted Warfighter and is intended to replace the current suite of NL munitions. The INS is designed to provide closer minimum-safe and farther maximum-effective engagement ranges than current NL munitions. The expanded operating envelope will improve response times to potential threats, increasing force protection and reducing the potential for user error.

NLW STRATEGY FOR THE FUTURE

Marine Corps

The Marine Corps Operation Concept (MOC) was published, in part, to shape Marine Corps efforts in designing and developing the capabilities and capacities of the future force. The MOC describes in broad terms how the Marine Corps will operate and fight and recognizes that operations in urban areas are the most likely to occur. The MOC further identifies these operational environments as complex terrain when considering the additional human aspects encountered. To improve the Marine Corps' ability to operate in this environment, the MOC specifically identifies the need to continue to explore NLWs and munitions specifically designed to disable, inhibit, or degrade personnel or materiel while minimizing civilian casualties and collateral damage. The Marine Corps will continue to analyze requirements and work within the Service and the JNLWP to field next-generation, cost-efficient non-lethal capabilities.

Army

The U.S. Army Non-Lethal Weapons Strategy is a guiding document for the Army's future NLW capabilities. It directs improved capability by moving from blunt trauma to directed-energy NLWs. Directed-energy weapons, such as the Solid State Active Denial Technology and Radio Frequency Vehicle Stoppers, provide combat-effective systems while meeting RSI requirements. The strategy's goal is to promote unity of effort among diverse stakeholders, providing them with a holistic approach to NLW capabilities, setting the foundation for force modernization of NLW capabilities across the DOTMLPF-P domains. To accomplish this goal, there is an emphasis on developing and maintaining strategic partnerships with policy-makers, other Services, industry, and academia involved in the non-lethal scalable disciplines to ensure the Army stays abreast of advancements and applications. Most importantly, these future systems must be lightweight, cost effective, and adaptable across the spectrum of combat operations.

> The SNS/RDD allows Warfighters to remotely deploy a vehicle-stopping capture device in the path of targeted vehicles.

Challenges

Not surprisingly, funding continues to be the primary challenge to fielding NLWs. A declining fiscal environment is based on several factors, ranging from the trend of reducing defense funding to the continued impacts of the Budget Control Act of 2011. The fiscal uncertainty of the last several years, coupled with the high demand on our operating forces, results in having to make efficient trades across the enterprise to gain capability and maintain a high state of readiness. This environment requires investments that deliver the highest priority capabilities to the Warfighter while accepting risk in other capability areas. In lean fiscal times, NLW initiatives typically struggle when competing against other higher priority programs.

Maturing technologies to address identified non-lethal capability gaps while meeting human effects RSI presents its own unique challenge. Commanders must understand what to expect when a capability is employed to decide how best to use it. NLW developers must identify the necessary amount of stimuli to achieve desired effects while remaining within the bounds of acceptable injury risk. Examining the trade space between effectiveness and acceptable risk can be extremely complex, typically leading to increased developmental cost or extended programmatic schedules and often hindering the decision to pursue capability development.

To achieve greater range and reduce RSI, progressing to directed energy NLW is necessary. However, with the use of directed energy comes new challenges. Policy and subsequent doctrine must be implemented to allow employment of this new capability. Policy-makers must have an understanding and willingness to implement changes that allow Service members to use directed-energy weapons as a viable non-lethal alternative.

CONCLUSION

Although significant challenges to the development and employment of NLW exist, changes in modern warfare continue to make this unique capability relevant on the future battlefield. Educating senior leaders will promote a better understanding of NLW capabilities, which in turn will garner greater support and translate into increased operational employment. Maintaining funding to develop next-generation capabilities that will reduce size and power consumption and increase effectiveness will improve operational utility. Finally, implementing consistent policy that encourages NLW use will free commanders to operationally employ NLW when appropriate. As the JNLWP moves forward, continued emphasis on these areas will make NLWs a common capability to U.S. forces. ■

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[1] U.S. Department of Defense. "DoD Executive Agent for Non-Lethal Weapons (NLW), and NLW Policy." DoD Directive 3000.03E, 25 April 2013.

[2] U.S. Department of Defense. "Non-Lethal Weapons (NLW) Human Effects Characterization." DoD Instruction 3200.19, 17 May 2012.

BIOGRAPHIES

NATHAN RUSH currently works for the SURVICE Engineering Company, serving as the Marine Corps Joint Non-Lethal Weapons Program Support Officer for the Force Protection Integration Division, Capabilities Development Directorate, Combat Development & Integration. He retired from the Marine Corps in 2016 after 22 years of service and has been working Marine Corps non-lethal weapons initiatives since 2012. Mr. Rush was a career logistics officer with operational and supporting establishment experience, highlighted by three combat tours in support of Operation Iraqi Freedom. He holds a B.A. in economics and business from the Virginia Military Institute and an M.M.S. (master of military studies) from the Marine Corps Command and Staff College.

ROSS MILLER currently works for the SURVICE Engineering Company and is the Army Joint Nonlethal Weapons Program Support Officer for the Army Capabilities Integration Center, a position he has held since 2006. He is a retired military police lieutenant colonel, having 40 years of experience in law enforcement and security for the Department of the Army and NASA. He earned a bachelor's degree in law enforcement from Eastern Kentucky University and a master of public administration degree from Georgia State University. Mr. Miller is a qualified DoD Law Enforcement Officer (retired), a Certified Protection Professional by the American Society for Industrial Security, and a Certified DoD Capability Developer.


U.S. Navy Photo

GAUSSIAN MIXTURE MEASUREMENT

MODELING FOR LONG-RANGE RADARS

By Ben Davis and Dale Blair

INTRODUCTION

Long-range radar systems designed to provide precise range measurements may, in certain cases, experience degraded tracking performance in range, which tends to negate the benefit of the designed sensor precision. The measurement uncertainty associated with long-range radar systems results in two major practical difficulties. First, when a system is tracking multiple targets closely spaced in a given region, the problem of assigning target measurements to existing tracks becomes more difficult, which may cause the radar to assign the wrong measurements to the wrong target and/or cause targets to be missed. Second, the estimation performance of the track filter employed by the radar processor may be degraded to the extent that the range reported by the filter is less accurate than the range reported by the raw measurements. In this case, the benefit of using a track filter is to a large extent negated.

The degraded tracking performance of long-range radar systems is due to the non-Gaussian nature of their measurement distribution when converted to Cartesian space. This distribution is often referred to as a "contact lens" or "banana" distribution due to its resemblance to these shapes in Cartesian space.

CURRENT METHODS OF ADDRESSING NON-GAUSSIAN MEASUREMENT DISTRIBUTIONS

In almost all real-world radar systems, measurements are performed in polar (two-dimensional) or spherical (three-dimensional) coordinates of range and angles (or angle sines). The transformations from these coordinate systems to the Cartesian coordinates in which target dynamics are described are nonlinear. Most radar-tracking algorithms make use of some form of the well-known Kalman filter algorithm, which guarantees optimal performance given linear state dynamics and measurement models.

> The degraded tracking performance of long-range radar systems is due to the non-Gaussian nature of their measurement distribution when converted to Cartesian space.

Popular modifications, such as the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF), may also be used to address real-world state dynamics and measurements with mild nonlinearities, resulting in reasonable (but suboptimal) performance. All of these methods rely on approximating the state and measurement uncertainties as Gaussian distributions with a known mean and covariance parameter, as the process of Bayesian updates for Gaussian distributions can be conveniently performed using closed-form equations rather than numerical integration.

In many cases, the nonlinear target dynamics can be effectively addressed by employing the linearization techniques of the EKF or UKF. However, under certain conditions, the measurement transformations become sufficiently nonlinear to the extent that a Gaussian distribution inadequately models the uncertainty region in Cartesian space.

In Lerro and Bar-Shalom [1], a metric known as "bias significance" was developed to quantify the curvature of a polar radar measurement for the two-dimensional problem. If the range and angle measurements are modeled by independent Gaussian uncertainties with means and variances $\bar{r}, \sigma_r^2$ and $\bar{\theta}, \sigma_\theta^2$, respectively, and the transformation from polar to Cartesian space is given by $x = r \sin\theta$ and $y = r\cos\theta$, then the bias significance (C_B) is given by

$$C_B = \frac{\bar{r}\sigma_\theta^2}{2\sigma_r}.$$

Empirical results from Lerro and Bar-Shalom [1] suggest that if $C_B < 0.2$, then a standard linearization may be used without significant error. For values exceeding this number, adjustments are required to remove bias in the distribution mean and inflate the covariance.

In addition to the difficulties with mean and covariance, when the bias significance is high, the distribution takes on a highly non-Gaussian shape, resembling a banana (or, in three dimensions, a contact lens), and more sophisticated techniques must be employed to represent the distribution accurately.

Figure 1 illustrates this situation. The left and right diagrams depict a two-dimensional transformed measurement distribution for values of $C_B = 0.1$ and $C_B = 1$, respectively, along with the distribution means and covariances. The covariances are plotted as ellipses over the 3-sigma region in each eigen-

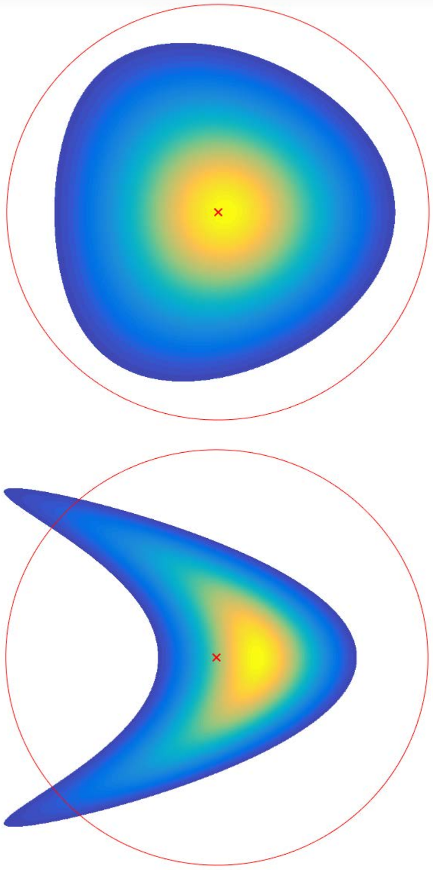

Figure 1: Measurement Distribution for C_B = 0.1 (top) and C_B = 1 (bottom).

axis. (For a Gaussian distribution, this represents the region containing approximately 99% of the distribution mass.) For the measurement depicted on the left, the region inside the covariance ellipse indeed contains most of the distribution, as it is approximately Gaussian. For the measurement indicated on the right, with $C_B = 1$, the covariance ellipse does not accurately represent the distribution limits, as the measurement distribution is highly non-Gaussian in Cartesian space. Portions of the distribution fall outside the ellipse, and large empty areas exist within the ellipse, presenting an opportunity for misassociation of measurements with other tracks or false alarms. Additionally, the inflated covariance in the range (horizontal) dimension results in degraded performance in range estimation.

Several potential solutions to this problem have been proposed by various authors. The Measurement Adaptive Covariance EKF (MACEKF) [2] is one method that evaluates the angle accuracy of the track and inflates the range variance of the measurements adaptively to preserve covariance consistency. This approach works well when the track has settled but sacrifices range performance early in the track due to covariance inflation.

The Consistency-based Gaussian Mixture Filter (CbGMF) [3] attempts to solve the problem by splitting the track into a Gaussian Mixture, where the individual Gaussian components of the mixture have a limited angular support in covariance, therefore reducing the effect of the nonlinearity. However, many track components are frequently needed to represent the track and guarantee consistency.

The Gaussian Mixture Measurement-Integrated Track Splitting (GMM-ITS) [4] filter instead splits the measurement into a Gaussian mixture to better represent the non-Gaussian nature of the distribution. However, the splitting method used does not preserve the covariance of the measurement distribution in range.

The work presented herein describes a new way to model radar measurements using a Gaussian mixture [5, 6]. Rather than using an ad hoc procedure for Gaussian mixture splitting, as performed in Tian et al. [3] and Zhang and Song [4], a Gaussian mixture that optimally models the measurement in an information-theoretic sense is generated. Furthermore, a method for intelligently choosing the number of mixture components that should be used to model a given measurement is provided. The proposed methodology will improve the performance of long-range radar tracking by allowing the full precision of the measurements to be captured.

GAUSSIAN MIXTURE DISTRIBUTION MODELS

A Gaussian mixture is defined as a weighted sum of Gaussian probability density functions (PDF). Let $N(x;\mu,\Sigma)$ denote a Gaussian PDF. Then a general Gaussian mixture is given by

$$q(x)=\sum_{k=1}^{N_G}\omega_k N(x;\mu_k,\Sigma_k),$$

where ω_k are the component weights, μ_k are the component means, and Σ_k are the component covariances. For a single-Gaussian model, the mean and covariance may be chosen to specify the distribution. On the other hand, a Gaussian mixture model provides a much larger number of parameters to be chosen.

One strategy of matching a Gaussian mixture to an arbitrary PDF is to attempt to match higher-order moments, as was done by Pearson [7], but the closed-form solutions associated with this approach quickly become unmanageable. In Tian et al. [3] and Zhang and Song [4], the strategy is to reduce the degrees of freedom by artificially restricting the covariances of the components to be equal, positioning the component means at equal intervals around the distribution mean, and then choosing the weights based on the likelihood of the means under the original distribution.

Our approach to choosing the distribution parameters is to attempt to optimize the distance between the mixture and the true distribution in an information-theoretic sense. The "distance" to be minimized is known as the Kullback-Leibler (KL) divergence, defined as

$$D_{KL}\left(p\|q\right) = \int p\left(x\right)\frac{\ln p\left(x\right)}{\ln q\left(x\right)}dx\,,$$

where $p(x)$ is the true distribution and $q(x)$ is the model distribution. This integral is essentially the expected value of the log likelihood ratio of the true distribution to the model distribution, with expectation taken over the true distribution.

In a practical sense, KL divergence describes the ease with which two distributions may be distinguished by log likelihood testing. If the KL divergence is low, then differences between them may only be discerned by examining the log likelihood evaluated over a large number of samples.

For discrimination applications, it is usually desired to maximize KL divergence between discrimination class distributions to more easily distinguish them from each other by log likelihood testing. However, in our application, the distributions should be as similar as possible so that when the measurement likelihood is used to update the PDF of the state, it provides a good representation of the true likelihood function. Therefore, to provide a "good" match of the Gaussian mixture model distribution $q(x)$ to the true measurement $p(x)$, the number of Gaussians N_G and the parameters $\omega_k, \mu_k, \Sigma_k$ should be chosen such that KL divergence is limited.

A single-Gaussian model of a polar radar measurement converted to Cartesian coordinates matched in mean and covariance to the true distribution has KL divergence $D_{KL}\left(p\|q\right) = \frac{1}{2}\ln\left(1+2C_B^2\right)$. This is the minimum KL divergence that may be achieved by a single-Gaussian model. This equation provides a direct relationship between bias significance and KL divergence.

> As the popularity of high-range-resolution, long-range radars continues to increase, the tracking difficulties associated with these systems continues to be a problem for operators, designers, analysts, and other practitioners dependent on these types of radar results.

NUMERICAL OPTIMIZATION OF DISTRIBUTION PARAMETERS

The KL divergence integral for the Gaussian mixture optimization involves the log of a sum that is difficult to analyze in closed form. Therefore, numerical optimization methods must be employed to choose the parameters. Given a set of samples of the true measurement distribution $p(x)$, the Expectation Maximization (EM) algorithm [8] can be applied to estimate a set of parameters, which minimizes KL divergence between the mixture and the distribution samples.

If a sufficiently large sample size is used and/or Monte-Carlo runs of the process are performed, an excellent estimate may be obtained of the optimal parameters needed to model the measurement distribution with a mixture of a given size. Additionally, the KL divergence achieved by the mixture approximation is provided by the final output of the EM algorithm.

This process generates a mixture model for a measurement with a given mean range and angle and their associated measurement variances. However, without some transformation of the results, this computationally intensive fitting process would have to be run for each distinct set of measurement input parameters, or equivalently a large (four-dimensional) lookup table of values stored for each mixture size desired.

