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Rapid Deployment of Airborne Directed Energy Weapons: A Strategic Solution to Evolving Aerial Threats

June 2026

Col Ariel Dvorjetski, Israeli Air Force

Thesis Advisors: Raymond Jones, Professor
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Department of Acquisition, Finance and Manpower

Naval Postgraduate School

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Prepared for the Naval Postgraduate School, Monterey, CA 93943

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ABSTRACT

This study evaluates the feasibility of rapidly integrating airborne Directed Energy Weapons (DEWs) to counter evolving aerial threats such as unmanned aerial vehicles (UAVs) and cruise missiles. The research is based on the hypothesis that high Technology Readiness Level solid-state laser systems can be deployed within a three-year timeframe using tailored acquisition strategies. The methodology combines technology assessment, scenario-based operational modeling, and cost-benefit analysis, alongside evaluation of acquisition frameworks including the Middle Tier of Acquisition. Two operational scenarios—a localized UAV swarm environment and a large-scale missile campaign—are used to assess system effectiveness and scalability. The findings demonstrate that solid-state laser systems in the 30–50 kW range represent a feasible key performance parameter for near-term airborne integration, enabling effective engagement of high-volume aerial threats while maintaining acceptable size, weight, power, and cooling constraints. Results indicate that power generation and thermal management remain the primary limitations, while cost-per-engagement advantages significantly improve sustainability compared to kinetic interceptors. The study concludes that airborne DEWs are feasible within a three-year timeline when supported by rapid acquisition and phased integration. These systems enhance layered defense by improving cost-efficiency, endurance, and strategic resilience.



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ABOUT THE AUTHOR

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Colonel Dvorjetski is married to Diana, and they have three children.



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LIST OF ACRONYMS AND ABBREVIATIONS

ACAT	Acquisition Category
AFRL	Air Force Research Laboratory
AI	Artificial Intelligence
BDA	Battle Damage Assessment
C2	Command and Control
CAM	Control Account Managers
CBA	Cost-Benefit Analysis
CCB	Configuration Control Board
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CFD	Computational Fluid Dynamics
CLWS	Compact Laser Weapon System
CONOPS	Concept of Operation
CPFF	Cost Plus Fixed Fee
C-UAS	Counter-Unmanned Aerial System
DCS	Direct Commercial Sale
DEW	Directed Energy Weapon
DoD	Department of Defense
DT&E	Developmental Testing and Evaluation
EVM	Earned Value Management
FEL	Free Electron Laser
FEM	Finite Elements Modeling
FFP	Firm Fixed Price
FMS	Foreign Military Sale
FOC	Full Operational Capability
FPI	Fixed-Price Incentive
FSR	Field Support Representative
GAO	Government Accountability Office
GFE	Government Furnished Equipment
HEL	High Energy Laser



HELIOS	High Energy Laser with Integrated Optical-Dazzler and Surveillance
HIL	Hardware In The Loop
HPM	High Power Microwave
ICBM	Intercontinental Ballistic Missile
IDIQ	Indefinite Delivery/Indefinite Quantity
IMS	Integrated Master Schedule
IOC	Initial Operational Capability
IPT	Integrated Product Teams
ISR	Intelligence, Surveillance, and Reconnaissance
JCIDS	Joint Capabilities Integration and Development System
KPP	Key Performance Parameter
LAR	Launch Acceptability Region
LCSP	Life Cycle Sustainment Plan
LRIP	Low-Rate Initial Production
MDA	Milestone Decision Authority
MOSA	Modular Open System Architecture
MTA	Middle Tier of Acquisition
MVP	Minimum Viable Product
NDAA	National Defense Authorization Act
NPV	Net Present Value
ODIN	Optical Dazzler Interdictor, Navy
OFP	Operational Flight Program
OTA	Other Transaction Authority
OT&E	Operational Testing and Evaluation
PBL	Performance-Based Logistics
PDR	Preliminary Design Review
PEO	Program Executive Officer
PPBE	Planning, Programming, Budgeting, and Execution
PMO	Program Management Office
R&D	Research and Development
RDT&E	Research, Development, Testing, and Evaluation
RMP	Risk Management Plan



SHIELD	Self-Protect High Energy Laser Demonstrator
SIOM	Systemic Inquiry in Operational Mediation
SEP	Systems Engineering Plan
SOD	Systemic Operational Design
SOW	Statement of Work
SWaP-C	Size, Weight, Power, and Cooling
T&E	Test and Evaluation
TDP	Technical Data package
TRL	Technology Readiness Level
UAI	Universal Armament Interface
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force
WBS	Work Breakdown Structure



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EXECUTIVE SUMMARY

This thesis examines the feasibility and strategic implications of rapidly integrating airborne Directed Energy Weapons (DEWs) into operational military platforms to counter evolving aerial threats such as unmanned aerial vehicles (UAVs), cruise missiles, and loitering munitions. The study focuses on identifying a balance between technological maturity, acquisition flexibility, and strategic urgency, proposing a structured implementation plan for short-term deployment within a three-year timeframe. By connecting technical, operational, and institutional dimensions, this research provides a comprehensive framework to support decision-makers in advancing DEW capabilities as part of the U.S. and allied airpower modernization efforts.

A. PURPOSE AND RESEARCH QUESTION

The central purpose of this study is to assess whether airborne DEWs can be rapidly deployed to provide an operationally valid and strategically beneficial solution to emerging aerial threats. The guiding research question is: Can high-TRL (Technology Readiness Level) solid-state laser technologies be effectively integrated into airborne platforms within three years to create a credible and sustainable defensive capability?

To answer this question, the research explores three interrelated objectives:

- **Technological feasibility:** examining DEW subsystems, power levels, and integration constraints.
- **Programmatic and acquisition feasibility:** Evaluating processes and frameworks that can enable accelerated procurement and fielding.
- **Strategic and operational value:** Analyzing how DEWs affect deterrence, force readiness, and campaign-level decision-making.

B. BACKGROUND AND CONTEXT

The background for this research lies in the changing character of aerial warfare. The increasing use of low-cost aerial threats by near-peer adversaries and non-state actors has challenged traditional kinetic defense systems. Conventional interceptors are expensive, limited in magazine depth, and unsuitable for persistent defense against massed attacks. In contrast, Directed Energy Weapons—particularly Solid-State Lasers



(SSLs)—offer deep magazines, low cost per shot, and scalable power, making them a potential paradigm shift in defensive warfare.

However, despite decades of investment, DEWs have remained largely experimental due to technical complexity, integration barriers, and bureaucratic acquisition cycles. The emergence of high-TRL solid-state laser systems and compact power management solutions now offers an opportunity to transition from research to fielding. This thesis focuses on exploiting this technological inflection point by identifying a pathway for rapid integration and operational deployment, aligned with modern acquisition reform trends such as Middle Tier of Acquisition (MTA) and Agile Development approaches.

C. METHODOLOGY AND FRAMEWORK

The research employs a systemic and multi-layered methodology, combining technical assessment, acquisition analysis, and strategic evaluation.

- ***Technology Assessment:*** The study analyzes current DEW technologies across key parameters—power output, weight, cooling requirements, and platform compatibility. The focus is on solid-state lasers, given their relatively high TRL (6–8) and demonstrated capability in airborne testbeds such as the High Energy Laser (HEL) Demonstrator programs. Comparative evaluation includes Free Electron Lasers (FELs) and Hybrid Electric Lasers, though these remain at lower TRLs.
- ***Acquisition and Programmatic Analysis:*** The thesis applies Defense Acquisition University (DAU) and DoD regulatory frameworks to map feasible pathways for rapid fielding. It identifies how requirements tailoring, incremental capability releases, and rapid prototyping authorities can bridge the gap between laboratory technology and operational capability. Special attention is given to Work Breakdown Structure (WBS), Statement of Work (SOW) design, and Test and Evaluation (T&E) scheduling as accelerators of execution.
- ***Strategic Analysis:*** Using Systemic Operational Design logic, the research evaluates DEWs as part of a force-building and deterrence ecosystem. The analysis considers strategic signaling, resource allocation, and inter-service integration, especially between the U.S. Air Force, Security assistance agencies, and allied forces such as the Israeli Air Force. The study explores the balance between “technology push” (innovation-driven) and “requirement pull” (operational need-driven) approaches in defense modernization.

D. KEY FINDINGS AND ANALYSIS



The analysis reveals that solid-state laser technology is the most mature and practical option for rapid airborne integration. Power levels of 30–50 kW are currently achievable in compact, flight-ready configurations, allowing for engagement of Class II–III UAVs and select missile threats. Key enabling factors include advances in thermal management, battery and generator efficiency, and beam control stabilization.