A recent Georgia Tech Research Institute (GTRI) discovery makes this method practical: ***For an EM mixture parameter fit of given size N_G with a fixed bias significance C_B, regardless of individual parameters, the final KL divergence obtained is approximately invariant.*** (This approximation holds effectively for $\sigma_\theta << 1$ rad.) Additionally, the component weights ω_k produced by the solution process are also the same. This suggests that the means μ_k and covariances Σ_k may also be transformed in such a way that the results are the same if the bias significance is held constant. The KL divergence achieved by these fits is shown in Figure 2.

Based on Lerro and Bar-Shalom [1], it is known that a single-Gaussian model with linearized mean and covariance estimates performs poorly above $C_B = 0.2$. This situation is corroborated by the KL divergence curve shown for the First-Order Single-Gaussian Model. An improvement in performance may be realized up to about $C_B = 0.5$ by using a properly moment-matched single-Gaussian model, but beyond this value, the Gaussian mixture models provide a much better level of performance.

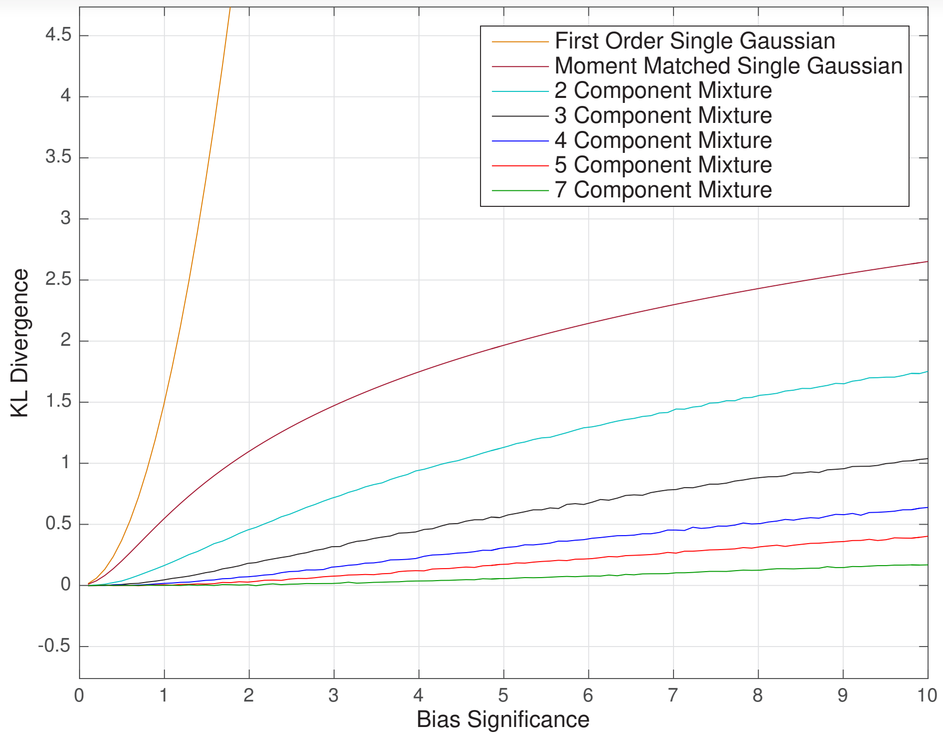

Figure 2: KL Divergence Achieved by Mixture Models.

This research determined that the following transformations of the component means and covariances resulting from EM are constant if the bias significance and number of Gaussian components are held constant. Let $[\mu_k]_x$ and $[\mu_k]_y$ represent the x and y Cartesian components of the component means. First, transform the Cartesian mean to polar coordinates.

$$r_k = \|\mu_k\| \quad \theta_k = \tan^{-1}\frac{[\mu_k]_x}{[\mu_k]_y}.$$

Then normalize these polar coordinates as follows:

$$\Delta\hat{r}_k = \frac{r_k - \bar{r}}{C_B \sigma_r} \quad \Delta\hat{\theta}_k = \frac{\theta_k - \bar{\theta}}{\sigma_\theta}.$$

For the covariance, perform an eigendecomposition of Σ_k such that $\sigma^2_{M,k}$ is the major axis eigenvalue (corresponding to cross-range variance for the long ranges involved in the contact lens problem) and $\sigma^2_{N,k}$ is the minor axis eigenvalue (corresponding to range variance). Furthermore, let ψ_k be the angle of the major eigen-axis measured counterclockwise from the x-axis. Then transform this eigendecomposition as follows:

$$\hat{\sigma}_{M,k} = \frac{\sigma_{M,k}}{\bar{r}\sigma_\theta} \quad \hat{\sigma}_{N,k} = \frac{\sigma_{N,k}}{\sigma_r\sqrt{1+2C_B^2}} \quad \Delta\hat{\psi}_k = \frac{\psi_k + \theta_k}{\sigma_\theta}.$$

The quantities $\omega_k, \Delta\hat{r}_k, \Delta\hat{\theta}_k, \hat{\sigma}_{M,k}, \hat{\sigma}_{N,k}, \Delta\hat{\psi}_k$, along with the KL divergence achieved by the solution, may now be placed into a lookup table, where the rows of the table are measurement bias significance, C_B, and number of components, N_G. This lookup table has only one unique dimension for a given number of mixture components (rather than four), resulting in a much more tractable implementation.

For an arbitrary measurement (subject to $\sigma_\theta << 1$ rad), a Gaussian mixture may then be generated by the following steps:

1. Compute the bias significance,
$$C_B = \frac{\bar{r}\sigma_\theta^2}{2\sigma_r}.$$
2. Consult the lookup tables to determine the KL divergence that may be achieved by using a given number of mixture components to model the measurement.
3. Choose the lowest number of components, N_G, required to achieve the desired KL divergence.
4. Look up $\left\{\omega_k, \Delta\hat{r}_k, \Delta\hat{\theta}_k, \hat{\sigma}_{M,k}, \hat{\sigma}_{N,k}, \Delta\hat{\psi}_k\right\}_{k=1}^{N_G}$ from the table for the given N_G and C_B.
5. Perform the inverse of the transformations described previously to compute $\left\{\mu_k, \Sigma_k\right\}_{k=1}^{N_G}$.

MODEL RESULTS

To demonstrate the effectiveness of this measurement modeling approach, Monte-Carlo simulations of the lookup-table-based mixture generation process were performed over a logarithmic grid of angle standard deviations from 1 to 300 mrad and bias significances from 0.3 to 10 (which in turn determine the range standard deviation). A fixed range of 100 km was used. The KL divergence from the lookup table (predicted) was compared to the empirical KL divergence calculated by sampling the original polar measurement distribution with 1 million points, converting these points to Cartesian coordinates, and calculating the expectation of the log likelihood.

Figure 3 shows the result of this analysis for $N_G=3$ components. The predicted KL divergence agrees well with the lookup-table measurement model over the domain of interest. Some slight deviation on the order of 0.01 is observed in the lower bias significance portions of the grid. This deviation is partly due to sampling error, as well as the fact that KL divergence is plotted on a log scale.

Figure 4 illustrates one of these three-component mixture densities in comparison to the true distribution. This figure shows that the mixture distribution represents the shape of the measurement PDF much more closely than a single-Gaussian ellipse. These results may be compared to Figure 5, which shows results for $N_G=5$ components. Again, some slight discrepancies on the order of 0.01 are present at low bias significance values. The KL divergence achieved here is lower (as can be seen by comparison to Figure 2), so sampling error effects can be seen at a higher C_B than in Figure 3. However, the lookup-table-based mixture models still achieve close to the expected KL divergence performance over the entire domain of interest.

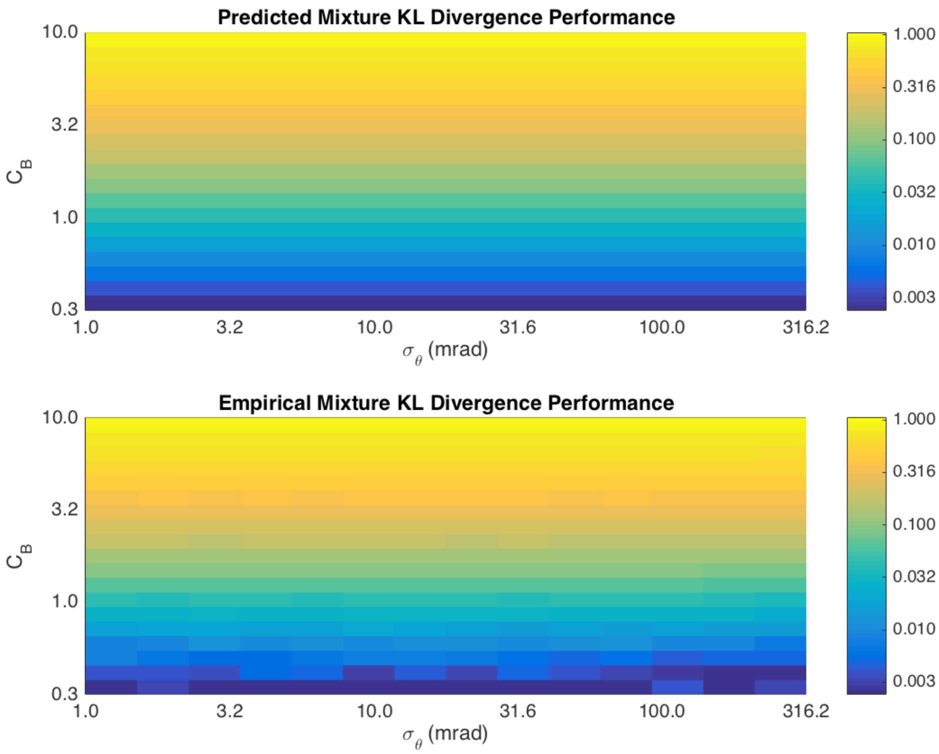

Figure 3: KL Divergence Performance N_G = 3.

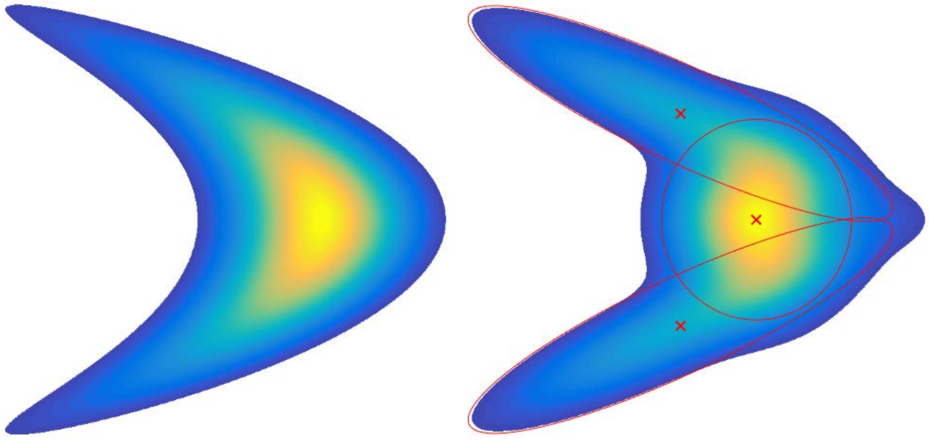

Figure 4: Measurement Distribution with C_B = 1 (left) and Three Component Gaussian Mixture Model (right).

CONCLUSION

As the popularity of high-range-resolution, long-range radars continues to increase, the tracking difficulties associated with these systems continues to be a problem for operators, designers, analysts, and other practitioners dependent on these types of radar results. However, the novel method described herein addresses this problem by modeling two-dimension polar radar measurements in Cartesian coordinates using a Gaussian mixture distribution. This method has already demonstrated some promising preliminary results when applied to tracking filters [5, 6], and developers are in the process of conducting research to extend this approach to three-dimensional monostatic and bistatic radar measurements as well. ■

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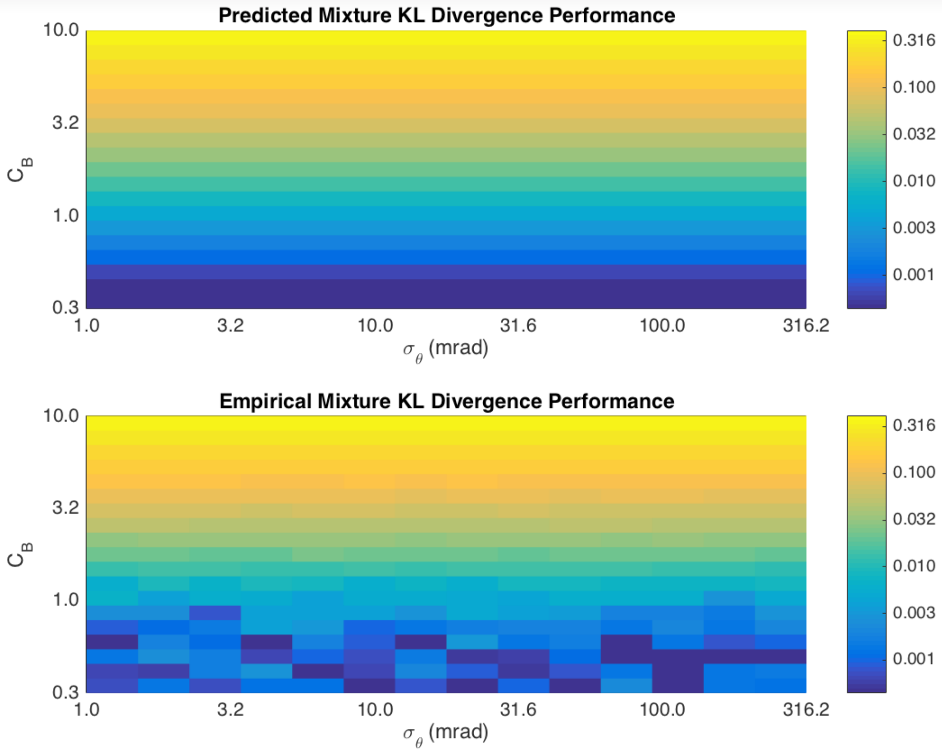

Figure 5: KL Divergence Performance for N_G = 5.

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BIOGRAPHIES

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(Source: U.S. Air Force)

ESTIMATING ENDGAME EFFECTIVENESS OF AIR-TO-AIR MISSILES:

An Overview of the Major Tools and Techniques

By Kevin McArdle

BACKGROUND

How well an air-to-air missile performs against a foreign target has long been of interest to military planners, designers, manufacturers, analysts, and operators. Early on, analysts used scale models and drawings to help them estimate the effectiveness of these missiles; but the computer revolution and continuous advancements in computation and visualization capabilities have made these estimates easier, faster, and more accurate than ever before.

In estimating the endgame effectiveness of air-to-air missiles, effectiveness is usually presented as the probability of damaging the target such that it is out of manned control in 30 s or less. Known as a K-kill, this probability minimizes the need to launch a second missile. K-kill also includes the more severe KK-kill (or sometimes a radar-recognizable kill), where the target breaks up immediately on warhead detonation. Another metric for air-to-air missile effectiveness (albeit less frequently used) is simply the ability to prevent the target from completing its mission. A practical problem in adopting this metric, however, is that the attacking aircraft may not be able to recognize a successful mission kill.

Many of the tools and techniques used to analyze air-to-air missile effectiveness are also used for aircraft survivability studies. That said, vulnerability studies are often extremely conservative, demanding damage levels that guarantee the quick defeat of the target. In contrast, survivability studies desire the aircraft to complete its mission if possible but definitely return to a friendly airfield.

Numerous computer programs (which are described in more detail in following text) are currently in use to evaluate missile effectiveness (both to investigate the design of new warheads and evaluate inventory warheads). These programs include the Advanced Joint Effectiveness Model (AJEM), TurboPk, Shazam, Endgame Manager, and Warhead Eval.

In their simplest application, these programs evaluate the effectiveness of a warhead at given burst points around the target. The burst points can be generated by a fuze model built into the effectiveness program or one that is external to it. Each of these programs has strengths, weaknesses, and proponents. All require the same basic information, a detailed knowledge of the target, the missile's warhead, and the encounter conditions. However, the input formats for these programs vary, and considerable effort is often expended translating them from one format to another.

AIR-TO-AIR MISSILE TARGET DEFEAT MECHANISMS

An air-to-air missile can defeat an aircraft target in three ways: (1) via a direct hit of the threat missile on the target, (2) via blast from the missile's detonating warhead, and (3) via the impact of fragments launched by the missile's detonating warhead. A direct hit kill can occur if the intact missile impacts certain regions of the target or if, after detonation, the residual missile parts impact certain regions of the target. In a similar fashion, the target can be defeated by the warhead's blast if, when the warhead detonates, it is within a specified distance of certain regions of the target. It is usually most efficient to determine if either of the first two mechanisms, direct hit or blast, defeat the target aircraft before evaluating the warhead's fragmentation.

Figure 1 illustrates the regions of a typical aircraft deemed vulnerable to blast and direct hit kill. While these vulnerable regions are defined in terms of skin sections on the outside of the aircraft, it is understood that massive lethal damage is actually inflicted on the interior components beneath the skin. Some analysts might believe the regions designated as vulnerable to blast and direct hit are too conservative; however, the K-kill criterion requires the aircraft to fall out of manned control within 30 s. Many times, fighter-size aircraft have suffered extreme physical damage (such as shown in Figure 2), causing these aircraft to lose manned control for 30 s, although they continued to fly and eventually land.

The evaluation of the warhead fragmentation of an air-to-air missile appears to be rather straightforward—at least at first. The analyst first determines the encounter parameters of the missile's exploding warhead relative to the target, then computes the trajectory of individual fragments generated by the exploding warhead and determines which fragments impact the target (as illustrated in Figure 3). Next, using fragment penetration equations, the analyst determines if those fragments could penetrate into the target through various internal parts and damage critical components. Finally, the overall effect of the damaged critical components on the fate of the target aircraft is evaluated through a Failure Analysis Logic Tree (FALT).

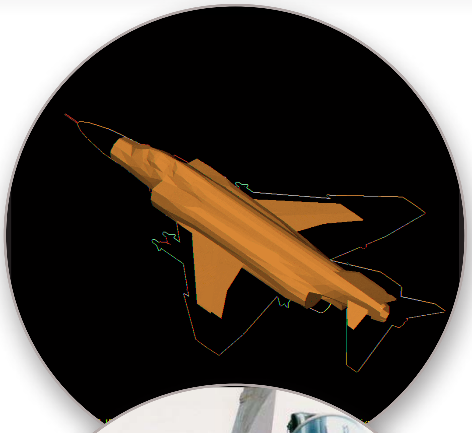

Figure 1 (top): Colored Surfaces Indicating Regions of Example Aircraft Vulnerable to Blast and Direct Kills.
Figure 2 (bottom): F-18 With Mid-Air Collision Damage.

The latest effectiveness codes can implement this approach directly while other, older codes, cannot. Designed at a time when computers were much slower, older codes compensate by using some form of precalculated vulnerability data. Nevertheless, the aforementioned evaluation sequence details the principal inputs required at some stage for all effectiveness calculations: a target model, warhead model, fragment penetration equations, component damage functions, and a FALT. These items may be used explicitly in the effectiveness code or may be used in the precalculations to prepare inputs for the effectiveness code.

TARGET DESCRIPTIONS

All of the effectiveness programs mentioned previously require a detailed physical description of the target. Depending on the effectiveness code, the detailed target description may be used directly by the code or used in preliminary calculations preparing inputs for the code. In contrast with survivability studies of U.S. aircraft, where vast amounts of vehicle descriptive data may be available, foreign aircraft data can vary from just a few photographs of a new aircraft to actual hardware of an older aircraft. For example, several Fulcrum and Flanker aircraft have been advertised online for sale in the United States for the past several years. Based on the descriptive data available, a computerized geometric model of the target aircraft (commonly referred to as a Target Geometric Model [TGM]), containing thousands of components, is constructed (as illustrated in Figure 4). Where detailed information is lacking, subject-matter experts use their knowledge of similar aircrafts to fill in the blanks.

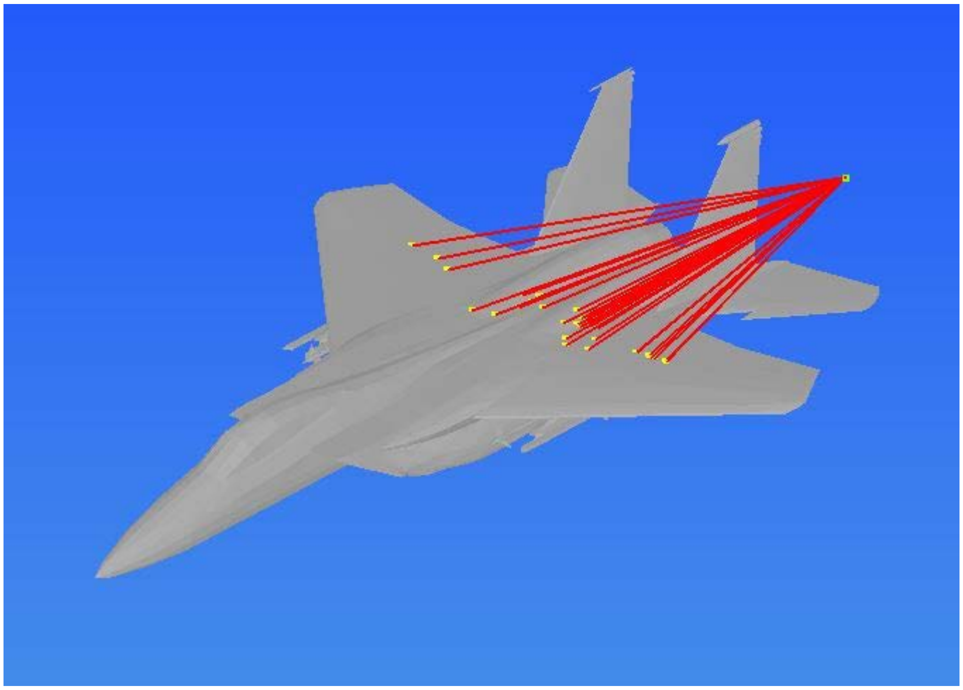

Figure 3: Tracing Fragments From Bursting Warhead to Target.

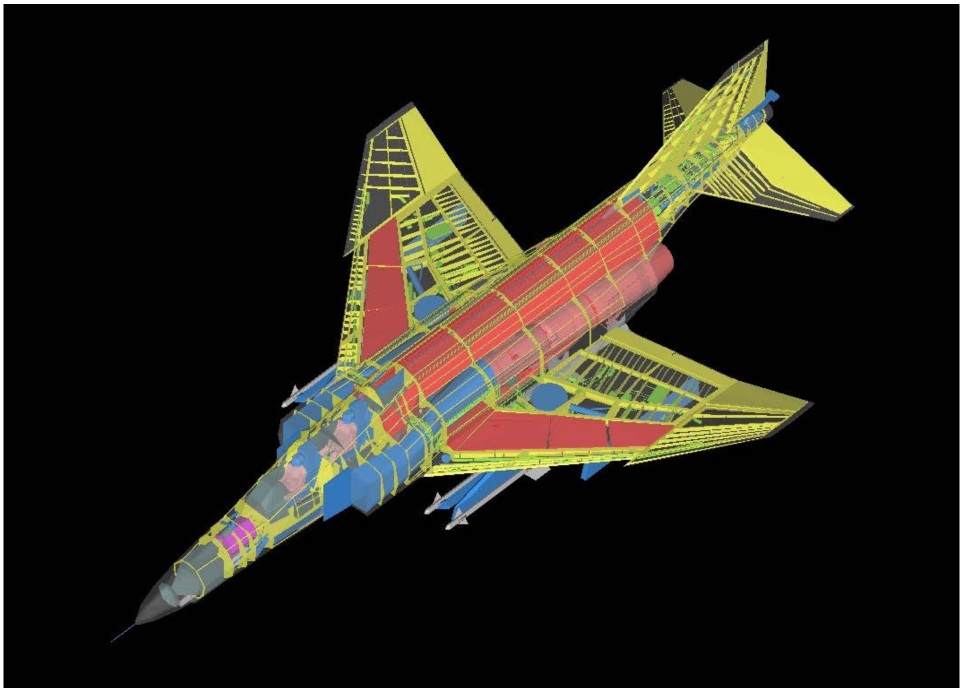

Figure 4: The Level of Detail in a Typical TGM.

The earliest vulnerability studies used scale models and drawings to estimate the location, size of components, and their shielding. Then, in the early years of computerized vulnerability analysis, targets were modeled in SHOTGEN format. This format allowed objects to be meshed with triangles. It also allowed linear components to be modeled as straight lines. Later, aircraft geometric models were constructed in FASTGEN format, which added the ability to model objects as boxes, wedges, cylinders, spheres, and variations of each.

With the adoption of AJEM as the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) standard tool for vulnerability assessments, newer target models are constructed in BRL-CAD constructive solid geometry format or are constructed using SolidWorks, exported as STL files, and then converted to the desired format. Not surprisingly, convertibility has become an increasingly important feature in target modeling. Targets are first constructed in the specific format required by the analysis tool in use but quickly find use in other applications requiring a different format. Thus, tools are available to convert from almost any commonly used format to any other commonly used format.

In addition to modeling the geometry of the skin and internal components of the aircraft, the type of material and thickness for each component must also be specified to accurately predict the ability of fragments to penetrate the component. Vulnerability codes allow for a wide range of materials, including steel, aluminum, titanium, tantalum, tungsten, magnesium, and lead. Most components are not homogeneous but may be modeled as if they were. For example, a piece of avionics equipment may be modeled as a solid box of aluminum. To account for voids in the actual equipment, a density ratio is assigned to it. An avionics box may be assigned a density ratio of 35%. Thus, in the course of an analysis, a fragment's computed straight-line path through the box would be reduced by 65%.

WARHEAD DESCRIPTIONS

The fragmentation characteristics of a warhead is usually obtained in testing by detonating the warhead at the center of a circular wall of fiberboard bundles that are thick enough to capture the fragments. After detonation, the location of each fragment is recorded, and the fragment is recovered and later weighed. Fragment speeds are determined by measuring their time of arrival after detonation at a known distance from the warhead detonation point. One popular technique is using high-speed video cameras to record the flash each fragment makes as it perforates a thin steel panel. Another popular technique is to use make-circuit screens instead of steel panels and record the time the fragment completes the electrical circuit when it perforates the screen. Figure 5 illustrates a typical arrangement of an arena test for a small warhead using both thin steel flash panels and make-circuit screens.

Almost all air-to-air missile warheads have cylindrical symmetry, thus simplifying the modeling of the warhead's fragmentation pattern, which is described in terms of polar zones. The forward end of the warhead axis is defined to be at 0° while the normal to the axis is at 90°. The region between 0° and 90° is divided into polar zones of 5°. For each polar zone, the numbers, masses, and ejection speeds are specified. Generally, most analyses consider all the fragments originating from a point at the center of the warhead. This is a reasonable assumption if the warhead is several warhead lengths away from the target.

FRAGMENT PENETRATION

The earliest extensive investigation into the penetration abilities of steel fragments was conducted under an effort called Project Thor [1]. That project conducted firings of fragment masses from 5 to 825 grains at speeds as high as 12,000 ft/s at 10

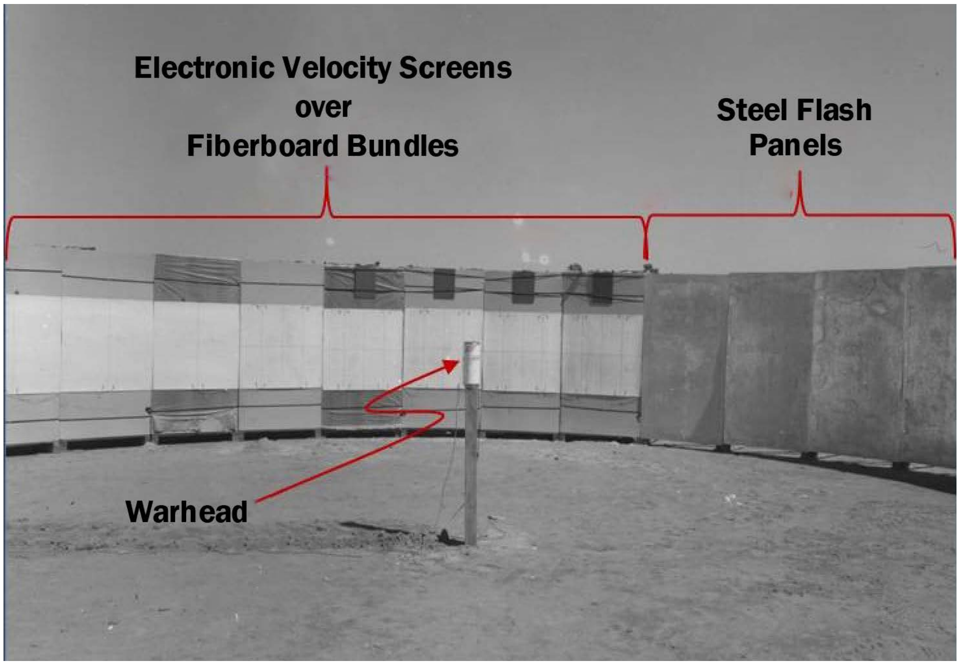

Figure 5: Typical Small Warhead Arena Test Setup.

different metallic materials. For each material, the test results were used to fit equations for residual speed and residual mass as functions of the impacting fragments mass and speed. Additional equations were developed for determining ballistic limit speeds as functions of fragment mass and target thickness. These fragment penetration equations have been used for many years in numerous vulnerability codes, such as the Computation of Vulnerable Areas and Repair Times (COVART).

In the 1980s, however, a need was recognized for an improved treatment of extremely high-speed steel fragments impacting aerial targets. The Thor mass loss equations did not predict the large decrease in residual mass when fragments shatter during high-speed impacts, thus spurring the development of the Fast Air Target Encounter Penetration Program (FATEPEN), which treats this issue and several others. Today, FATEPEN, which is the JTCG/ME-recommended penetration methodology for AJEM users, continues to be developed, adding more and more improvements and features.

COMPONENT DAMAGE FUNCTIONS

K-kill component damage functions specify the probability that a fragment, with a certain mass and speed, impacting the component will, within 30 s, prevent the component from functioning as intended. With few exceptions, analysts have little success predicting the time to failure. Therefore, requiring massive physical damage ensures the component cannot perform its intended function almost immediately. For example, a flight control tube that has 75% of its circumference cut may fail in less than 30 s or may function for more than 30 min. But a flight control tube that has 100% of its circumference cut has failed immediately. As mentioned, vulnerability criteria are often extremely conservative.

> The Thor mass loss equations did not predict the large decrease in residual mass when fragments shatter during high-speed impacts.

Ideally, component damage functions would be determined by firing various fragments at the actual component. Although this firing has been conducted for certain selected components, it is unfortunately neither practical nor affordable in most cases. Test firings are expensive, and, in the case of foreign aircraft, the components are rarely available. In lieu of this approach, vulnerability analysts approach the solution by viewing the component as a target itself. From available descriptive and functional information, the analysts infer what physical damage would defeat the component. Many times, it is decided that a perforation in some part of the case of the component will defeat the intended purpose of the component. The analyst can then, using penetrations, determine what masses and speeds are required to accomplish this perforation from various views of the component.

FALT

As defined previously, the FALT is a logical expression specifying the components and combinations of components that, if rendered inoperative, will result in a kill of the aircraft. The development of the FALT is preceded with a Failure Modes Effects and Critically Analysis (FMECA), which considers each component in the target and decides how its defeat will affect the aircraft. Some components may be redundant with other components, requiring two or more components being defeated before a K-kill is obtained. Of course, many components are not considered critical for K-kills.

Historically, most FALTS are constructed from a system view point (e.g., hydraulic system, fuel system, electrical system, etc.). A slightly different approach constructs the FALT from a functional approach. In this approach, the top-level FALT consists of the aircraft structure, propulsion, and directional control. The aircraft structure houses everything. It is not considered vulnerable to single fragments of the sizes used in air-to-air missiles. However, as discussed previously, selected portions of it are considered vulnerable to a direct hit by the missile body or to the blast produced by the detonation of the missile's warhead.