The research identifies that power availability and platform compatibility are the main limiting factors. Larger platforms such as C-130J can host higher-power systems, while fighter-class aircraft remain constrained by weight and energy generation capacity. A hybrid deployment strategy—prioritizing airborne command and ISR aircraft for initial integration prior to a fighter jet operational evaluation —offers a realistic near-term path while informing future miniaturization for tactical fighter aircraft.

From the acquisition perspective, the study finds that the traditional PPBE process and ACAT I oversight are incompatible with three-year integration timelines. Instead, Middle Tier of Acquisition (MTA) pathways provide a compliant yet flexible framework for rapid prototyping and fielding. Integration of DEWs under an Urgent Capability Acquisition model could further compress schedules if justified by operational need. The research also notes that collaboration between FMS and DCS channels can facilitate international cost-sharing and interoperability, enhancing industrial and political feasibility.

At the strategic level, DEWs offer a credible and scalable complement to kinetic systems, enhancing deterrence through persistent, non-escalatory defense options. The ability to neutralize UAV swarms without depleting missile inventories strengthens resilience and operational endurance. However, the study warns that premature fielding without sufficient testing may risk system credibility and operator trust. Therefore, a spiral development approach—deploying limited capabilities while refining subsystems—balances speed with reliability.

E. CONCLUSIONS

The findings support the central hypothesis: airborne solid-state laser systems can be integrated within three years using mature technologies and tailored acquisition



frameworks. Such integration is both technically feasible and strategically advantageous, provided that power, cooling, and testing constraints are managed systematically.

The study concludes that success depends on three critical enablers:

- **Institutional Adaptation:** Shifting from rigid, milestone-based acquisition toward flexible, iterative models emphasizing prototype feedback loops.
- **Industrial Coordination:** Synchronizing efforts between prime contractors, subsystem developers, and international partners to minimize redundancy and accelerate integration.
- **Operational Experimentation:** Embedding early DEW capabilities in live exercises to build user confidence and inform incremental upgrades.

The research reinforces that DEWs should not be viewed as replacements for kinetic systems but as integrated layers within a broader defense architecture. The adoption of airborne DEWs aligns with the strategic logic of cost-imposition, escalation control, and sustained readiness in modern warfare.

F. RECOMMENDATIONS

- ***Adopt a Rapid Integration Pathway (MTA Model):*** The U.S. Air Force and allied partners should designate the airborne DEW program as a Rapid Fielding Initiative under MTA authorities, targeting initial operational capability within three years.
- ***Prioritize Platform Integration Sequencing:*** Begin with 30–50 KW High Energy Laser integration on large multi-mission aircraft (e.g., C-130J) to validate laser performance and thermal management before adapting the technology for fighter platforms.
- ***Implement a Spiral Test and Evaluation Process:*** Use iterative testing cycles, combining simulation, ground testing, and live flight demonstrations, to reduce risk and accelerate certification.
- ***Establish Joint International Collaboration:*** Encourage cooperative development between the U.S., Israel, and select NATO partners to share R&D costs, standardize interfaces, and strengthen operational interoperability.
- ***Align Doctrine and Training:*** Update operational doctrines, pilot training, and maintenance procedures to integrate DEWs as a functional component of air defense missions rather than as stand-alone technologies.

G. SUMMARY

This research demonstrates that the rapid integration of airborne Directed Energy Weapons represents a realistic and strategically necessary evolution in modern air defense. The convergence of mature solid-state laser technologies, adaptive acquisition



policies, and urgent operational demand provides a unique opportunity to transition DEWs from laboratory concepts to battlefield assets. By combining technological readiness with organizational agility, this thesis contributes a practical roadmap for turning potential into capability—bridging the gap between innovation and national defense.



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DISCLOSURES

The views expressed in this thesis are those of the author and do not necessarily reflect the official policy or position of the Naval Postgraduate School, the Department of Defense, or any other U.S. Government agency, as well the Israeli Air Force, the Israeli Ministry of Defense, or any other Israeli Government agency. This thesis was prepared as part of an academic requirement and is not intended to represent official guidance, policy, or endorsement by any institution.



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I. INTRODUCTION

This chapter establishes the foundation of the research by presenting the evolving aerial threat environment and the limitations of current defense approaches. It defines the core operational problem, introduces the main and supporting research questions, and outlines the methodological framework used in the study. In addition, the chapter clarifies the scope and limitations of the research and provides an overview of the thesis structure, linking the problem to the analytical and solution-oriented chapters that follow.

A. PROBLEM STATEMENT

The need for airborne Directed Energy Weapons (DEWs) is becoming more urgent as modern aerial threats, especially unmanned aerial vehicles (UAVs) and cruise missiles, evolve faster than traditional kinetic defense systems can respond. This urgency is emphasized by recent studies exploring the economic and strategic challenge of countering low-cost aerial threats (Rassler, 2024). Conventional interceptors like surface-to-air missiles are expensive and limited in capacity, making them ineffective against low-cost, swarming threats. This imbalance, in which expensive interceptors are used against cheap and disposable adversaries, creates an unsustainable defense strategy that consumes resources and reduces strategic advantages over time.

High Technology Readiness Level (TRL) solid-state lasers, a type of DEW, present a promising alternative by offering low-cost and high-efficiency engagement capabilities. These systems can neutralize multiple targets during a mission, significantly improving the cost-effectiveness of aerial defense. Recent studies highlight the progression of technological solutions from traditional methods to disruptive technologies (Jordan, 2021), aligning with the rapid deployment of DEWs to counter evolving threats.

Recent real-world examples, such as operations in the Red Sea, have shown the potential of DEWs to effectively counter aerial threats at much lower costs compared to traditional munitions (Johnson, 2024).



Deploying DEWs within a three-year timeframe highlights the need to focus on mature technologies that can avoid the long development periods associated with experimental systems. This study identifies the key performance parameters (KPPs) of such a system that can be operational within this timeframe, determines the most suitable technologies, and evaluates whether an airborne platform with an integrated DEW is a valid solution. It focuses on the complex link between the strict requirement of having an operational product within a short timeline, using mature technology, and the program milestones and activities needed to make this achievable.

A key question of this research is whether to follow a “technology push” or a “requirement pull” approach, or possibly a unique combination of both, to develop a technological solution that meets operational needs. This approach seeks to balance the push for cutting-edge technology with the demands of the battlefield, aiming to deliver an operational system within the defined constraints.

This study examines the power levels required for a DEW that can be integrated into an airborne system using mature technology deployable within a three-year timeframe. A critical question is which laser technology: solid-state laser, free electron laser (FEL), or chemical laser, provides the most suitable balance between performance, integration feasibility, and operational effectiveness. The analysis also evaluates whether a system with limited capabilities can offer a more cost-effective solution than current air-to-air missiles. In addition, the study determines the minimum number of targets per sortie required to justify the system’s operational effectiveness within an airborne platform.

Another important aspect of the research is determining the physical size requirements of the DEW on an airborne platform, which affect other performance requirements. A key question is whether an intermediate step of integrating the system on a transport aircraft as a risk reduction phase would be beneficial, or if it might have negative consequences for the overall program. These interconnected requirements, combined with the challenging timeline, greatly influence the KPPs and the technical design of the system.



This study focuses on a scalable and adaptable approach, such as deploying a solid-state laser around 30 kW with the capability of approximately 10 shots per sortie, to effectively address both current and future threats. This approach aligns with broader defense strategies that emphasize rapid deployment and technological integration to maintain superiority in increasingly complex aerial environments. The research validates the proposed concept from a holistic programmatic perspective, assessing its feasibility within the strict requirements and time constraints of modern defense needs.