Propulsion moves the aircraft through the sky, and directional control determines which way. Propulsion consists of one or more engines, which in turn require fuel. For twin-engine aircraft, K-kills require both engines to be defeated. In addition to providing propulsion, the engine-driven accessories provide hydraulic and electrical power. Directional control requires flight control surfaces and the means to move them. The means to move them requires a pilot, hydraulic power, mechanical linkages, and possibly flight control computers. Directional control is separated into pitch, roll, and yaw. Loss of pitch control leads to a K-kill, but loss of both roll and yaw control are frequently required for a K-kill. These top-level requirements are continually being expanded upon, ending with the individual components.

SPECIFIC EFFECTIVENESS CODES

The earliest computerized effectiveness programs did not trace the paths of individual fragments from the warhead to the target. Rather, they employed the vulnerable area concept and considered the expected number of fragments hitting the target. Warhead Eval, which is still in limited use, employs vulnerable areas. For a given fragment mass, speed, and attack direction, the vulnerable area of a component is the product of its presented area and its probability of being killed.

In the simplest case, the vulnerable areas for the individual critical components can be summed to a total target vulnerable area and considered as being located at the center of the target. These vulnerable areas can be precalculated using FASTGEN/COVART or AJEM. The effectiveness program determines the expected number of fragment hits on this total target vulnerable area. This approach has the advantage of calculation speed and can be adequate if the target is covered by the warhead's fragment spray. It falters when the latter is not true, which can occur if the warhead is extremely close to the target or if the missile generally guides to a specific location on the target (e.g., a jet engine's exhaust). In an attempt to compensate for this issue, rather than summing the vulnerable areas, the individual component vulnerable areas can be positioned at the component's location.

The effectiveness codes Shazam and Endgame Manager trace the paths of individual fragments from the warhead to the target. Both codes rely on precalculated probability-of-kill (Pk) values determined for a range of fragment masses, speeds, and attack directions.

Shazam, the methodology used since the mid 1970s to evaluate the Advanced Medium-Range Air-to-Air Missile (AMRAAM), employs a model consisting of the target's exterior and critical components but does not include the noncritical components. With few exceptions, the critical components are inside the target. The degradation of the mass and speed of fragments while traveling through the aircraft's exterior and internal components (both critical and noncritical) is accounted for using precalculated tables. These tables are generated using COVART or AJEM and a target model that includes both critical and noncritical components. For a given mass, speed, and attack direction, these tables contain the average Pk for each of the critical components. Figure 6 illustrates the Pk values associated with each of the critical components for one set of these conditions. The Pk values, and thus the colors, change as the mass, speed, or attack direction changes.

Endgame Manager, the effectiveness code used by the JTCG/ME, is similar to Shazam in that it also uses precalculated tables. The skin of the target is divided into tens or hundreds of panels. As illustrated in Figure 7, for each combination of fragment mass, speed, and attack direction, every panel has a Pk associated with it. This approach eliminates the internal components from Endgame Manager's TGM. These Pk values are precalculated

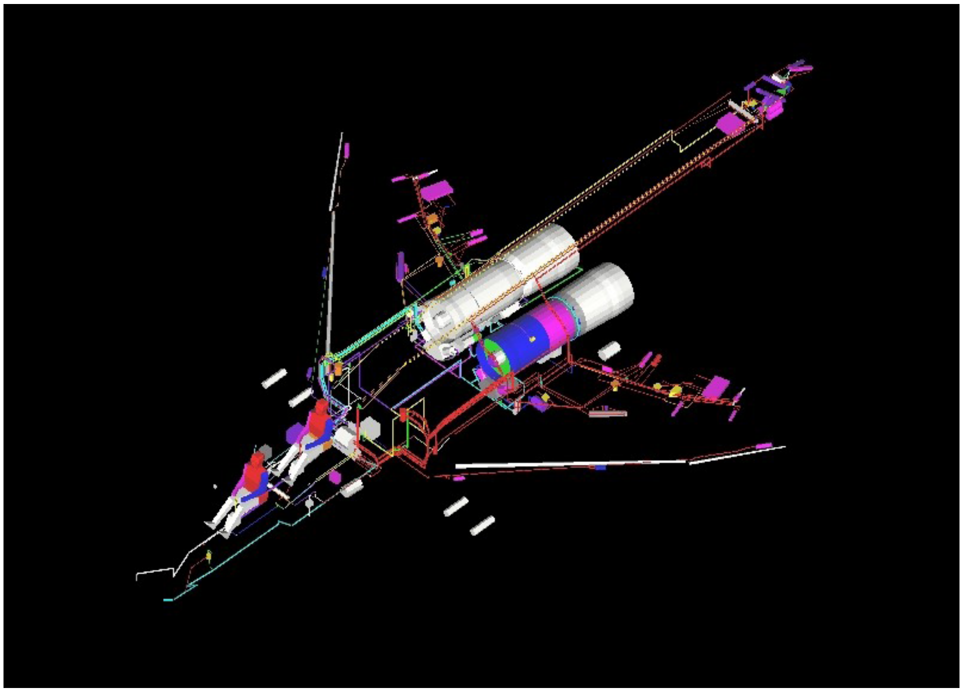

Figure 6: K-Kill Critical Components Color Coded According to Their Pk Values for a Specific Fragment Mass, Speed, and Attack Direction. The Pk Values and Colors Change as the Mass, Speed, or Attack Direction Changes.

using the MSPK program, which performs a FASTGEN/COVART analysis on the complete TGM, skin, and all internal components.

The TurboPk code, described in detail in the fall 2015 issue of the *DSIAC Journal*, is the latest effectiveness tool to implement the missile-target evaluation detailed at the beginning of this article. It is a fragment ray tracing code, self-contained and not requiring any separate vulnerability precalculations. The code was developed to take full advantage of the parallel processing possible with the multi-core central processing units incorporated into today's personal computers. It operates with detailed geometric descriptions of targets using penetration equations, component damage functions, and FALTs in formats similar or identical to other effectiveness codes. The code also includes a warhead design tool.

CONCLUSION

To be sure, the rapid emergence and advancement of today's inexpensive, fast personal computers have enabled the latest effectiveness codes to accomplish warhead design trade studies more quickly, more easily, and more effectively than ever before. The vital fragment ray traces that took so much time (and money) to accomplish just a few decades ago can now be generated, used, and discarded in just a few minutes. It should be noted, however, that if an older, well-established code continues to satisfy all the requirements, there may be no need to replace it, especially if an organization has a deep investment in it and changing to a newer code may require revisiting or rerunning many prior analyses. ■

Figure 7: Example of MSPK Output for a Specific Fragment Mass, Speed, and Attack Direction. In Practice, the Skin Would Be Divided Into Tens to Hundreds of Components, and the Pk Values and Color Would Change as the Mass, Speed, or Attack Direction Changes.

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BIOGRAPHY

KEVIN McARDLE is currently a senior analyst for the SURVICE Engineering Company, with more than 40 years of experience in aircraft vulnerability, lethality, munitions effectiveness, and related modeling and simulation efforts (including extensive support of the AMRAAM, AIM-9X, and many Joint Technical Coordinating Group and foreign and domestic air programs). Prior to joining SURVICE, he served as a branch chief for the Air Armament Center's Analysis Division; as a vulnerability analyst for the Air Force Aeronautical Systems Center; and as a technical advisor, team chief, and project engineer for the Air Force Armament Laboratory at Eglin Air Force Base. Dr. McArdle is also a prolific author, with approximately 50 technical reports and papers published. He holds a B.S. in physics from Villanova University and a Ph.D. in physics from Florida State University.

VULNERABILITY AND LETHALITY ANALYSIS TOOLS

For more information on and/or access to many of the vulnerability and lethality analysis tools mentioned here, contact the Defense Systems Information Analysis Center (DSIAC) or visit the following websites:

- https://www.dsiac.org/resources/models_and_tools/vulnerability-toolkit
- http://www.ajem.com
- http://www.turbopk.survice.com
- https://www.amsaa.army.mil/home.html.

(Source: Michael Helle)

Recent Advancements in

ULTRASHORT PULSE LASERS

Shed New Light on Directed Energy Applications

By A. Valenzuela, A. Schmitt-Sody, J. Peñano, M. Helle, A. Nachman, E. Parra, J. Harvey, J. Elle, G. Fischer, and G. DiComo

INTRODUCTION

Researchers from across the U.S. DoD seek to use the unique properties of ultrashort pulse lasers (USPLs) for directed energy applications. While the laser technology for a fielded system remains on the horizon, the fundamental physics and material science can be researched today with current USPLs. Given limited resources, the DoD research offices have complementary internal programs with the support of academic and industrial research, including numerous multidisciplinary university research initiatives (MURIs).

The result has been a rapid acceleration in the knowledge base of USPL effects and remarkable improvements in the modeling capabilities. Simultaneously, improvements have occurred in USPL technology to meet DoD requirements for force application and force protection. This article highlights some of the efforts, primarily in the basic research realm, where the DoD's collaborative effort is making a significant contribution to this field.

OVERVIEW OF USPLs

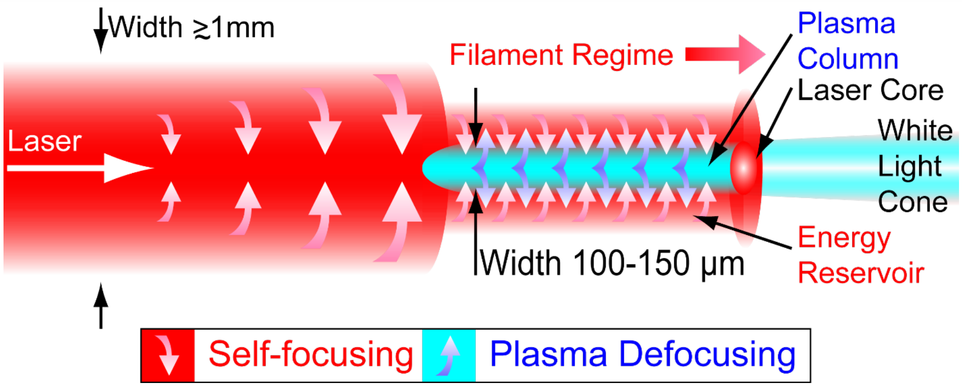

Figure 1: Filamentation Where an Intense Laser Self-Focuses to Generate a Defocusing Plasma Column. The Self-Focusing Energy Reservoir and Defocusing From the Plasma, Accounting for Losses, Are Balanced in the Filament Regime. At the End, a Narrow Cone of White Light Continuum Is Generated *(Source: Anthony Valenzuela).*

Both basic and applied research with USPLs are active areas with numerous different applications in fields such as chemistry, material science, and directed energy. For the directed energy field, the ability to achieve extreme intensities coupled with lower loss transmission across long distances (compared to longer pulses and continuous-wave lasers) is fundamental to how USPLs are viewed as unique tools.

USPLs are systems that deliver extremely short pulses, generally less than 1 ps (1 ps = 10^{-12} s). With sufficient energy in a pulse, peak intensities of gigawatts (10^9 W), terawatts (10^{12} W), or higher can be achieved. Such high intensities easily access the regime of nonlinear optics, where higher-order terms for the refractive index of transparent media become relevant. In addition, because these pulses are essentially instantaneous on and then off, atoms and molecules react differently than longer-pulse excitations.

One particularly interesting effect of USPLs interacting with a transparent propagation medium (air, water, glass, etc.) is filamentation [1–3]. Filaments arise when the intensity of USPLs cause a small increase in the second-order nonlinear index of refraction, which acts like a slow lens (see Figure 1). As the pulse focuses itself, the intensity increases, thereby increasing the self-focusing to the point where the medium is ionized. In air, the free electrons generated by ionization have their own nonlinear effect: defocusing. If the self-focusing can be balanced by the defocusing and losses from ionization, a stable filament can be created in which the cross section of the laser (typically a diameter of 100 μm) is maintained over long distances even up to hundreds of meters [4].

A common hallmark of filamentation is the generation of a narrow cone of supercontinuum radiation that can span, for a driving near-infrared (NIR) laser, the spectrum from ultraviolet (UV) to mid-infrared (IR) and beyond [5]. A clear advantage of a filament is the ability to affect matter in a consistent way without needing to know the precise location of a target.

Another advantage from the consistency of filaments is the ability to create a channel that assists in the creation of harmonics of the laser frequency, leading to ultrashort generation of extreme-UV (XUV) and soft x-rays as well as attosecond (10^{-18} s) pulses. These pulses are seen as unique tools to interrogate matter with immense precision from a relatively compact source.

While efforts to determine how filaments propagate and interact with targets have made significant gains, the applicability of this technology to military applications has been limited by the laser technology. Most systems today with adequate energy use titanium:sapphire (Ti:S) gain media and chirped pulse amplification to achieve the required intensities. This technology provides a trade-off between pulse energy and pulse repetition rate. Additionally, the complexity and sensitivity of this technology require highly skilled maintenance and strict control of the environment.

Nonetheless, as demonstrated by the European Teramobile project [6], this maintenance/control can be accomplished in a transportable system. Recent advances in ultrashort pulse fiber lasers [7] are seen as a significant game changer that could lead to both high pulse energies and higher repetition rates, with the possible added advantage of operating at “eye-safe” wavelengths. This is commensurate with increased research moving beyond Ti:S technology in the NIR to USPLs that operate across a wide range of IR wavelengths where transmission in air is actually better than at visible wavelengths (see Figure 2).

The following sections survey projects and findings from different research organizations united by the goal to advance the basic science of USPLs.

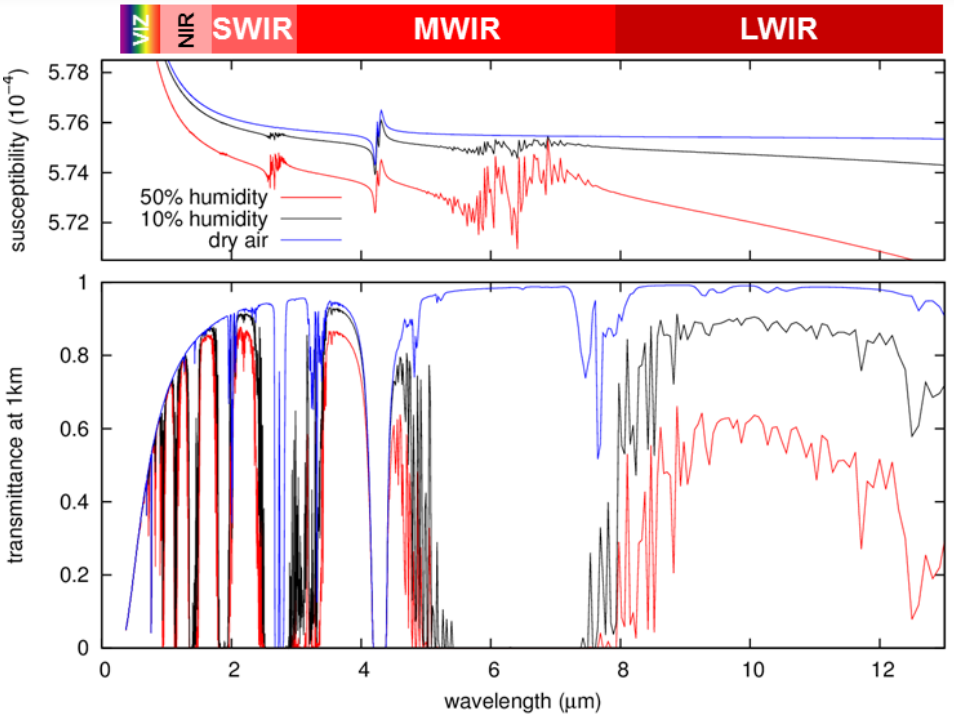

Figure 2: Atmospheric Effects on the Propagation of Light Based on Wavelength and Humidity From the HITRAN Modeling Code (Courtesy of Jerome Moloney). The Visible Spectrum Is Roughly 0.4–0.75 μm, NIR Is 0.75–1.4 μm, SWIR Is 1.4–3 μm, MWIR Is 3 – 8 μm, and LWIR Is 8–12 μm *(Source: Jerome Moloney).*

THE NAVAL RESEARCH LABORATORY (NRL) AND AIR FORCE RESEARCH LABORATORY (AFRL)

NRL and AFRL are performing theoretical and experimental research on the propagation of USPLs through the atmosphere. The utility of USPLs for defense applications depends on their ability to deliver high-intensity pulses to targets at tactically relevant ranges, often through challenging atmospheric conditions. Because of the relatively low energy per pulse of present-day USPL systems (less than 1 J), most applications rely on self-focusing to deliver the required intensity. When the peak laser power is many times larger than the critical self-focusing power (about 5 GW in atmospheric air), the pulse can break up into several filaments (see Figure 3) [8]. The distance at which filamentation occurs can be difficult to control, especially when turbulence, aerosols, dispersion, and other processes affect the propagation [9, 10].

NRL is modeling the propagation of USPLs through the atmosphere using its internally developed HELCAP code [11]. HELCAP can model high-energy laser effects such as thermal blooming, as well as USPL effects such as self-focusing, dispersion, plasma generation, and spectral broadening. In addition, the code can model propagation through turbulence and aerosols. Recent theoretical studies include modeling nonlinear self-focusing in turbulence to control the focal range [12], long-range self-channeling of ultrashort pulses in turbulence [13], and possible challenges for adaptive optics for USPLs [14].

NRL and AFRL have also designed and constructed unique experimental facilities to characterize USPL propagation through turbulence. These facilities include NRL's propagation laboratory (30–90-m range), AFRL's PHEENIX laser propagation range (180–540-m range) [15], and the propagation range at the Naval Surface Warfare Center Carderock Division (NSWCD) (~1-km range). These facilities use a turbulence generator that consists of several heated wires that extend the length of the propagation path and generate Kolmogorov turbulence conditions characteristic of the atmosphere [15] (see Figure 4). At the longer-range facilities, the turbulence generator can controllably create optically weak (Rytov variance <<1) to optically strong (Rytov variance >5) turbulence.

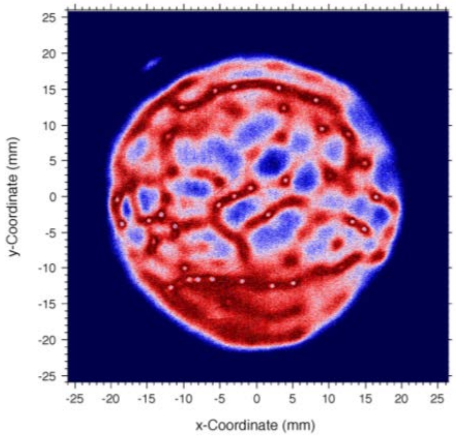

Figure 3: Experimentally Observed Laser Intensity Profile of a Pulse Undergoing Filamentation in Air (NRL TFL Laser) *(Source: Michael Helle).*

Figure 4: The Pheenix Laser Propagation Facility at AFRL *(Source: Andreas Schmitt-Sody).*

At the NSWCCD facility, turbulence conditions characteristic of slant paths and boundary layers can be simulated. The Ti:S USPLs being used in these experiments include the kilohertz Ti:S femtosecond laser (kTFL) with 20-mJ/pulse and optical parametric amplifier to access 1.1- to 2.6-µm wavelengths (NRL range); the PHEENIX 40-TW, 10-Hz laser (AFRL range); and the Astrella laser (currently installed at the NSWC range), which is a ruggedized, portable laser capable of a 7 mJ/pulse at a 1-kHz rep-rate. Experiments (e.g., Figure 5) have demonstrated long-range, nonlinear self-channeling of ultrashort pulses (up to 10 Rayleigh lengths) through deep turbulence (Rytov variances >1).

Future research may include the use of adaptive optics to improve ultrashort pulse propagation. Additionally, AFRL investigates how the plasma generated by USPL filamentation interacts with large external electric fields, including guiding electric discharges by placing the filament between high-voltage electrodes. Research has been conducted to understand the complex dynamics of filamentation-driven discharges. Initially, the hypothesis was that the filament acted as a conducting wire placed between the electrodes. Experiments reveal that the process is more complex, driven by space charge and shock wave mechanisms [16–18]. As a spin-off from this research, AFRL is currently analyzing the broadband electromagnetic radiation emission from the filament as a means to characterize the properties of USPL filament-generated plasma.

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)

AFOSR has a basic research portfolio dedicated to the interaction of USPLs with matter. The objective of the program is to explore and understand the broad range of physical phenomena accessible via the interaction of USPL sources with matter to further capabilities of interest to the Air Force, including but not limited to, directed energy. The high peak powers accessible with USPL sources give rise to a rich assortment of nonlinear laser-matter interaction physics.

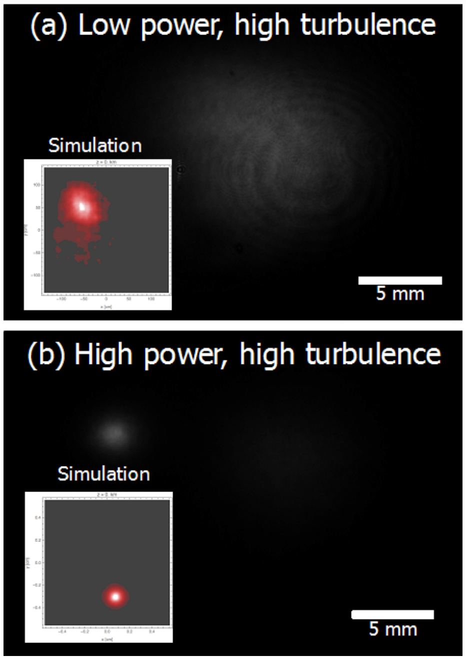

Figure 5: Experimentally Observed Laser Intensity Profiles for (A) Low-Power and (B) High-Power Propagation Through Turbulence. High-Power Cases Show Tightly Focused Spot, Which Is Characteristic of Nonlinear Channeling. Insets Show Results Using The HELCAP Simulation *(Source: Michael Helle).*

More explicitly, the USPL laser program is interested in mechanisms to control dynamics of femtosecond laser propagation in transparent media (e.g., filamentation) as well as concepts for monochromatic and tunable laser-based sources of secondary photons (e.g., x-rays and gamma rays) and particle beams (e.g., protons and neutrons). If successful, the research portfolio will develop the capability to (1) propagate ultraintense laser pulses kilometers downrange through the atmosphere to produce unique nonthermal effects on materials, components, and systems; and (2) produce a compact, transportable single source of both photon and particle radiation for nondestructive evaluation (NDE) of critical DoD components.

The delivery of high-energy mid-IR USPLs to a remote target is limited by high atmospheric transmission windows and turbulence conditions and is unavoidably influenced by intrinsic nonlinear optical properties of air. Under continuing AFOSR funding, new paradigms have emerged, predicting novel nonlinear effects that modify and can potentially enhance the effective USPL delivery range.

Currently, high-power USPLs are the exclusive domain of sources with wavelengths around 1 µm—the Ti:S multi-TW laser with a wavelength of 0.8 µm being the dominant source. Sources in the NIR exhibit poor atmospheric transmission and are strongly distorted through turbulent pathways. Moving to longer wavelengths and into mid-wave IR (MWIR) 3.5–4.2-µm or long-wave IR (LWIR) 8–12-µm high-transmission windows offers many potential advantages over 1-µm sources, such as improved atmospheric transmission and longer propagation paths through turbulence.

Specifically, these wavelengths are already exploited for a host of applications, including remote sensing and thermal imaging (seeing through fog, etc.). However, these advantages are offset by the need for large beam launch apertures due to rapid diffractive spreading, which becomes more severe at longer wavelengths—Rayleigh range. If this diffractive spreading could be offset by somehow confining the beam waist, the obvious advantage of MWIR and LWIR sources could revolutionize long-range, high-energy USPL delivery. This could result in a significantly reduced launch aperture and propagation over tens of Rayleigh ranges.

Research has identified two paradigms at longer wavelength that profoundly modify the physics and consequently the manner in which such high-energy MWIR and LWIR pulses propagate in the atmosphere. One is electromagnetic optical carrier shock waves, and the second is many-body weak Coulomb correlations between remote ionized electrons (plasma). These enable low-loss long-range transmission well beyond the classical Rayleigh range for LWIR multi-Joule ultrashort pulses [19, 20].

The USPL portfolio is also exploring the fundamental role that the laser wavelength, fixed by the choice of gain medium, plays in dictating the laser matter interaction physics. Coherent sources of MWIR radiation are of great interest for a wide range of scientific and technological applications, from spectroscopy and frequency metrology to information technology, industrial process control, photochemistry, photobiology, and photomedicine. The MWIR spectrum, which may be defined as wavelengths beyond 2 μm, covers important atmospheric windows; and numerous molecular gases, toxic agents, air, water, soil pollutants, components of human breath, and explosive agents have strong absorption fingerprints in this region.

Coherent MWIR sources also offer important technologies for atmospheric chemistry, free-space communication, imaging, rapid detection of explosives, chemical and biological agents, nuclear material, and narcotics, as well as applications in air- and sea-borne safety and security. The timely advancement of capable coherent MWIR sources is, therefore, vital to future progress in many application areas across a broad range of scientific, technological, and industrial disciplines.

AFOSR has a number of basic research efforts exploring the wavelength dependence of strong field processes, with particular emphasis on the MWIR spectral region. The 3–5-μm atmospheric propagation window is an area of particularly high interest to the DoD, with numerous useful applications, including chemical detection via light detection and ranging (LIDAR), remote aerosol detection via MWIR molecular spectroscopy, and directed energy.

> The utility of USPLs for defense applications depends on their ability to deliver high-intensity pulses to targets at tactically relevant ranges, often through challenging atmospheric conditions.

The AFOSR research portfolio also has a strong focus on the interaction of USPL pulses with solid materials. Contrary to irradiation with conventional laser sources, the laser energy deposition occurs on timescales shorter than the electron-phonon coupling time, leading to high-quality, reproducible material processing with minimal thermal collateral damage. Much of the research to date has been phenomenological; the physical processes are not understood in detail, and many open questions remain unanswered.

AFOSR has numerous basic research initiatives aimed at developing a rigorous understanding of the femtosecond laser-solid interaction near and beyond the material damage threshold. Such a rigorous understanding is expected to result in the ability to control and optimize laser properties to predictably perform tailored material modification as desired for important defense capabilities.

THE ARMY RESEARCH LABORATORY (ARL)

As the DoD's premier laboratory for ground forces, ARL plays a key role in guiding basic research toward Army applications. Directed energy has been an area of research at ARL for many decades, and USPLs have factored into that for more than a decade. As an integral part of ARL, the Army Research Office (ARO) (which is discussed in following text) has been key in motivating the state of the art in USPL research and technology across the U.S. and narrowing the gap in capabilities and understanding compared to global peers.

The concept of using the long propagation properties of filaments to guide other forms of energy has proven difficult to implement, due to limitations of USPL technology. Plasma recombination happens within a few nanoseconds, requiring a 100-MHz or higher repetition rate for a quasi-steady-state effect, which currently beyond the state of the art for high-energy ultrashort pulses.

Professor Howard Milchberg's group at the University of Maryland [21] has recently demonstrated that the heat dissipated from plasma recombination can alter air's refractive index sufficiently to provide a quasi-steady-state channel provided a repetition rate of 1 kHz or higher. This coincided with USPL technology advances that meet this requirement in a more compact, transportable system. ARL is collaborating with the Milchberg group to further investigate the ability to channel a fiber laser with a filament thermal waveguide. This ability would provide a radical new method of inscribing an atmospheric channel that better resists turbulence, thereby lessening the demands on adaptive optics.

ARL also examined the effects of filament ablation on solid, opaque targets, including metals, ceramics, and polymers. Femtosecond laser machining (FLM) has attained widespread success in achieving material removal with minimal damage effects. However, FLM uses a short local-length lens to produce high intensities on a target whereas filaments focus more gradually and have a trailing plasma column. Kiselev et al. [22] demonstrated that filament-induced laser machining (FILM) is able to achieve accurate ablation at long range. Our initial study [23] sought to compare the effects on a target between FLM and FILM with and without a focusing lens. We demonstrated that while FILM is not as efficient in material removal, it is consistent in ablation geometry across a range far larger than FLM Rayleigh ranges.

Analysis of the ablation craters indicated generation of laser-induced periodic surface structures (LIPSS). LIPSS has been an enigmatic research area owing to the elusiveness of a comprehensive theoretical explanation. The two dominant forms of LIPSS are low-spatial frequency LIPSS (LSFL) where the peak-to-peak (P2P) spacing is ¾ the laser wavelength (λ), and high-spatial frequency LIPSS (HSFL), where P2P is ¼ λ. To date, the prevailing theory of photon-phonon interference to explain LSFL has not been successfully extended to HSFL. Our data add to the puzzle by generating extremely low-spatial frequency LIPSS (~30–50 λ) on polymers; additionally, we confirm that the polarization direction is maintained during filamentation [24]. LIPSS is of interest for generating unique surface textures that increase surface area, enhance light absorption, and can change hydrophilicity.

> The USPL portfolio is also exploring the fundamental role that the laser wavelength, fixed by the choice of gain medium, plays in dictating the laser matter interaction physics.

THE ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER (ARDEC)

Applications of USPLs, particularly filamentation, will be driven by the capabilities of new laser architectures. Motivated by U.S. Army ARDEC interest in filamentation in air, MIT-Lincoln Labs (MIT-LL) designed and built a laser that meets all specifications. The project called for a repetition rate of 5 kHz, and the seed laser selected could be configured for pulses at multiples of 625 Hz up to 5 kHz. Because the laser was designed to study self-focusing and filamentation in air, steps needed to be taken to avoid self-focusing in the laser rods.

To avoid intracavity damage, MIT-LL stretched the laser pulse in time and frequency in a standard technique known as chirped amplification. To achieve a short pulse, a large bandwidth is needed. To broaden the bandwidth, two host materials were used for the Yb^{3+} ions. Yb^{3+}:YAG is a standard laser rod material and was used in the power stages of the system where the beam was larger. Yb^{3+}:GSAG was developed for this laser and has gain at slightly longer wavelengths. Sections large enough for the first amplifier stage were successfully grown, cut, and polished by MIT-LL. The additional bandwidth allowed for compression down to several picoseconds. The laser system was built successfully and is an asset available for basic and applied research that requires high-repetition-rate picosecond laser pulses.

THE ARMY RESEARCH OFFICE (ARO)

The ARO is the ARL directorate with the primary mission of funding extramural basic research. As part of the tri-Service MURI program, ARO has managed a large MURI team of U.S. universities (including the University of Central Florida [UCF], the University of New Mexico [UNM], Rensselaer Polytechnic Institute, Northwestern University, the State University of New York [SUNY] Buffalo, the University of North Carolina [UNC] Charlotte, and Southern Methodist University [SMU]), collaborating with a number of European institutions and several government laboratories. Facilities include a 500-mJ, 30-fs, 10-Hz NIR and a 2-mJ, 5-fs (single-cycle) NIR laser at UCF; a 200-mJ, 40-fs, 10-Hz NIR and a 300-mJ, 200-fs UV laser at UNM; indoor laser range facilities at UCF and UNM; a 15-km and upper atmospheric overhead range in Florida; and a mobile USPL lab with high-speed tracking unit at UCF.

Areas of investigation include the nature and modeling of the filament physics, arrays of filaments, microwave guiding and focusing, the formation of virtual hyperbolic metamaterials from the beams, filament-aerosol (cloud) interactions, phase-controlled structured filaments, large filament arrays, backward emission and lasing, and millimeter-wave and terahertz generation.

The MURI program is in year 6. Research in an ARO single-investigator program at the University of Maryland has demonstrated that the shock wave caused by the filament formation [21] forms a low-pressure guide for high-voltage electrical discharges, that filaments can be formed that are topologically protected from dissipation or interaction, and that the air guide can be selectively heated by coherently exciting rotational modes of the air molecules. In addition, the research is exploring potential electrical phenomena in the filament generated air guide.

Furthermore, research funded by the Defense Research Advanced Projects Agency (DARPA), AFOSR, and the Office of the Secretary of Defense (OSD) at the University of Colorado Boulder has demonstrated bright, coherent extreme UV and soft X-rays from extreme High Harmonic Generation in NIR filaments in noble gases. Research in the ARO single investigator program has demonstrated the "UV surprise," unexpected strong generation of soft X-rays from femtosecond UV filaments, and the investigation of generating higher energy X-rays (approaching 10 keV) in femtosecond 10-μm laser filaments is ongoing.