B. RESEARCH QUESTIONS

In addressing the urgent need for innovative defense solutions against modern aerial threats, this research is guided by a central question: How can Directed Energy Weapons be effectively integrated onto airborne platforms within a three-year timeframe to counter threats such as UAV swarms and cruise missiles in a cost-effective and sustainable manner? To support this overarching inquiry, five secondary questions shape the investigation. These include identifying the essential key performance parameters (KPPs) needed for DEWs to be viable on airborne platforms, determining the most suitable DEW technology for rapid deployment, and evaluating the cost-effectiveness of DEWs compared to traditional defense systems. Additionally, this study explores the integration challenges posed by SWaP-C (Size, Weight, Power, and Cooling) constraints and examines the strategic adaptability of DEWs across different threat scenarios. These research questions are informed by systemic operational design principles that emphasize the need to align technological advancements with operational requirements while maintaining flexibility to adapt to changing defense landscapes (Graicer, 2017). Addressing these questions requires incorporating leadership strategies that emphasize systemic alignment, iterative learning, and adaptability (Montgomery, 2008). By integrating insights from operational research and scenario-based planning, this study aims to contribute to the strategic deployment of DEWs in modern aerial defense. The research questions are as follows:



1. Main Research Question:

How can Directed Energy Weapons be effectively integrated onto airborne platforms within a three-year timeframe to counter modern aerial threats, such as UAV swarms and cruise missiles, in a cost-effective and sustainable manner?

2. Top Five Secondary Research Questions

Key Performance Parameters (KPPs): What are the essential key performance parameters required for DEWs to meet operational needs on airborne platforms within a three-year deployment timeline?

Technology Selection: Which DEW technology (e.g., solid-state lasers, free electron lasers) offers the best balance of performance, integration feasibility, and operational efficiency for use on airborne defense platforms?

Cost-Effectiveness Analysis: How does the cost per engagement of DEWs compare to traditional kinetic systems when countering high-volume, low-cost threats, and what are the broader economic impacts on defense budgeting and resource allocation?

Operational Challenges and Integration Feasibility: What are the primary challenges associated with the SWaP-C requirements for DEWs on airborne platforms, and how can these challenges be mitigated to ensure reliable deployment and functionality?

Strategic Adaptability: How can DEWs be incorporated into layered defense strategies to address both localized threats (e.g., UAV swarms) and long-range, strategic threats (e.g., missile campaigns), ensuring their adaptability and resilience across different operational scenarios?

C. METHODOLOGY

1. Project Management Imperatives and Strategic Implementation

To achieve the rapid deployment of Directed Energy Weapons within a three-year timeframe, a strong and flexible project management approach is needed, focusing on speed, adaptability, and strict oversight. Key actions include setting clear and realistic



milestones, using agile development methods, and fostering close cooperation between military stakeholders and industry partners. These methodologies align with principles that emphasize the importance of adaptive strategies for achieving rapid technological innovation under tight timelines (Reeves et al., 2015).

Project management should also address the specific technical challenges related to DEWs, ensuring that the systems are reliable, adaptable, and capable of meeting the fast deployment schedule. The Department of Defense’s Directed Energy Futures report highlights the importance of managing these challenges through structured acquisition frameworks and cross-sector collaboration (Air Force Research Laboratory, 2020). Setting realistic goals and aligning them with operational requirements ensures smoother transitions from development to deployment.

Strategic implementation requires effective coordination of resources, compliance with regulatory requirements, and careful risk management throughout the development of the DEW system. Directed energy systems must be aligned with broader defense goals, focusing on rapid deployment and technological innovation. The U.S. Government Accountability Office (GAO, 2023) underscores the importance of transition planning and the need to mitigate the “valley of death” that often hinders emerging technologies from moving into full operational capacity.

To align project management with broader strategic goals, the integration of Systemic Operational Design (SOD) principles offers a dynamic framework for addressing the complexities of deploying DEWs within a constrained timeline. SOD encourages viewing systemic tensions—such as balancing technological innovation with operational readiness—not as barriers but as opportunities to optimize strategy and prioritize critical resources (Graicer, 2017). For instance, framing the three-year deployment window as a “productive tension” can accelerate decision-making and drive innovation. By incorporating SOD’s iterative feedback loops and modular design principles, project managers can create adaptive pathways that account for both immediate deployment goals and long-term scalability. This strategic alignment ensures that DEWs are positioned not merely as technical solutions but as pivotal elements in achieving multi-domain defense superiority.



Setting up dedicated testing and evaluation processes enables ongoing feedback and allow for continuous improvements, ensuring that DEWs achieve the high standards needed for operational use. Tools like digital twins and predictive analytics can further enhance the development process. As highlighted by Weinberg (2023), these advanced tools allow project teams to model potential challenges and optimize development paths in real-time, improving decision-making and minimizing risks.

Using advanced project management tools, like digital twins and predictive analytics, can further improve the development process by modeling potential challenges and optimizing the development paths. These tools help project teams to foresee risks, make better decisions, and adjust strategies in real-time, ensuring that the DEW system is delivered on schedule, stays within budget, and meets the operational needs.

2. Scalable Airborne Directed Energy Weapon Solution for Operational Scenarios

As part of the effort to define the “sweet spot” between the technology push and requirements pull for the system design of airborne DEWs, this study provides an additional layer of analysis, transitioning from the integration of DEWs on a single aircraft to evaluating a full fleet-wide operational solution. To ensure the system’s validity across different operational contexts, a full-scale operational research approach is necessary. This forms the foundation for mission engineering and fleet-wide effectiveness, addressing the broader strategic needs of national defense.

For this purpose, analyzing two distinct scenarios is crucial. The first is a short-range, Israel-Hezbollah-driven scenario that reflects localized threats relevant to U.S. forces in specific Areas of Responsibility (AORs). In this scenario, daily swarm UAVs and missile barrages overwhelm existing defense systems, posing a high-volume, low-cost threat. By evaluating DEWs in this constrained environment, the research assesses how effectively these systems can alleviate the pressure on traditional kinetic defenses, providing rapid, cost-effective engagements while maintaining operational resilience (Chaari & Al-Maadeed, 2020; Taylor, 2021).

The second scenario, driven by Iran’s missile and UAV capabilities demonstrated in its attack on Israel, represents a long-range, full-scale campaign, such as one that could



be relevant to a future challenge in INDOPACOM, where intercontinental threats are a primary concern. This scenario allows the research to explore the scalability of DEWs across a fleet-wide deployment, focusing on how the technology can be utilized to defend against advanced, strategic threats, including ballistic missiles. By modeling these scenarios, the research helps determine the optimal number of DEW systems required, their positioning across multiple platforms, and the overall operational efficiency of the defense system (Sayler et al., 2024; Othman, 2024).

These scenarios are essential for understanding the robustness of the DEW solution, where operational scalability remains critical. This aligns with strategic principles for scenario-based planning in modern defense (Danzig, 2011). The scenarios test the system's versatility across diverse environments and provide insights into the Command and Control requirements crucial for effective mission integration. A critical element of this research is assessing whether a single, rapidly deployable DEW solution can address both scenarios, as developing two unique systems within the highly constrained schedule is not feasible. This constraint represents a hard requirement in the research, emphasizing the need for a flexible, multi-role system capable of adapting to different threat environments (Williams et al., 2022).

3. Cost-Benefit Analysis as a Methodological Framework

To assess the economic and operational viability of DEWs, this study employs Cost-Benefit Analysis (CBA) as a central evaluative framework. CBA enables a systematic comparison of the financial investments required for DEW integration against their expected operational benefits, such as cost per engagement and strategic adaptability. This methodology incorporates key metrics, including cost-effectiveness ratios, net present value (NPV) calculations, and long-term scalability projections. Drawing on frameworks like those outlined by Melese et al. (2015) and operational insights from the Naval Postgraduate School (Fiedler et al., 2015), the study evaluates whether DEWs provide a sustainable alternative to traditional kinetic defense systems. By embedding CBA within the methodology, the research ensures a rigorous, data-driven approach to understanding the trade-offs associated with deploying DEWs in modern defense architectures.



Ultimately, the research delivers a holistic approach to integrating Airborne DEWs into both localized skirmishes and large-scale campaigns, ensuring the system design is optimized for fleet-wide deployment and capable of adapting to evolving and diverse threats.

D. LIMITATIONS AND SCOPE

This study focuses on the rapid deployment and integration of airborne Directed Energy Weapons as a cost-effective solution to evolving aerial threats within a constrained three-year timeline. While the research aims to provide actionable insights, certain limitations must be acknowledged to manage expectations and contextualize findings.

1. Time Constraints

This research is bound by a strict timeline of three years to achieve operational deployment of DEWs on airborne platforms. Given the urgency of countering evolving aerial threats, the study focuses exclusively on technologies that are at a high TRL, which ensures maturity and feasibility within the defined timeframe. Low-TRL technologies, such as free electron lasers and experimental chemical lasers, are deliberately excluded as their developmental timelines extend beyond the project's constraints.