CONCLUSION

USPLs provide a unique method to access a new class of interactions with matter that lends itself to DoD applications. We are now at the cusp of the technological development of USPL sources enabling new theoretical and experimental results to advance laser-based directed energy weapons. And basic research is stretching the bounds of wavelength, pulse duration, laser repetition rate, and material interactions toward new and exciting regimes.

Yet, the community currently remains relatively small and interdependent for experimental and modeling support. While each Service has its own viewpoint on the application of USPLs, the core physics remains the same.

It is conceivable that fieldable USPLs will be achievable in the mid-term future that can serve a wide variety of applications including stand-off detection, remote ablation, guiding electrical discharges, and cooperative effects with other forms of electromagnetic energy. By furthering the advancement of USPLs and nonlinear optics, the DoD has served to put the United States at the forefront of these quickly developing fields. ■

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ACKNOWLEDGMENTS

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HPM DEWs

AND THEIR EFFECTS ON ELECTRONIC TARGETS

By John Tatum

Directed-energy weapons (DEWs) show great promise for the U.S. Warfighter in that they are a speed-of-light, all-weather weapon that can generate a relatively unlimited number of low-cost shots and produce scalable target effects that range from temporary to permanent depending upon the target and the separation distance (range). There are three main types of DEWs: high-energy laser, high-energy particle beam, and high-power radio frequency (RF)/microwave (HPM) weapons. This article provides a basic introduction to HPM DEWs and their effects on electronic targets, including why HPM DEWs are important to the Warfighter and how they are like and unlike traditional electronic warfare/electronic attack (EW/EA) and electromagnetic pulse (EMP) weapons. Also discussed is how HPM energy couples into an electronic target and produces effects that range from temporary

(Source: Boeing)

upset to permanent damage. Finally, ways to estimate/measure HPM effect levels on systems as well as to harden a system to mitigate the effects are presented.

HPM DEWs DEFINED

HPM DEWs are electromagnetic (EM) sources that can generate and direct RF/microwave pulses at a target. Typically, these weapons have peak effective radiated power of >100 MW, or >1 J per pulse. HPM DEWs can radiate energy at frequencies ranging from high-frequency to microwaves/millimeters. They can couple RF energy into a target via intentional and unintentional antennas (i.e., front doors and back doors, respectively) and produce long-term effects that last long after the HPM is gone. HPM DEWs are also known as RF weapons, EM weapons, and non-nuclear-generated EMPs.

THE IMPORTANCE OF HPM DEWs TO THE WARFIGHTER

HPM DEWs are of interest to the Warfighter because they provide the potential for "speed-of-light" engagements of multiple targets, with instantaneous fly-out times and no lead angle 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 target.

Because DEWs typically use fuels to generate energy pulses, they also represent a weapon with "deep magazines," which can produce a relatively unlimited number of shots without needing to reload ammunition. This capability represents reduced logistics and the associated cost. DEWs can also produce "scalable effects," ranging from temporary to permanent based on the target's vulnerability level and the separation distance between the DEW and the target (i.e., range).

One advantage that HPM DEWs have over kinetic energy weapons (and lasers) is that they have wide beams that can cover large target areas and therefore produce a high probability of target hit (although it should be noted that the probability of target kill ultimately depends upon how much energy can be coupled into the target's electronics and their failure levels).

THE HPM DEW SYSTEM

Figure 1 shows a block diagram of an HPM DEW and its major subsystems. On the far left is the prime power source to provide the power/energy needed to produce the HPM pulses. The prime power can be provided by an electrical generator or, in some cases, a battery pack. It can also be provided by explosives that convert the explosive energy into electrical energy. However, explosively driven sources tend to be less efficient than traditional generators.

Next to the prime power source is the pulse power conditioning section, which transforms the prime power into electrical pulses. This action may be accomplished in several ways. Typically, some form of pulse modulator, consisting of pulse-forming networks and high-power switches, converts the prime power into the electrical pulses with specific pulse durations or "pulse widths" and pulse repetition frequencies.

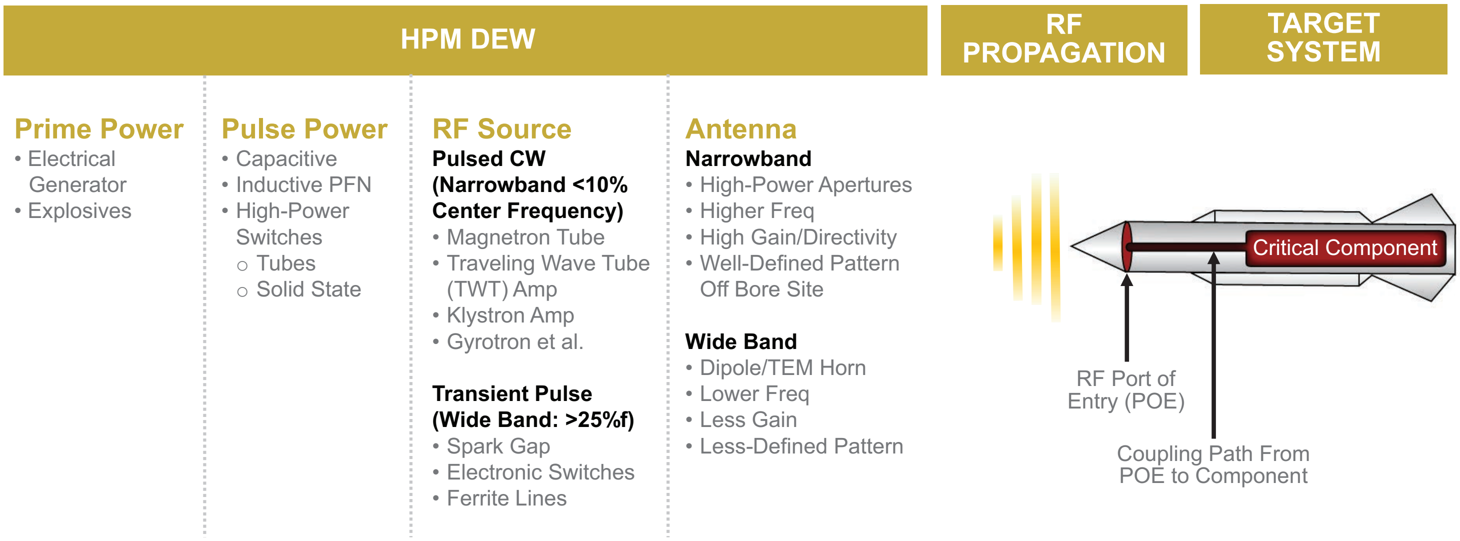


Figure 1: Major Components of an HPM DEW System.

The RF source (shown in the middle of Figure 1) converts the electrical pulses from the modulator into RF energy. Here, the source can be one that generates pulse-modulated sinewaves (or a so-called "narrowband source") or one that generates transient electrical pulses (or a "wide-band" source).

For narrowband sources, high-power tubes, such as magnetrons, or high-power amplifiers, such as klystrons or traveling wave tubes, are typically used. These sources use the high-power pulses from the modulator to produce high-power RF pulses. The magnetron is known as a power oscillator, and the klystron and traveling wave tube are known as power amplifiers. For the wide band sources, high-power switches and spark gaps are typically energized and then switched to produce a transient pulse. Ferrite lines can also be used to sharpen the pulses and increase the bandwidth of the transmitted signal.

Next, the antenna radiates the RF energy into space toward the target of interest. For narrowband sources, aperture-type antennas, such as horns and/or large parabolic reflectors, are typically used. These types of antennas can handle the high-power output of the RF source and provide directional gain for the energy transmitted toward the target. For the wideband sources, dipoles and transverse electromagnetic (TEM) horns are typically used. Because wideband signals have lower frequency content, their antennas tend to have less gain and directivity.

Next, the RF energy propagates through the atmosphere to the target. The energy radiated by the antenna spreads out in range and decreases as one over the range squared. The RF energy is also attenuated by the atmosphere and weather. However, one of the advantages of RF weapons over lasers is that they have a high probability of hitting the target because they have a much wider beam. Furthermore, they are typically not affected by weather unless they are radiating energy that is higher in frequency than 10 GHz (i.e., x band) and there is heavy rain or snow.

Lastly, on the far right of the figure, the target itself is represented by RF ports of entry to critical components. When the HPM DEW illuminates the target, the RF energy couples from the outside of the target interior via intentional antennas (often called "front doors") and unintentional antennas, such as cracks, seams and cables, (often called "back doors"). When the RF reaches the internal components, the pulse modulation can be rectified or stripped off by the semiconductor junctions, producing a modulated signal that can interfere with the target's operation and cause temporary interference or upset. If the energy is high, then it can overpower the semiconductors and produce permanent damage.

Figure 2 shows some examples of HPM DEW systems (although they are technology demonstrators and not fielded systems). Each picture shows the location of the generator or prime power supply, P, the RF transmitter, T, and the antenna, A. The system on the far left is a technology demonstrator designed and built by the Army Research Laboratory (ARL) for the Joint Non-Lethal Weapons Directorate (JNLWD) to demonstrate that commercial vehicles can be radiated by HPM pulses at tactically significant ranges to produce an engine stall. The center photo is another technology demonstrator designed and built by ARL for the Naval Surface Warfare Center Dahlgren Division (NSWC-DD) to demonstrate that an HPM source could be installed in the back of a small truck and used for EA on computers in buildings. The photo on the far right shows a wideband RF system developed by the Air Force Research Laboratory (AFRL) using its impulse-radiating antenna for EA experiments.

DEVELOPING HPM DEW SYSTEMS

Figure 3 shows a flow chart for developing HPM DEWs. Starting with the left-most block, the targets of interest and the desired engagement ranges are identified. This identification is often performed in collaboration with the

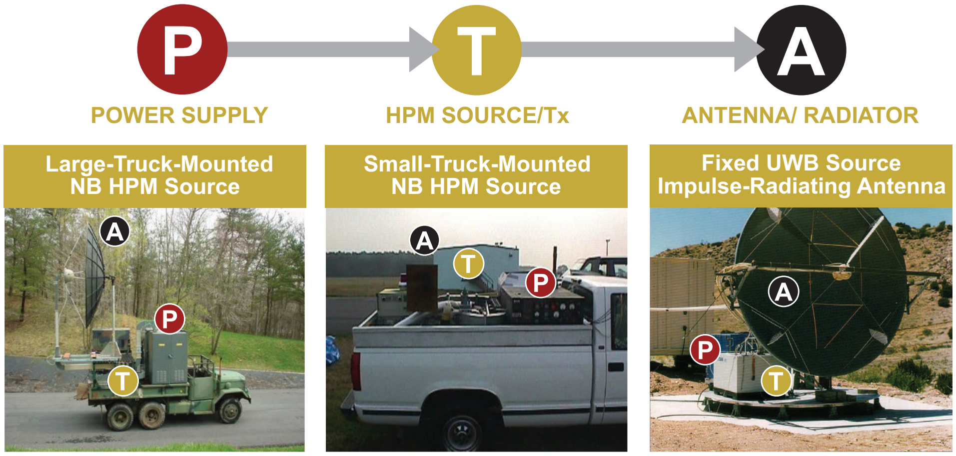


Figure 2: Examples of HPM DEW Systems.

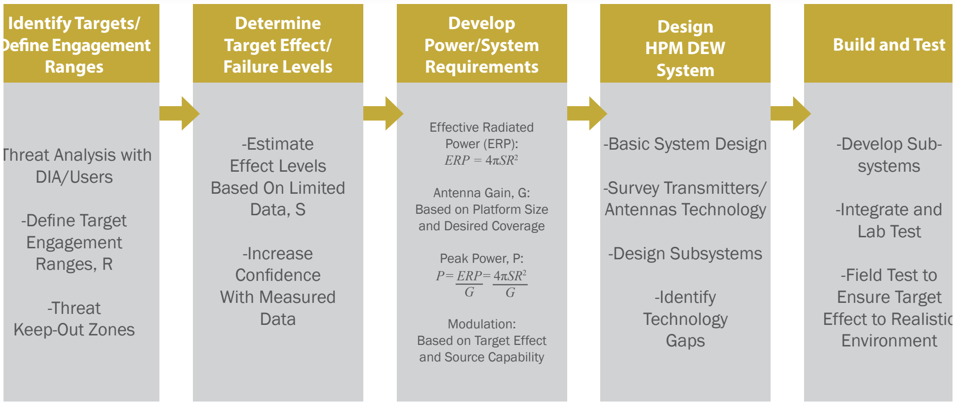


Figure 3: Methodology for Developing HPM DEWs.

Warfighter and intelligence communities, as they know the targets of interest and target details. During this process, it is important to try to identify the critical components of the target and RF ports of entry that lead to these components.

Next is the estimation of the RF power density required on the target to produce an effect, S, or the “target vulnerability level.” The target’s RF effect level is a combination of how much power is required to affect the critical components and the effective coupling areas of the components. It must be understood that these are only target effect estimates and must be verified by target vulnerability tests in which the entire target is instrumented and irradiated at increasing levels of HPM energy to see if there is an effect (and if so, at what level).

Once the target vulnerability level and desired engagement range, R, are known, the one-way radar equation can be used to calculate the effective radiated power required for an HPM weapon to irradiate a target with the appropriate power density [1].

Next, the size of the HPM platform is considered, and the largest antenna that will fit is determined. Based on the antenna’s size and efficiency, the maximum gain available can be determined. By dividing the source’s effective radiated power by the gain of the antenna, G, the transmitted power, P, required of the HPM source can be obtained. Once the required transmitter power and antenna gain are known, a commercial technology survey to find appropriate subsystems can be conducted. If the subsystems are not available commercially, then they must be developed.

Finally, the subsystems to produce an HPM demonstrator are integrated, and tests are conducted against targets of interest to determine its effectiveness.

APPLICATIONS OF HPM DEWs

HPM DEWs can be used to attack all forms of electronic weapons, sensors, and communication systems, not just RF receivers. The effects are often subtle and difficult to diagnose quickly, thus providing plausible deniability of an EA. The operation and maintenance of HPM DEWs are like those of radar systems and therefore should not require personnel to develop new military occupational specialties.

HPM DEWs also represent non-lethal weapons to humans that typically will not cause permanent damage for short dwell times. An important exception is an HPM system that produces millimeter-wave energy and can cause temporary pain by stimulating the nerves in the skin. This system is called the Active Denial System because it non-lethally denies access to controlled places. The system was developed by AFRL and its contractors for JNLWD. The system produces an effect only while the millimeter waves are illuminating a human. There is a large safety margin between temporary pain and permanent damage. The Active Denial System has been tested several times over the years by AFRL and JNWLD and has met all safety, legal, and treaty requirements.

Finally, it should be mentioned that shielding against the effects of HPM (i.e., countermeasures) is theoretically possible with metal wrap (i.e., a Faraday shield); however, this shielding may be difficult in practice since the energy coupling to the target’s electronics can increase depending upon the type and placement of the shielding material.

Figure 4 illustrates some DEW applications. The red lines represent lasers, and the curved lines represent HPMs. Both airborne and ground-based DEWs are considered. One of the major applications for DEWs is counter air (i.e., air defense) and counter command, control, communications, computers, and intelligence. Rockets, artillery, mortars, missiles, and unmanned air systems are major threats to the Services that can possibly be handled by kinetic energy weapons, but at great cost. Because DEWs produce a relatively unlimited number of low-cost shots (i.e., energy pulses), it is hoped that they could be a more economic and effective means for countering these types of threats.

Also shown is the use of HPMs for countermines/improvised explosive devices, which represent a serious threat to U.S. forces and our allies. Because the power on target from an HPM DEW is greater for short ranges, these types of targets may be well suited for defeat by HPMs.