2. Scope of Technology

The scope of this study is confined to Directed Energy Weapons, specifically solid-state lasers, due to their relative maturity, scalability, and suitability for airborne applications. While other DEW systems, such as microwave-based systems, have potential, their integration and operational testing fall outside the study's focus. Additionally, ground-based and naval applications of DEWs are beyond the scope of this research, as the objective is to develop a scalable solution specifically for airborne platforms.

3. SWaP-C Constraints

SWaP-C factors present significant limitations in integrating DEWs onto existing aircraft. Airborne platforms, especially fighter jets and transport aircraft, have strict



SWaP-C requirements that influence the design, power management, and operational performance of DEWs. These constraints dictate the feasibility of integrating high-power laser systems without extensive and costly modifications to the host aircraft.

4. Operational Context

This study assumes two primary operational scenarios to evaluate the deployment of DEWs: (1) localized, high-intensity UAV swarm threats and (2) strategic, long-range missile campaigns. The findings and recommendations may not generalize to other operational contexts, such as naval or ground-based applications. Furthermore, the study is constrained to the U.S. Department of Defense (DoD) context, with limited applicability to allied or international forces unless explicitly stated.

5. Data Availability

The analysis relies on publicly available data, reports, and historical case studies. Classified or proprietary data from defense contractors and military agencies, which could offer deeper insights into DEW integration challenges and performance metrics, are not accessible for this research. This limitation may constrain the granularity of the findings and necessitate certain assumptions about system performance and deployment feasibility.

6. Programmatic Focus

The research is focused on providing a programmatic and technological roadmap for DEW integration rather than exhaustive tactical or strategic doctrine development. While integration into layered defense strategies is discussed, the study does not involve doctrinal or command-and-control frameworks that govern multi-domain operations.

7. External Factors

Uncontrollable external factors, such as regulatory hurdles, unforeseen technical failures, or budgetary constraints, are acknowledged as potential risks to the successful deployment of DEWs. These factors, while critical, are outside the scope of this study's direct control and are highlighted as areas for further investigation and mitigation planning.



E. THESIS OUTLINE

Chapter I, **Introduction**, lays the foundation for your thesis, addressing the core issue of modern aerial threats and the pressing need for DEWs. It articulates the problem statement, emphasizing the unsustainable defense strategies currently employed against low-cost aerial threats like UAVs and cruise missiles. The chapter also presents the research questions, outline the scope and limitations of the study, and provide a roadmap for the subsequent chapters, setting the stage for a focused and systematic exploration of the topic.

Chapter II, **Background**, provides the contextual groundwork for the research. It begins with a deep dive into the evolving threat landscape, highlighting the inadequacies of traditional kinetic defense systems. Enhanced technological comparisons showcase the strategic advantages of DEWs, such as cost efficiency and rapid engagement, while also discussing their technical and operational challenges. The chapter also introduces risk mitigation strategies and frames the conceptual framework that ties together the strategic importance of DEWs within broader defense initiatives.

Chapter III, **Literature Review**, critically examines existing literature to establish the academic and practical foundation of the study. It begins by analyzing the **policy and strategic context** relevant to the development and deployment of DEWs, followed by a detailed review of the **technological landscape**, including the maturity and potential applications of various DEW systems. The **operational effectiveness** of DEWs is assessed through case studies and empirical evidence, highlighting their advantages and limitations. Finally, the chapter identifies significant **research gaps and challenges**, particularly in the areas of rapid deployment, system integration, and cost-effectiveness.

Chapter IV presents **the strategic methodologies** for crafting an effective acquisition strategy for airborne Directed Energy Weapons (DEWs). Utilizing Systemic Operational Design (SOD) principles, the chapter explores the integration of technological capabilities with operational requirements while addressing the complexities of deployment. Rogers' Five Factors framework is employed to identify and mitigate adoption challenges, ensuring compatibility, trialability, and observability in the transition of DEWs to operational readiness. Drawing from case studies of DARPA, USPS, Tesla, and the FBI, this chapter highlights critical lessons on balancing innovation



with immediate operational needs. **Leadership’s role in aligning technology with strategic goals** is emphasized, particularly in fostering adaptability and collaboration. Finally, the chapter proposes modular design strategies for phased integration, prioritizing scalability and efficiency to support DEWs’ incorporation into layered defense systems.

Chapter V explores the application of the **Middle Tier of Acquisition (MTA) framework to expedite the prototyping and deployment of airborne DEWs**. It critiques traditional acquisition frameworks for their inability to accommodate disruptive technologies, advocating for MTA’s emphasis on rapid capability delivery. By analyzing successful programs, the chapter underscores the importance of balancing speed with oversight to ensure sustainability and operational effectiveness. Strategies for iterative testing and risk management are discussed, alongside enhancements needed in tailoring the MTA to address the complexities of DEWs, such as scalability and system integration. The chapter concludes by affirming MTA’s viability as a mechanism for meeting the urgent need for DEWs within a constrained timeline while maintaining strategic alignment.

Chapter VI, **Modeling the Battlefield: The Threat and the Airborne Directed Energy Weapon Solution**, presents a detailed simulation-based analysis of the evolving threat environment and the operational performance of airborne DEWs in countering it. Using scenario modeling, the chapter examines how DEWs perform against various threat types—including UAV swarms, cruise missiles, and long-range precision attacks—under realistic combat conditions. It identifies critical factors such as range, power, and engagement cycles, translating them into operational requirements and Key Performance Parameters (KPPs). Additionally, a **Cost-Benefit Analysis (CBA)** is conducted to compare the economic efficiency of DEWs against traditional kinetic defense systems, ensuring that the proposed solutions are both cost-effective and operationally viable. The chapter demonstrates how DEWs provide a decisive advantage by reducing intercept costs, extending engagement duration, and enhancing force resilience, thereby validating their role as a sustainable countermeasure in modern warfare.

Chapter VII, **Implementation Plan: Rapid Acquisition of Airborne Directed Energy Lasers**, translates the study’s analytical findings into a practical execution



framework. It presents a detailed implementation plan grounded in rapid acquisition principles, focusing on a three-year integration timeline. The chapter defines the organizational structure, program milestones, and acquisition pathways required to transition airborne DEWs from prototype to operational capability. It also introduces a fundamental Statement of Work (SOW) and Work Breakdown Structure (WBS) that delineate development phases, integration tasks, and testing objectives. Risk management, cost considerations, and interagency coordination are integrated to ensure executable and accountable progress toward full deployment.

Chapter VIII, **Summary**, synthesizes the findings, drawing conclusions about the feasibility and impact of integrating DEWs into modern aerial defense strategies. It highlights the research contributions, including the identification of critical KPPs, the evaluation of integration challenges, and the demonstration of DEWs' cost and operational efficiency. The chapter provides actionable **recommendations** for policymakers and defense planners, emphasizing the importance of addressing technical and strategic challenges to achieve successful deployment. It concludes by identifying **areas for further research**, suggesting directions for future studies to build on the findings and address unresolved issues.



II. BACKGROUND

The purpose of this chapter is to establish the foundational context for understanding the strategic and operational relevance of airborne Directed Energy Weapons (DEWs). Building on the problem outlined in Chapter I, this chapter expands the discussion by examining the broader defense environment, the evolving nature of aerial threats, and the limitations of existing solutions. By framing these elements, the chapter sets the conditions for analyzing why a new approach is required.

A. PROBLEM CONTEXT

The defense landscape is rapidly changing due to the increasing use of low-cost, high-volume aerial threats like unmanned aerial vehicles (UAVs) and cruise missiles, which disrupt conventional defense strategies. These threats are known for their ability to swarm, overwhelm, and take advantage of weaknesses in kinetic defense systems that rely on expensive interceptors with limited ammunition. The current kinetic defense approach, mainly based on surface-to-air missiles and similar technologies, is not sustainable against such tactics, where high-cost interceptors are used against disposable, low-cost targets.

DEWs, especially solid-state lasers, have emerged as a promising alternative, providing near-instant engagement capabilities at a much lower cost per engagement compared to traditional kinetic systems. Unlike conventional missiles, which are limited by reload times and physical stock of munitions, DEWs can operate continuously, constrained only by their power supply. Systems such as Optical Dazzler Interdictor Navy (ODIN) and High Energy Laser with Integrated Optical-Dazzler and Surveillance (HELIOS) have already shown their effectiveness in real-world situations, offering reliable defense against aerial threats at considerably reduced costs (Sayler et al., 2024). However, moving from prototype to operational deployment involves overcoming various challenges, including technical, logistical, and regulatory barriers, which are critical to achieve the pressing goal of a three-year deployment timeline.