RELATING HPM TO EW AND NUCLEAR-GENERATED EMP

Figure 5 illustrates EW's three main pillars: Electronic Protect (previously known as electronic counter-countermeasures), Electronic Support (previously known as electronic support measures), and EA (previously known as electronic countermeasures). Under EA (on the right side) is traditional EA with jammers that can attack only targets with RF receivers and produce temporary interference while the RF is on. On the left side, HPM DEWs can attack targets with and without RF receivers and produce long-term

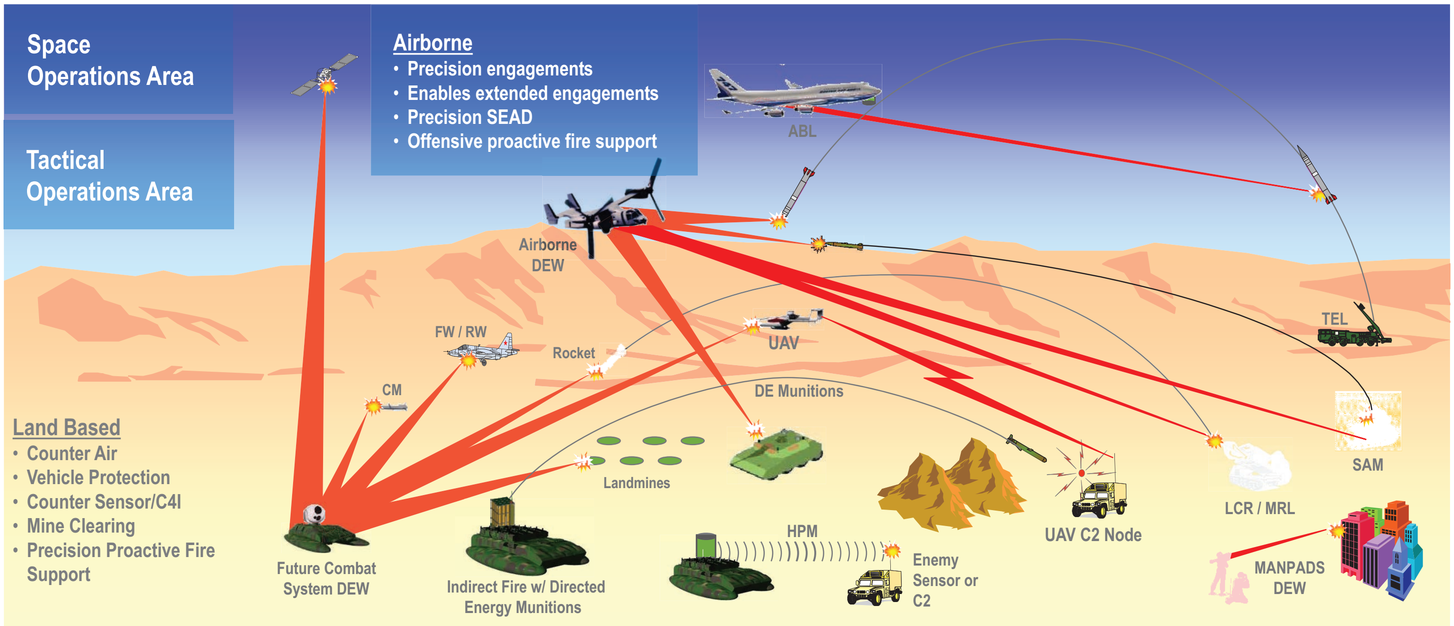


Figure 4: Examples of DEW Applications *(Source: DoD HPM DEW Effects Panel).*

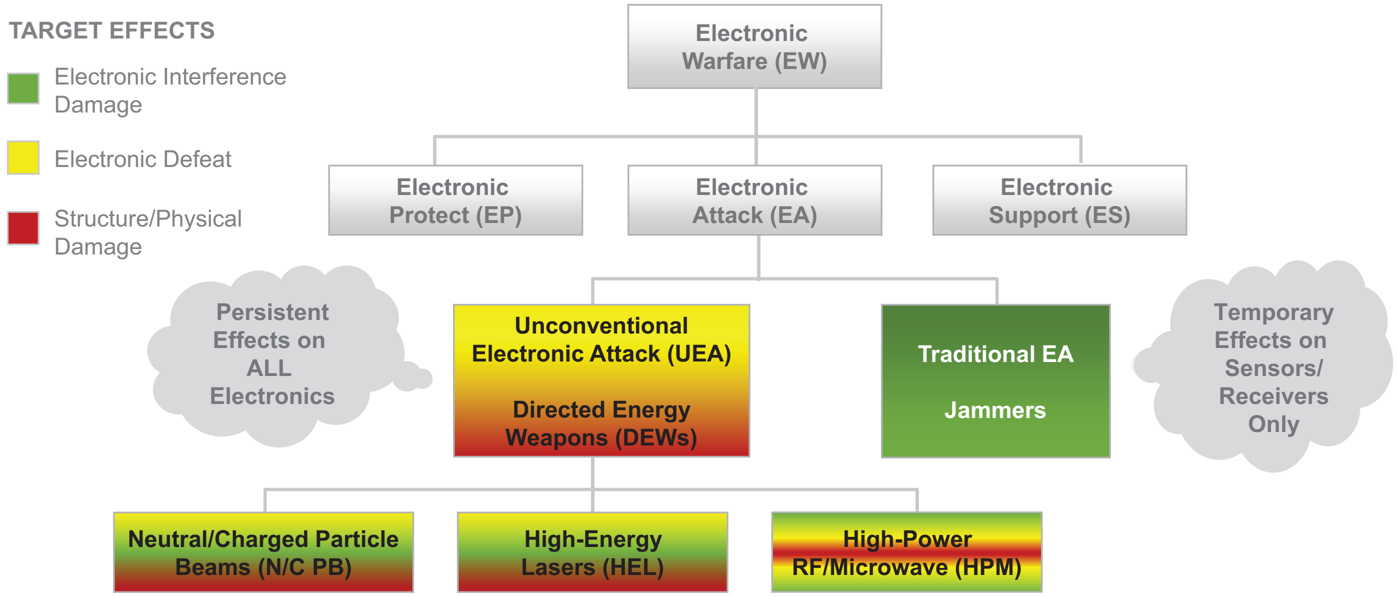


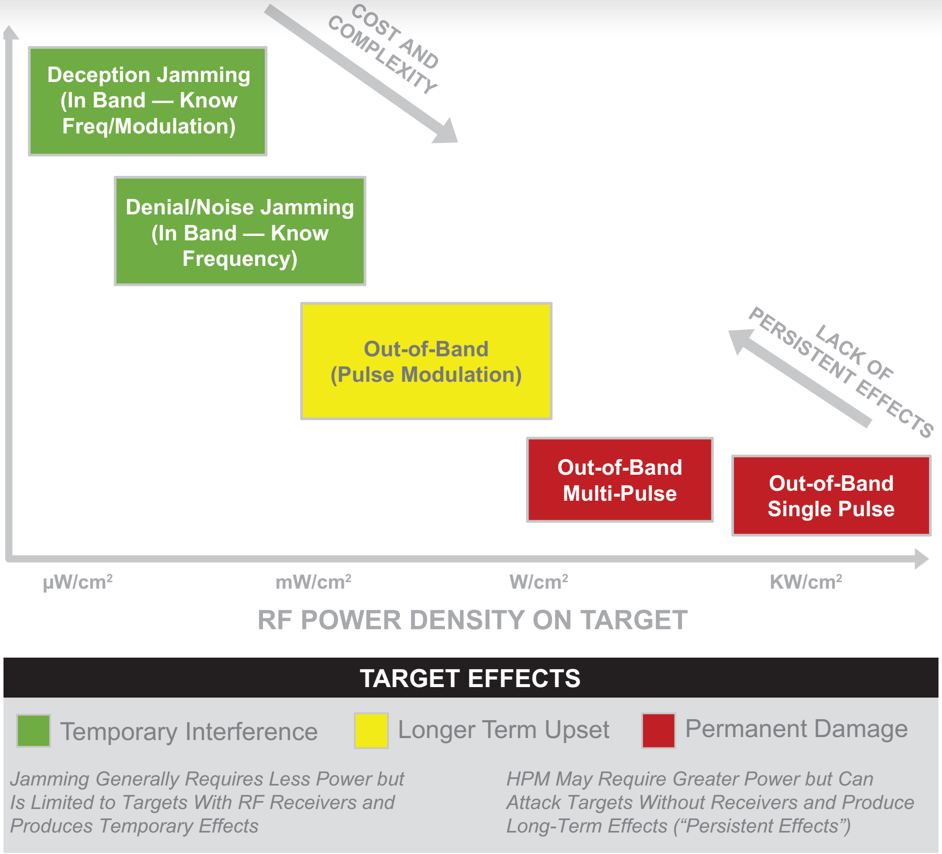
Figure 5: EW and HPM Weapons Providing UEA.

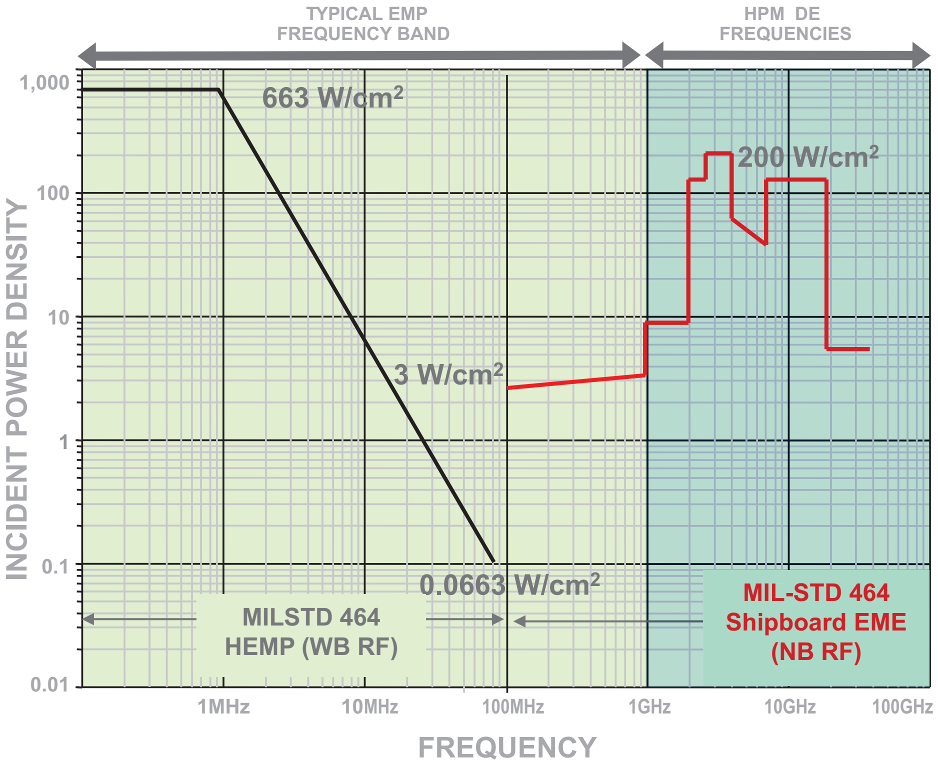
effects. Thus, HPM represents an "unconventional EA" (UEA) capability that can address classes of targets vs. a single RF receiver.

Figure 6 shows the relationship between traditional EA and HPM DEWs in another way. If one plots target knowledge vs. power required for effect, it can be seen that jammers can use little power if one knows the target receiver's operating frequency and modulation. However, the jamming effect is only when the RF is on and is temporary. On the other side of the curve, it can be seen that a high-power single pulse can be used to produce permanent damage in an electronic target. However, it may take hundreds to thousands of watts per square centimeter to produce the effects. If a repetitive HPM pulse is used, the power required can be reduced to some degree; but a lot of power is still required. The middle of the curve appears to be the most promising area for EA since it requires less target knowledge and uses moderate power to produce long-term upset.

An HPM DEW is also similar to a nuclear-generated EMP, but different in terms of the frequency range and other parameters. Both EMP and HPM involve EM energy coupling from the outside of a target to sensitive interior components. Figure 7 shows the frequency range for EMP vs. HPM. Note that the frequency content of EMP is much lower than HPM and has much longer wavelengths. Table 1 compares the typical frequencies and characteristic wavelengths for EMP and wideband and narrowband RF.

Another major difference for an EMP is that it is a well-defined waveform with known field strengths. HPM is not as well defined and can span a large range of frequencies, pulse widths, and pulse





Reference: Military Standard 464 - DoD Interface Standard – Electromagnetic Environmental Effects Requirements for Systems, March 18, 1997

Figure 6 (top): EA Techniques: Traditional Jamming vs. HPM DEW.
Figure 7 (bottom): Nuclear-Generated EMP vs. HPM.

Table 1: Comparison of Frequencies and Characteristic Wavelengths for Nuclear EMP and Wideband and Narrowband HPM

	TYPICAL FREQUENCIES	CHARACTERISTIC LENGTH
Nuclear EMP	DC to 100 MHz	3 m or more
Wideband RF	~30 MHz to ~3 GHz	~10 cm to ~10 m
Narrowband HPM	~1 GHz and up	up to 30 cm

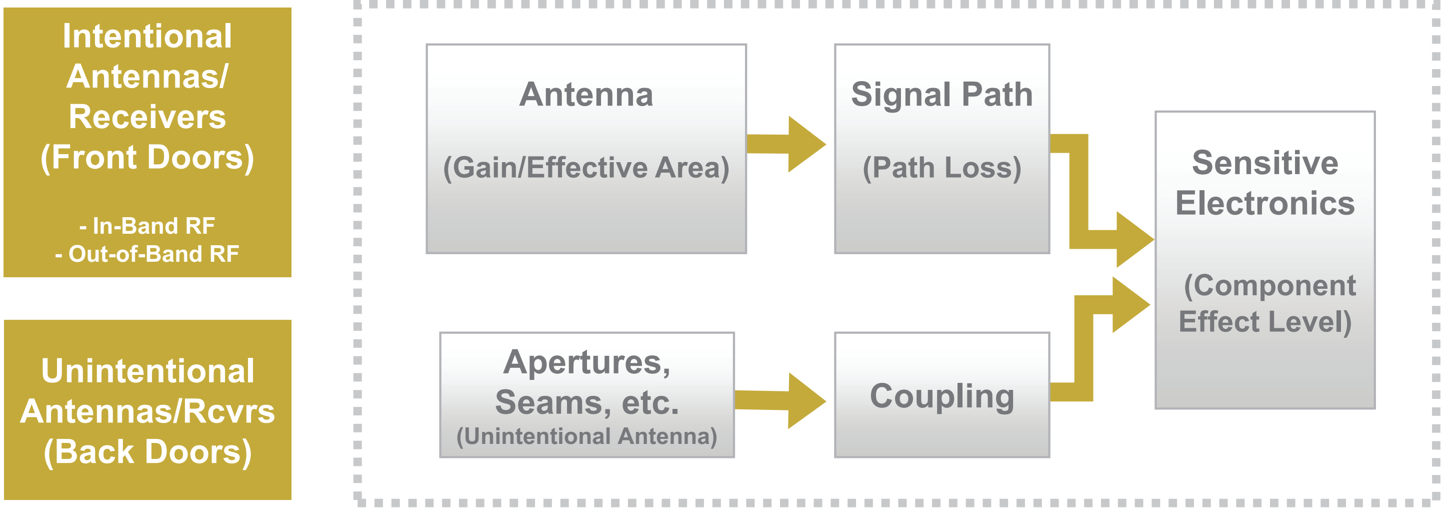
repetition frequencies. Both EMP and HPM require complex coupling codes and testing to determine the RF coupling to the component (i.e., the “stress”) and the component’s failure level (i.e., the “strength”). For both, the stresses and strengths are best represented by statistical quantities, resulting in a probability of effect vs. an effect threshold or level. Today, it is possible to use a source that will generate large EMP pulses with amplitudes greater than tens of kilovolts/meter without a nuclear blast. Therefore, an HPM DEW is sometimes called a “non-nuclear EMP.”

As previously mentioned, HPM can couple into a target’s electronics through intentional antenna or “front doors” and through unintentional antennas or “back doors” (as shown in Figure 8). When the HPM enters through the front door, often the entry path is the normal signal path to the first sensitive component. If the HPM is in band to the receiver, then it gets amplified by the target’s antenna gain and experiences low path loss. If the HPM is out of the band, then it is attenuated by the lower antenna gain and higher path loss. For back door HPM, the energy is coupled into the circuit boards and components by reradiated energy inside the target. Front door paths lend themselves to more accurate predictions of HPM levels because one typically knows more about the path to the component and the losses.