This research focuses on addressing these challenges by integrating high-Technology Readiness Level (TRL) DEWs into existing airborne platforms. It involves



identifying the most suitable technologies and defining clear key performance parameters (KPPs) that align with strategic defense goals, including rapid deployment, cost-efficiency, and flexibility to adapt to evolving threats.

Deploying airborne DEWs within a constrained three-year timeline presents a host of operational challenges that impact every stage of development, from system design to integration and testing. A primary concern is the system's affordability and efficiency compared to traditional missile-based defenses, which are not cost-effective for countering low-cost, high-volume threats like UAV swarms. DEWs offer a sustainable alternative, but their deployment requires overcoming several critical technical hurdles. To achieve the rapid deployment of DEWs within a three-year timeframe, project management strategies must prioritize adaptability and alignment with strategic goals, as outlined in agile development frameworks (Reeves et al., 2015).

One of the major challenges is integrating DEWs into existing aircraft without extensive and costly modifications. Airborne platforms have strict size, weight, power, and cooling (SWaP-C) requirements that limit the feasibility of introducing new systems, as noted in analyses of integrating laser systems onto military platforms (Blau et al., 2018).

Solid-state lasers, the leading candidate for this application due to their maturity and reliability, still face challenges related to power management and beam dispersion in atmospheric conditions, which can degrade performance (Sabatini et al., 2015). Ensuring that these systems maintain effectiveness against advanced threats, such as maneuvering cruise missiles, requires ongoing development in beam control technologies and adaptive optics (Shi et al., 2023).

Another critical aspect is developing a comprehensive engagement doctrine that maximizes the DEWs' capabilities within a broader defense framework. DEWs need to be integrated with existing kinetic systems to form a layered defense that leverages the strengths of each approach. This integration will require new tactical concepts and doctrines that account for DEWs' unique characteristics, such as unlimited magazine depth and rapid engagement. Safety protocols must also be established to prevent



collateral damage or unintended harm to friendly forces, especially given the precision and power of laser systems (Cannin, 2021).

B. ENHANCED TECHNOLOGICAL COMPARISONS

Directed Energy Weapons offer several key advantages over traditional kinetic interceptors, particularly in terms of cost, speed, and precision (Johnson et al., 2023).

A significant advantage is the drastic reduction in cost-per-engagement. For example, while a single missile interceptor can cost millions of dollars per shot, the cost of firing a high-energy laser is only a few dollars. This cost differential becomes even more pronounced when dealing with large numbers of low-cost threats, such as drones or small cruise missiles, where traditional missile systems are economically unviable.

DEWs operate at the speed of light, providing near-instantaneous engagement capabilities that are critical against fast and maneuverable threats, such as hypersonic missiles. Unlike kinetic interceptors that must account for time-of-flight and target trajectory, DEWs can deliver pinpoint strikes on specific components of a target, disabling it without causing widespread collateral damage. This precision is particularly beneficial in environments where minimizing unintended damage is essential, such as urban areas or near friendly forces (Steinvall, 2021; Lazov et al., 2021).

Despite these advantages, DEWs face ongoing challenges related to power scaling, beam control, and integration into various platforms. Solid-state lasers are at the forefront of DEW development due to their maturity and scalability, but they still require significant advancements in power management and beam quality to reach their full potential (Blau et al., 2018; Weinberg, 2023). Free electron lasers (FELs) offer high power and tunable wavelengths but are less mature and face substantial size and cost constraints. Chemical lasers, while capable of high outputs, are largely outdated due to their reliance on hazardous chemicals and complex logistics.

Investments in advanced beam control, adaptive optics, and compact power systems are critical to overcoming these barriers and fully realizing the strategic value of DEWs. As these technologies mature, DEWs will become increasingly capable of



addressing emerging threats, such as stealthy drones and hypersonic missiles, solidifying their role as a cornerstone of modern and future defense strategies.

C. RISK MITIGATION STRATEGIES

The deployment of airborne DEWs involves dealing with a range of risks that can affect the system's performance, safety, and integration into existing platforms. The integration of airborne DEWs represents a pivotal advancement in modern aerial defense. As suggested by Rogers' Five Factors, achieving operational adoption involves addressing challenges like trialability and complexity in the deployment process (Gourville, 2006).

Among the primary technological challenges are power generation, cooling, and beam control, which are particularly difficult in the airborne environment. To address these issues, developing advanced solutions for power and thermal management is crucial. Sylvester (2014) emphasizes the importance of energy storage systems and scalable power solutions in mitigating these risks. Enhancing adaptive optics and beam quality is also necessary to ensure precise targeting, especially given the variable atmospheric conditions that can interfere with the laser beam. Advancements in adaptive optics have been shown to mitigate atmospheric interference and improve beam control for laser systems (Kim, 2024). Safety risks, such as unintentional exposure of the laser to friendly forces, civilians, or unintended targets, are significant challenges that must be carefully managed. To reduce these risks, strategies like implementing automated safety systems, geofencing, and deconfliction measures are important, as they can shut down the laser when non-combatants are detected in the operational area. Additionally, comprehensive training programs are vital to prepare operators, equipping them with the necessary skills and knowledge to handle DEWs safely and minimize the potential for accidents or errors.

Integration risks are inherent when introducing DEWs into existing defense platforms. (Lazov et al., 2021). Ensuring compatibility with current command-and-control networks and other defensive systems is vital to creating a cohesive multi-domain defense architecture.



Open architecture interfaces that facilitate seamless data exchange and coordinated operations are essential to maximizing the impact of DEWs. Ongoing collaboration between defense contractors, military stakeholders, and regulatory bodies will be necessary to address these challenges and standardize protocols for DEW integration.

D. COST-BENEFIT ANALYSIS AS AN EVALUATIVE FRAMEWORK

The integration of airborne DEWs into modern defense systems represents a crucial advancement in addressing vulnerabilities posed by emerging threats such as UAV swarms and cruise missiles. Evaluating the economic and operational feasibility of such systems is essential to inform strategic decision-making. Within this context, Cost-Benefit Analysis (CBA) emerges as a critical framework to assess the trade-offs inherent in the deployment of DEWs. This section explores the rationale for adopting a CBA approach, its core components, and its application to the current study.

Field and Spergel's foundational analysis (Field & Spergel, 1986) of space-based laser systems underscores the importance of balancing development costs with scalability. These insights are directly applicable to assessing the affordability and operational feasibility of airborne DEWS systems, particularly when deploying within stringent fiscal constraints.

Modern defense systems are increasingly constrained by budgetary limitations and resource shortages, requiring innovative solutions to effectively counter dynamic and evolving threats. DEWs present a compelling alternative to traditional missile-based systems due to their notably low cost-per-engagement and scalable operational capabilities. A recent analysis in the Journal of Economic Analysis (Mun et al., 2024), identifies cost-per-engagement as a critical metric for evaluating non-kinetic weapon systems. Applying this principle to DEWs can ensure a sustainable balance between operational performance and budgetary constraints.

However, DEWs implementation involves significant initial investments in research and development, platform modifications, and integration processes. The application of CBA allows defense planners to systematically evaluate these costs and



benefits, ensuring alignment with strategic objectives such as resource sustainability and interoperability within coalitions. Melese et al. (2015) provide a comprehensive framework for military cost-benefit analysis, emphasizing the integration of operational effectiveness metrics with economic models. Their approach offers a structured methodology to assess the trade-offs between cost and capability in the deployment of directed energy weapons.

The CBA framework in this study focuses on several essential elements. First, it assesses the cost per engagement, comparing DEWs, estimated at negligible cost per shot, against traditional missile systems, which range from \$750,000 to \$2.5 million per engagement. Second, it considers the substantial upfront investments required, including substantial budget in research and development over three years and Recurring Engineering (RE) cost for aircraft platform modifications. Third, the analysis examines operational benefits, such as theoretical “unlimited magazine” depth and enhanced engagement capabilities, allowing DEWs to neutralize multiple threats per sortie. Additionally, the framework incorporates a long-term economic evaluation through net present value (NPV) calculations, which include operational savings and engagement efficiencies projected over long term horizon. The CBA also acknowledges non-quantifiable impacts, such as strategic flexibility in adapting to diverse threat scenarios and the potential for improved coalition interoperability.

In applying this framework, the research addresses key questions that inform the practicality and scalability of DEWs. These include identifying the break-even point for engagements per sortie that surpass the cost-effectiveness of traditional missile systems, evaluating the impact of DEWs on resource allocation and mission readiness under constrained supply conditions, and exploring the broader strategic implications of transitioning to DEWs within a limited deployment timeline. It is interesting to note that a study by the Naval Postgraduate School (Fiedler et al., 2015) highlights the efficiency improvements achievable with HEL (High Energy Laser) systems when paired with advanced Battle Damage Assessment (BDA) capabilities. Their modeling and simulation approach demonstrated a 33% increase in kill effectiveness, providing a solid foundation for integrating cost-benefit metrics into HEL deployment scenarios.



Several foundational assumptions would guide such analysis. It is assumed that solid-state lasers will achieve operational readiness within three years, reflecting current research and development advancements. A sensitivity analysis, to reflect the different scenarios and battlefield arenas, is critical to assess the KPPs. Furthermore, the discount rate should be applied for the NPV calculations, to be consistent with established defense budgeting practices. These assumptions could provide a realistic foundation for evaluating the cost-effectiveness and operational feasibility of airborne DEWs.

The adoption of CBA significantly enhances strategic decision-making by providing evidence-based insights into resource allocation, scalability, and risk mitigation. The framework enables a comprehensive understanding of DEWs' economic and operational trade-offs, addressing challenges such as environmental sensitivity and integration costs while highlighting opportunities for expanded deployment across platforms and scenarios. A recent evaluation of radar-guided HEL systems (Bookout et al., 2019) highlights the cost-effectiveness of leveraging compact, vehicle-mounted solutions. This approach could be adapted to optimize airborne platform integration, reducing logistical footprints and operational costs.

In summary, CBA serves as a pivotal evaluative tool for determining the feasibility of integrating DEWs into modern defense systems. By quantifying both tangible and intangible impacts, the CBA framework ensures that DEW deployment aligns with strategic objectives and addresses practical challenges, reinforcing their role as a critical component of sustainable and adaptive defense strategies.

E. STRATEGIC THEORETICAL FRAMEWORKS

Theoretical frameworks provide the conceptual foundation for understanding and addressing the complex challenges associated with DEWs. Revisiting and refining these frameworks in the context of the literature reviewed is critical for aligning the theoretical underpinnings of DEWs with their practical and operational realities. This section explores the application of systems thinking, operational design principles, and emerging conceptual models to guide the development and deployment of DEWs, emphasizing methodologies that support strategic framework analyses, to be used for the current research, to address main research questions from a strategic standpoint.



1. Systemic Operational Design and Systemic Inquiry in Operational Mediation

Systemic Operational Design (SOD) offers a framework for integrating Airborne DEWs into defense systems by aligning strategy with technological innovations. SOD identifies systemic tensions and coordinates across multiple defense domains, focusing on principles like systemic framing, innovation-integration trade-offs, and decentralized command. These principles are essential for effective DEW deployment, ensuring a balance between technological advancement and operational readiness. Logistical challenges, including SWaP-C limitations, are addressed through modular design and collaborative innovation, enabling the successful integration of DEWs into modern defense architectures. The key elements and relationships of this framework are illustrated in Figure 1.

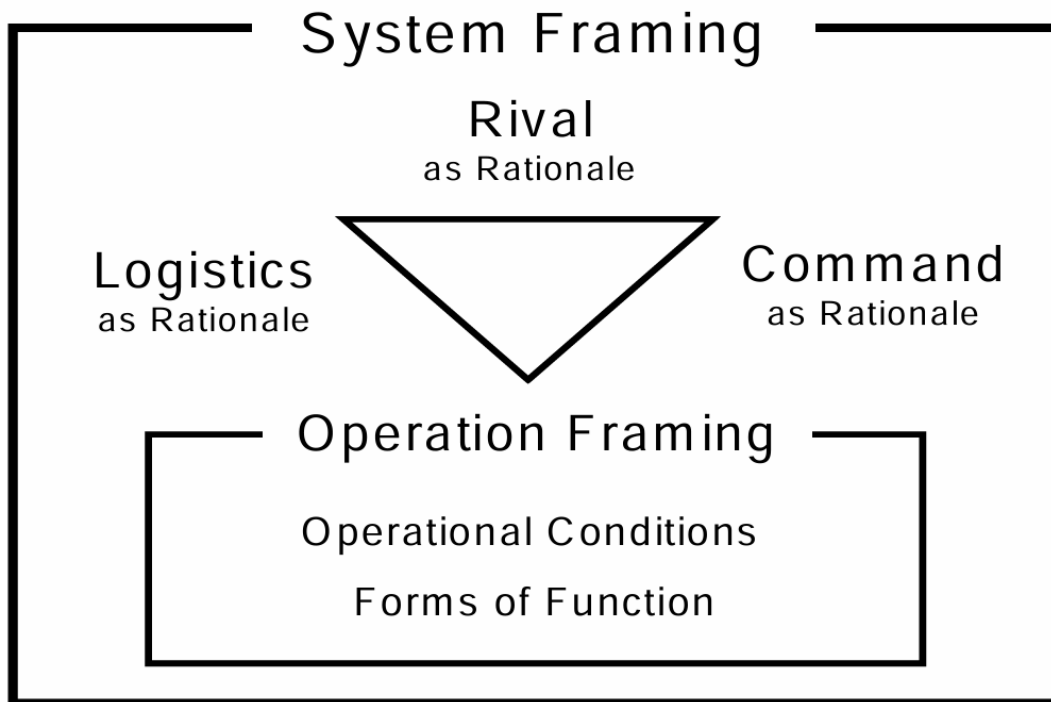


Figure 1. Systemic Operational Design (SOD) Framework
Source: Sorrells et al. (2005)

The evolution of this approach into the Systemic Inquiry in Operational Mediation (SIOM) framework is presented in Figure 2.

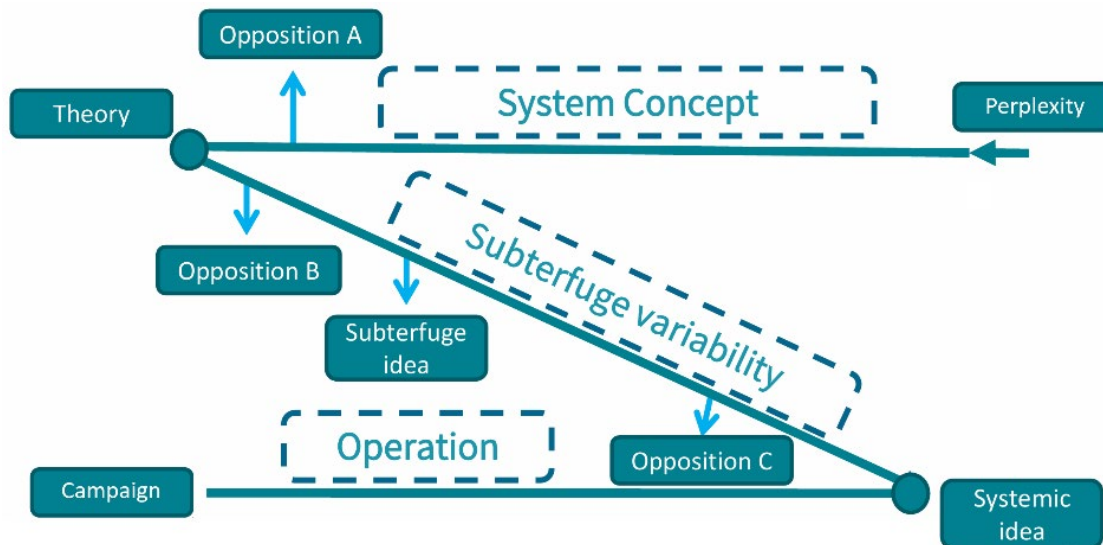


Figure 2. Systemic Inquiry in Operational Mediation Framework (Z-Model)
Source: Graicer (2017).

SIOM framework advances SOD principles by fostering cognitive agility and adaptability to dynamic environments. This approach is particularly useful for DEWs, where integration challenges often arise from SWaP-C constraints and the need for real-time adaptability in layered defense architectures (Graicer et al., 2022). For example, the Z-Model, an evolution of SOD, focuses on addressing systemic challenges through iterative refinement, emphasizing modularity and scalability in DEW deployment (Graicer et al., 2022). The SIOM framework facilitates the mediation of tensions between competing priorities, such as technology-push and requirement-pull dynamics, enabling defense planners to align innovation with operational readiness. The balance between technology-push and requirement-pull remains a central theoretical consideration in DEW development.