HPM COUPLING INTO TARGETS AND THE RELATED EFFECTS

Once the HPM reaches a critical component, if the stress is greater than the component’s strength, then the component can fail (as shown in Figure 9). The diagram shows each of the key parameters in an EA scenario and the difference between jamming and HPM effects. If the component is critical to the target’s operation, the component failure can lead to system failure. Component failure can occur if the RF power at the component is greater than the semiconductor’s junction failure level. In some cases, over-voltages in which the electrical current punctures the semiconductor device can occur. Because both the HPM energy coupled to a component and the component’s failure level are statistical in nature, the failure level is best described in terms of a probability of failure.

Figure 10 shows a scale of HPM effects and the associated definitions. This



RF Energy Can Enter Target via Intentional Antennas (i.e., “Front Doors”) or via Unintentional Antennas (i.e., Apertures, Cables, etc.) (i.e., “Back Doors”).

Figure 8: HPM Coupling Paths.

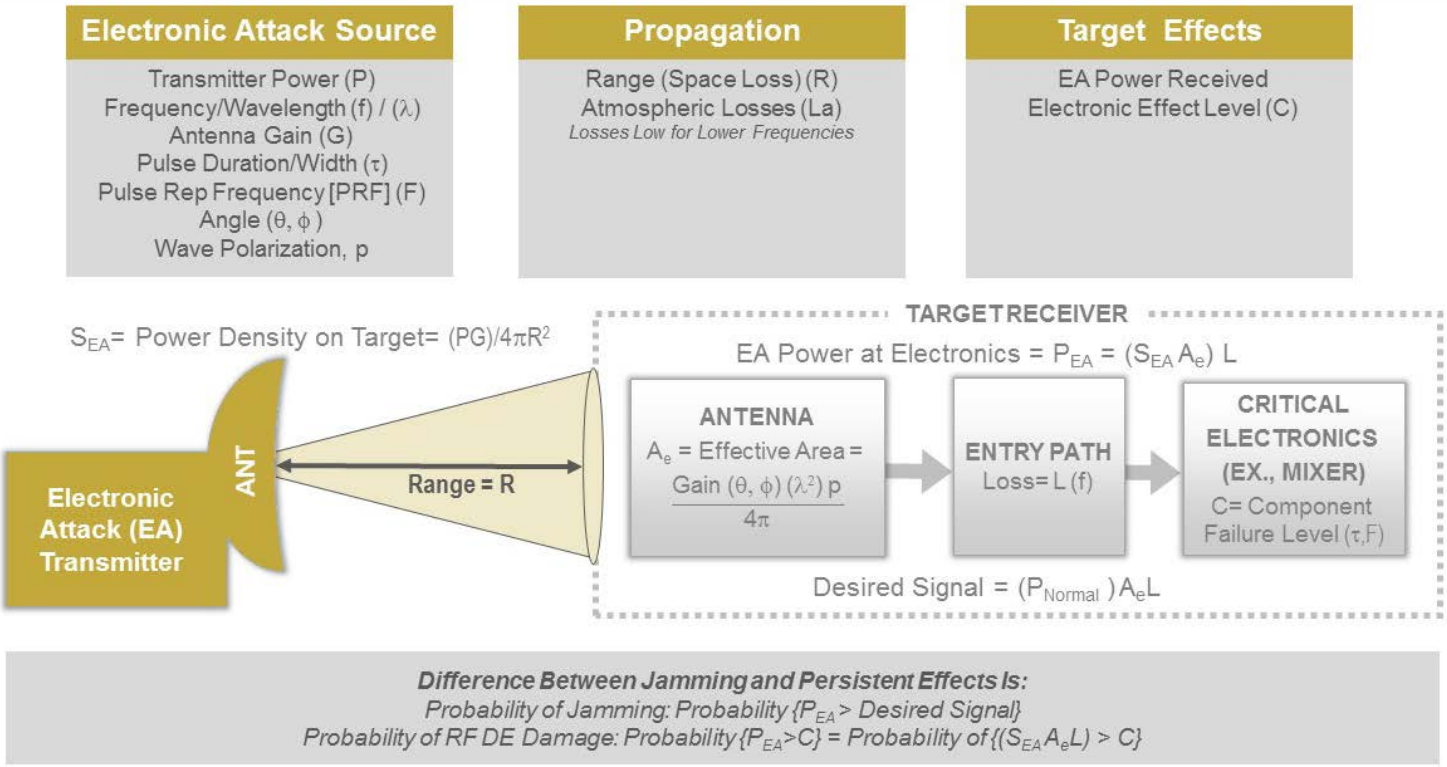


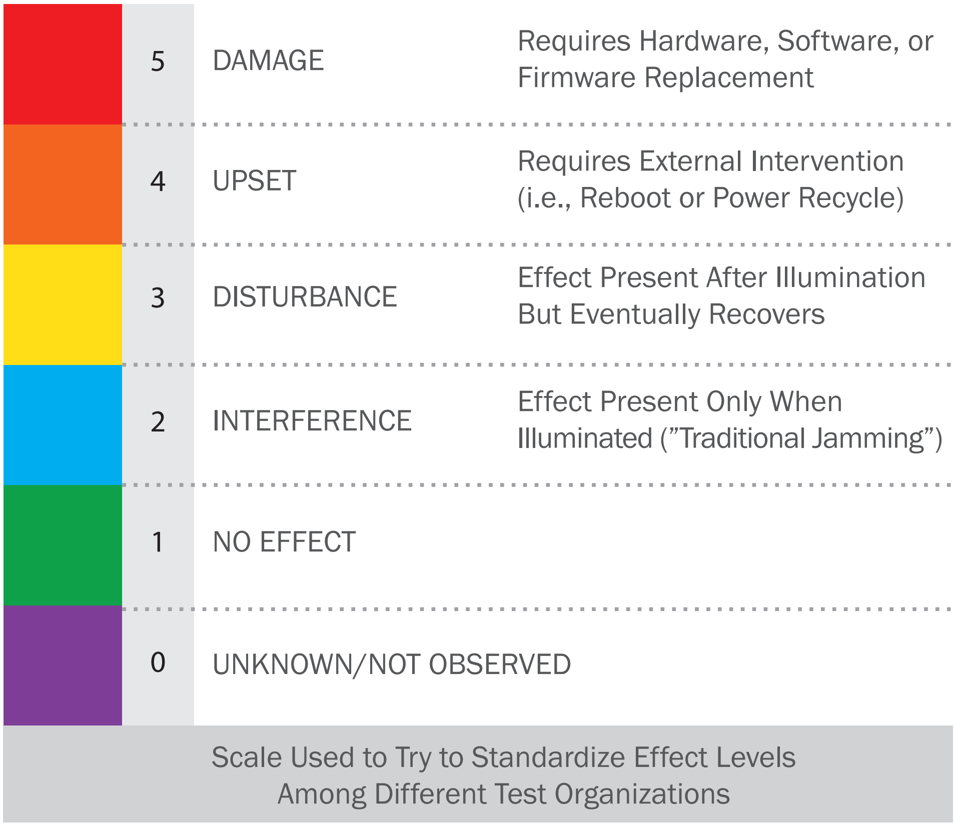
Figure 9: A Typical EA Scenario and the Key Parameters to Determine the Probability of Jamming and the Probability of HPM Damage.

scale has been proposed to try to standardize the meaning of effect levels throughout organizations doing HPM tests. The scale includes temporary effects, such as interference and upset, all the way to permanent damage.

HPM MODELING AND SIMULATION (M&S)

M&S is extremely important in predicting/estimating HPM effectiveness against electronic targets. It can also be used in performing tradeoffs to optimize HPM DEWs and their effects. M&S tools are also useful for conducting sensitivity studies to identify critical parts of a problem and areas where experiments are needed. Figure 11 shows the M&S structure for HPM DEWs.

The base of the pyramid represents the underlying physics and engineering models that are used to determine the



🟥	5	DAMAGE	Requires Hardware, Software, or Firmware Replacement
🟧	4	UPSET	Requires External Intervention (i.e., Reboot or Power Recycle)
🟨	3	DISTURBANCE	Effect Present After Illumination But Eventually Recovers
🟦	2	INTERFERENCE	Effect Present Only When Illuminated (”Traditional Jamming”)
🟩	1	NO EFFECT	
🟪	0	UNKNOWN/NOT OBSERVED	

Scale Used to Try to Standardize Effect Levels Among Different Test Organizations

Figure 10: HPM Effect Scale and Definitions *(Source: DoD HPM DEW Effects Panel).*

HPM coupling inside a target. The next level up is "one-on-one engagement models," which estimate the probability of failure of a target as a function of the incident HPM energy and range. These models include AFRL's Radio Frequency Propagation and Target Effects Code (RFPROTEC) and ARL's Directed RF Energy Assessment Model (DREAM). In addition, the Directed Energy Panel for the Joint Munitions and Effectiveness Manual has recently developed the Joint RF Effectiveness Model (JREM), which is a combination of the best attributes of RFPROTEC (realistic RF generation and propagation models) and DREAM (target vulnerability model). The model manager for RFPROTEC, JREM, and now DREAM is the AFRL DE Directorate at Kirtland AFB, NM.

The next level up in the pyramid comprises the mission models, or "few-on-few models," such as Suppressor and the Extended Air Defense Simulation (EADSIM). These models use the probability of target failures from JREM or other models to determine measures of effectiveness, such as probability of mission success and loss exchange ratios.

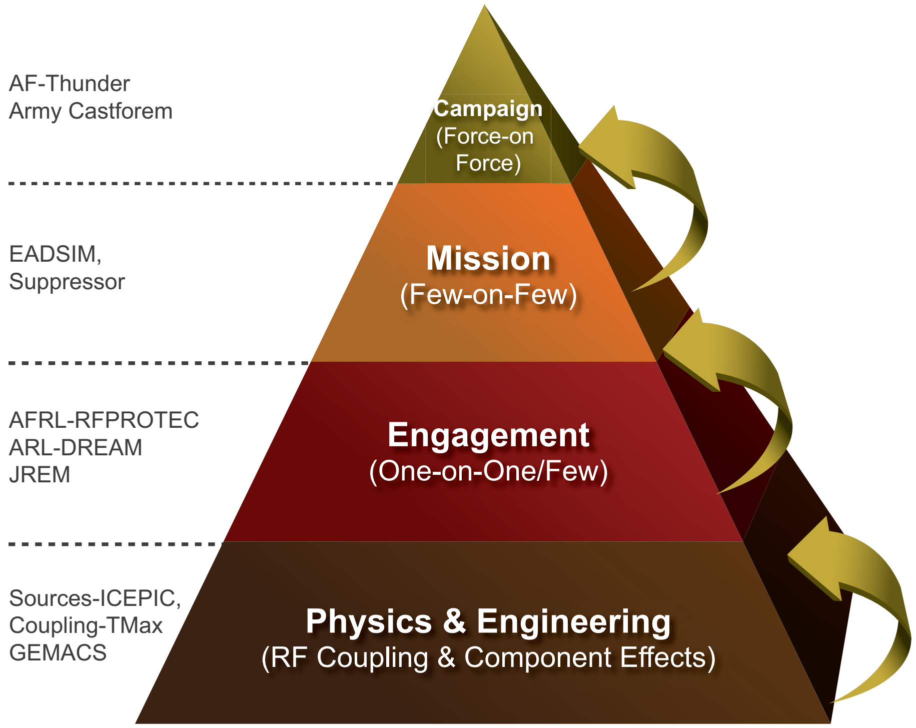
At the top of the pyramid are the campaign, or "force-on-force," models, such as the Army's Combined Arms and Support Task Force Evaluation Model (CASTFOREM) and the Air Force's Thunder model. These models can be used to look at the effectiveness of HPM DEWs on the battlefield. Typically, the results of each level are aggregated and passed up the pyramid as inputs to the next level.

PROTECTING SYSTEMS AGAINST HPM DEWs

To protect our systems against an adversary's HPM DEW, a combination of robust components, filters, and limiters must be used to reduce the amount of energy that gets to the component. New semiconductor technologies, such as silicon carbide and gallium nitride, can handle higher junction temperatures and thus show promise of being more robust to HPM pulses. In addition, the filters reduce the out-of-band energy, and limiters reduce in-band high-power pulses. For back door entry paths, grounding, bonding, and shielding appears to be the most practical solution.

In 1992, the U.S. Army Harry Diamond Laboratories (which is now part of ARL) developed a "High-Power-Microwave Hardening Design Guide for Systems [1]." The objective of the guide was to help system program managers and offices better understand HPM threats and how to mitigate them. The document consists of four volumes and is accessible through the Defense Technology Information Center.

Note that hardening against HPM energy is theoretically easy but may be difficult in practice due to changes in coupling. HPM effects on a target may also be subtle and difficult to determine unless there is some way of monitoring the target's behavior. That said, it is much cheaper to build in the hardening at the design stage of a system (estimated to be about 1 to 15% of the systems cost based on EMP hardening studies) as opposed to doing retrofit hardening after the system is built.



Model Results Are Aggregated and Passed Up Pyramid

- *M&S Useful for Predicting/Estimating RF DEW Effectiveness Against Electronic Targets*
- *Performing Tradeoffs to Optimize RF DE Systems and Effects*
- *Conduct Sensitivity Studies to Determine Critical Parts of Problem and Areas Where Experiments Are Needed*

Figure 11: Models and Simulations Used in HPM Studies.

CONCLUSION

Although HPM DEWs used to be thought of as a weapon of the future, with all the recent advances in technology and engineering, the future is now. These weapons offer the potential for speed-of-light engagements of multiple targets in all-weather with a high probability of hit, and they can produce scalable target effects from temporary to permanent. In addition, they can provide a relatively unlimited number of low-cost shots that are limited only by their fuel supply. And because HPM DEWs can attack targets with and without antennas and produce effects that last long after the energy is gone (dependent on the dwell time), they represent a unique UEA capability. ■

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BIOGRAPHY

JOHN TATUM is currently an electronic systems engineer with the SURVICE Engineering Company and has more than 43 years of experience in radar, EW, and RF DEWs. For more than 36 years, he served at ARL, where he was a team leader for the RF Effects Branch and directed and participated in RF effects experiments on various systems, ranging from avionics to missiles to computers and mines/improvised explosive devices. Mr. Tatum is a fellow of the Directed Energy Professional Society and has served on several Army/DoD panels for RF weapon threats, effects assessment methodology, and RF DEW M&S. He is also a member of the Association of Old Crows EW Society and the IEEE Microwave Theory and Techniques group. He holds a B.S. in electrical engineering from the University of Maryland and has completed graduate courses in communications and radar at the University of Maryland and The John Hopkins University.

CONFERENCES AND SYMPOSIA

JULY 2017

AIAA Propulsion and Energy Forum and Exposition (2017)
10–12 July 2017
Hyatt Regency
Atlanta, Georgia
http://www.aiaa-propulsionenergy.org/futureevents/ ▸

AUGUST 2017

Ground Vehicle Systems Engineering & Technology Symposium & Advanced Planning Briefing for Industry (GVSETS)
8–10 August 2017
Surburban Collection Showplace
Novi, Michigan
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2017 Strike Challenge
15–17 August 2017
Camp Rilea Armed Forces Training Center
Special Operations Training Ranges
Warrenton, Oregon
https://www.dsiac.org/events/2017-strike-challenge ▸

2017 Ground Vehicle Survivability & Force Protection Short Course
22–24 August 2017
TARDEC University Classroom
Warren, Michigan
https://www.dsiac.org/events/2017-ground-vehicle-survivability-force-protection-short-course ▸

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Advanced Technology Electronic Defense Systems (ATEDS) 2017
29–30 August 2017
Pavilion of the Hilton La Jolla Hotel
La Jolla, California
https://www.dsiac.org/events/advanced-technology-electronic-defense-systems-ateds-2017 ▸

SEPTEMBER 2017

JAS FY17 Program Review
19–21 September 2017
414 Combat Training Squadron (Red Flag)
Nellis AFB, Nevada
https://www.dsiac.org/events/jas-fy17-program-review ▸

DECEMBER 2017

Defense Manufacturing Conference (DMC) 2017
4–7 December 2017
Tampa Convention Center
Tampa, Florida
http://www.dmcmeeting.com/index.html ▸

For more events, visit:
dsiac.org/resourses/events ▸

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