Technology-push refers to the proactive advancement of innovations, such as high-energy lasers (HELs) and adaptive optics, while requirement-pull focuses on addressing specific operational demands, such as countering UAV swarms or integrating DEWs onto legacy platforms (Tolliver et al., 2012; Shen et al., 2021).

2. Strategic Frameworks: Visionary, Adaptive, and Shaping Approaches

Frameworks such as adaptive, visionary and shaping strategy models provide actionable methodologies for navigating this dichotomy (Reeves et al., 2015). Adaptive

strategies prioritize iterative development and pilot programs, ensuring that DEWs meet immediate operational needs while refining capabilities for long-term deployment. Visionary strategies, on the other hand, focus on disruptive innovations that redefine defense paradigms, such as the development of multi-domain DEWs capable of engaging targets across land, sea, air, and space. Shaping strategies leverage collaboration across defense sectors, fostering partnerships with private firms and allied forces to streamline deployment.

3. Roger's Five Factors

Rogers' Five Factors is a framework that identifies the key attributes influencing the adoption of innovations: relative advantage, compatibility, complexity, trialability, and observability (Rogers, 2003). These factors evaluate how new technologies are perceived, integrated, and ultimately accepted by stakeholders, guiding strategies to overcome adoption barriers and enhance their success. It could offer strategic lens for accelerating the adoption of DEWs. The key dimensions of this framework are illustrated in Figure 3.

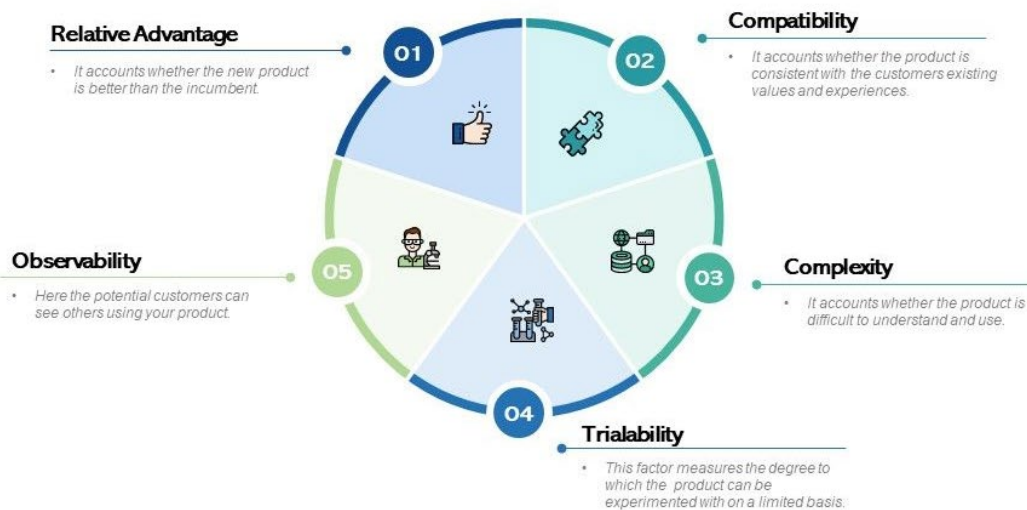


Figure 3. Roger's Five Factors Framework. Source: SlideTeam (2026).

Relative advantage highlights DEWs' cost-efficiency and scalability over traditional systems, with pilot programs demonstrating their operational superiority against threats like UAV swarms. **Compatibility** emphasizes seamless integration with existing platforms through modular designs, ensuring adaptability without extensive

infrastructure overhauls. **Complexity** is addressed by simplifying interfaces and providing operator training to foster trust and usability. **Trialability** enables phased rollouts, using airborne platforms to test engagement protocols and refine deployment strategies. Finally, **observability** underscores the importance of high-profile demonstrations to showcase DEWs' effectiveness, build stakeholder confidence, and reinforce their strategic value. Together, these factors guide the alignment of DEW innovation with defense objectives, ensuring their successful integration into modern military frameworks.

4. Emerging Conceptual Models

Emerging conceptual models, including modular design and adaptive systems, provide innovative approaches to DEW deployment. Modular design emphasizes flexibility and scalability through the use of interchangeable components, enabling customization for diverse operational scenarios (Michalska et al., 2024). For instance, modular architectures allow DEWs to be tailored for naval, airborne, and ground-based platforms, enhancing interoperability and cost-efficiency (Wostenberg et al., 2024). Insights from modular platform strategies further emphasize that standardization across components accelerates integration while lowering production and maintenance costs (Mckinsey, 2024). Adaptive systems focus on real-time responsiveness to dynamic conditions, such as atmospheric disturbances that degrade beam quality. Integrating machine learning algorithms into DEWs enhances their ability to analyze environmental data and adjust beam control parameters, ensuring consistent performance in adverse conditions (Edwards, 2021). Adaptive frameworks also facilitate cross-domain applications, positioning DEWs as integral components in multi-domain operations, a hallmark of strategic modularity frameworks (Mckinsey, 2024).

F. STRATEGIC IMPACT OF THE RESEARCH

The integration of airborne Directed Energy Weapons represents a pivotal advancement in modern aerial defense, addressing critical vulnerabilities posed by evolving threats such as UAV swarms and cruise missiles. This research highlights the viability of deploying high-TRL DEW systems within a three-year timeline,



demonstrating how mature, scalable technologies can transform defense strategies to counter cost-effective, high-volume adversaries efficiently (Sayler et al., 2024).

DEWs provide a paradigm shift in aerial defense, offering unprecedented capabilities in cost efficiency, precision, and rapid engagement. Unlike traditional kinetic systems, DEWs offer the potential for virtually unlimited magazine depth and lower per-shot costs, establishing a sustainable defense model for addressing both localized and strategic threats. By prioritizing technologies like solid-state lasers and focusing on operational requirements such as SWaP-C, this study outlines a clear path for integrating DEWs into existing airborne platforms without excessive risk or delays (Blau et al., 2018). These advancements underscore the importance of integrating mature systems while addressing technical challenges through incremental innovation (Danzig, 2011).

Strategically, the deployment of DEWs will enable the establishment of multi-layered defense systems that integrate kinetic and non-kinetic solutions, ensuring superior operational flexibility and resilience. The adaptability of DEWs to both localized, high-intensity skirmishes and large-scale campaigns positions them as a cornerstone of future defense architectures. By leveraging systemic operational design (SOD) principles, DEWs can be framed not only as tactical solutions but as key enablers of strategic adaptability, enhancing immediate readiness while paving the way for continued technological evolution and fleet-wide scalability (Graicer, 2017).

However, achieving these outcomes requires addressing key challenges. Technical hurdles, such as power generation, cooling, and beam control, must be resolved through targeted investments in adaptive optics, advanced power management, and modular system designs (Kim, 2024). Regulatory barriers and safety protocols must also be established to ensure responsible deployment, with emphasis on minimizing risks to civilians and friendly forces. These considerations align with scenario-based planning principles, which emphasize proactive mitigation of systemic risks to enhance operational outcomes (Williams et al., 2022).

The broader strategic implications of airborne DEWs extend beyond immediate operational gains. Their integration signifies a commitment to maintaining technological superiority in an era where asymmetric threats challenge traditional defense paradigms.



The success of this initiative will serve as a model for leveraging cutting-edge innovation to achieve rapid deployment, operational sustainability, and cost-effective defense solutions.

In conclusion, this research underscores the transformative potential of DEWs in redefining aerial defense. By bridging the gap between technology push and requirement pull, the deployment of DEWs offers a scalable, adaptable, and efficient solution to modern and future threats. With focused development and strategic implementation, airborne DEWs will not only address today's challenges but also establish a robust foundation for future defense capabilities, ensuring a decisive edge in an increasingly complex and contested security environment.



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III. LITERATURE REVIEW

The purpose of this literature review is to provide a deep and detailed analysis of the existing research and knowledge related to Directed Energy Weapons (DEWs). This review is a key part of the study because it helps to build a full picture of what has been done so far and where there are still gaps that need to be filled. By examining the technological, operational, economic, and strategic dimensions of DEWs, this chapter establishes the broader context within which these systems operate, highlighting their significance in modern defense architectures. DEWs, such as high-energy lasers (HELs) and high-power microwaves (HPMs), are becoming a central focus in modern defense technologies. These systems bring unique benefits like high precision, cost-effectiveness, and the ability to engage threats quickly. At the same time, they also bring challenges, including issues with integration, power supply, and the influence of environmental conditions on their performance. This review demonstrates a professional understanding of these issues and explains how they are addressed in the existing literature, while also pointing out areas where further research is necessary.

The review is organized to explore the major themes and trends in DEW development. These include the technological advancements that enable DEWs to operate effectively, their performance in real-world operations, and their economic and strategic value for modern defense systems. By analyzing a wide range of sources, including academic papers, government reports, and technical evaluations, the review paints a clear picture of what is currently known and identifies where knowledge is missing or incomplete. This chapter also looks ahead, discussing how new technologies and future developments might solve some of the current challenges. Areas like artificial intelligence, better beam control, and applications in space-based systems are examples of where DEWs may make a big impact in the future. This connection between what has already been achieved and what could be possible in the future is an important part of the research.



A. THE THREAT

The accelerating development and deployment of advanced aerial threats pose a significant challenge to national and global security frameworks. Traditional defense systems are increasingly inadequate against modern threats such as unmanned aerial vehicles (UAVs) and cruise missiles, which offer adversaries cost-effective, highly maneuverable, and scalable options to exploit gaps in existing defenses. These systems, particularly when deployed in swarms, can overwhelm interceptors and strain resource-limited air defense networks. Unlike conventional kinetic weapons, UAVs are not constrained by high production costs or limited operational flexibility. Instead, they benefit from rapid technological advancements, accessibility to dual-use components, and the ability to execute precision attacks or carry out reconnaissance missions with minimal logistical demands. As state and non-state actors continue to leverage these capabilities, the threat spectrum extends beyond military targets, increasingly targeting critical civilian infrastructure, disrupting economic stability, and challenging the geopolitical balance.

The proliferation of this threat is well documented in the literature, in researches like Iran's UAV Army – A Global Threat (Beeri, 2021), as well as The Propagation of the Iranian UAV Threat into Europe: Creating Opportunities Towards International Actions (Beeri & Lappin, 2023). The recent crisis in the middle east provided even additional most updated information, with the analysis on the emergence of Long-Range Stand-off Terrorism (Rassler, 2024).

Iran's "UAV Army" exemplifies a growing global threat, with its operations extending well beyond the Middle East. One prominent example is the use of Iranian Shahed 136 UAVs, which were supplied to Russia and used extensively in the war against Ukraine, as could be observed in Figure 4. These drones have targeted critical energy infrastructure, leading to widespread power outages that affected millions of homes and destroyed 40% of Ukraine's electricity grid during coordinated strikes in late 2022. Similarly, Iranian proxies such as the Houthi insurgents in Yemen have utilized Qasef-1 UAVs to attack the Saudi Arabian Abha airbase, damaging a passenger aircraft and infrastructure. Another alarming instance occurred when Iran's Shahed 129 UAVs,



equipped with anti-tank precision missiles, were deployed from Syria's T4 airbase against targets in Israel.

Hezbollah, one of Iran's primary proxies, operates an arsenal of over 2,000 UAVs, including Mohajer and Ababeel models. These drones have been used for both reconnaissance and direct attacks against Israeli targets, often evading detection due to their low radar signatures. In 2021, Hezbollah launched a series of UAV strikes against American forces in Syria, demonstrating how these drones are used to advance Iran's geopolitical objectives.

Moreover, Iran has extended its influence into the Western Hemisphere by transferring Mohajer-6 UAVs to Venezuela. With a range of 2,000 kilometers, these drones present a direct threat to the United States, as they could potentially be launched against targets in Florida or Puerto Rico. Iran's ability to produce and export such UAVs remains largely unaffected by international sanctions, as their components—often off-the-shelf civilian items—are easily procured through global markets.

To compound the threat, Iran has demonstrated the capacity to operate drone swarms, such as its "Swarm UAVs"—capable of overwhelming traditional air defense systems. These UAVs, each carrying combat warheads weighing up to 15 kilograms, can coordinate attacks on multiple targets simultaneously, increasing their lethality. For instance, in October 2021, a coordinated attack using Iranian drones targeted the U.S. Al-Tanf base in Syria, marking a significant escalation in the region.

This evolving threat is exemplified by Iran's missile and UAV programs, which have rapidly advanced in both sophistication and operational scope. For example, the April 2024 True Promise operation involved an unprecedented assault using 170 drones, 30 cruise missiles, and 120 ballistic missiles targeting Israel (Othman, 2024). This marked a significant escalation in Middle Eastern conflict dynamics, showcasing Iran's ability to coordinate multi-platform strikes involving UAVs like the Shahed 136 and advanced ballistic missiles such as the Kheibar and Emad.

These examples highlight the multi-dimensional threat posed by adversary's UAVs—spanning continents, targeting critical infrastructure, and leveraging proxy networks to destabilize regions. This asymmetry creates an unsustainable defense



dynamic, where high-value resources are consumed disproportionately against disposable, low-value targets. Furthermore, emerging technologies in hypersonic weapons and stealth capabilities continue to complicate threat detection and engagement, leaving critical gaps in aerial defense. The rapid advancement of these threats underscores the urgency for innovative solutions, such as DEWs, to address the growing tactical and economic vulnerabilities in modern defense architectures.

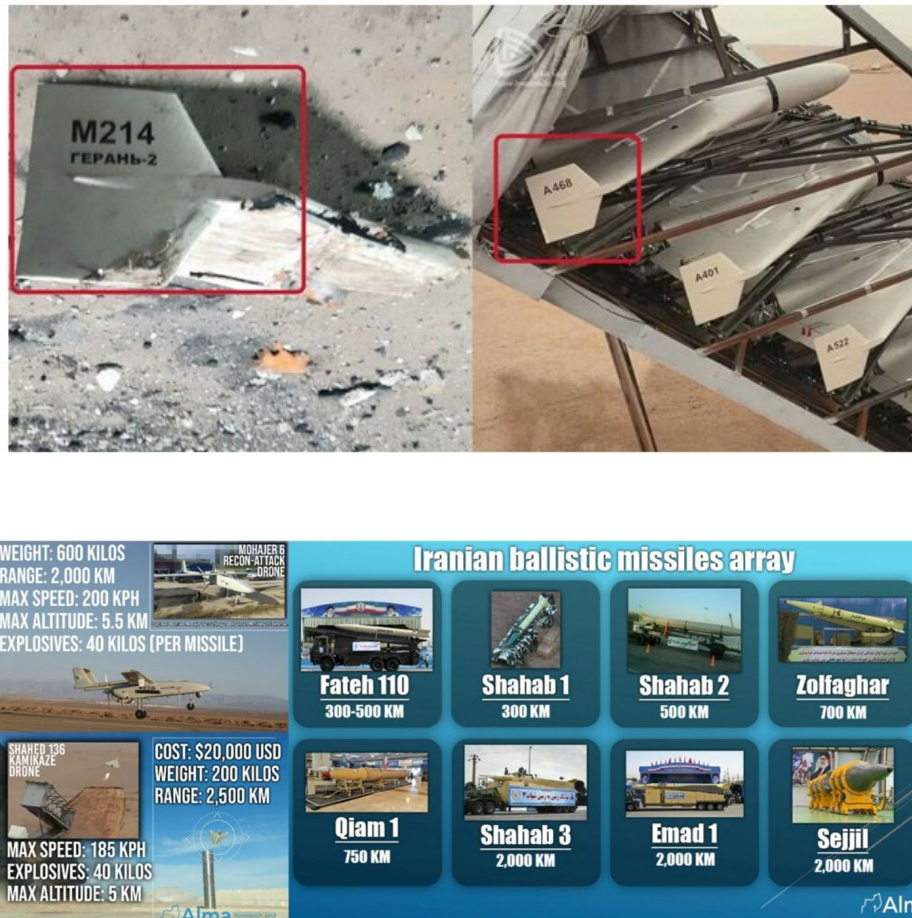


Figure 4. Upper Picture: The Wing of a Shahed 136 as It Appeared in an Iranian Propaganda Video (right) and a Wing of a Shahed 136 Shot Down in Ukraine

Lower Picture: The Propagation of the Iranian UAV Threat
 Source: Beerli & Lappin (2023).

B. TECHNOLOGICAL LANDSCAPE

The technological landscape of DEWs represents a critical advancement in modern defense capabilities, offering unique operational advantages and addressing the limitations of conventional weapon systems. DEWs encompass a range of systems that

utilize concentrated electromagnetic energy to incapacitate or destroy targets. These systems are broadly categorized into HELs, HPMs, and other electromagnetic spectrum technologies, each offering distinctive capabilities for various applications.

1. Definition and Classification of DEWs

Directed Energy Weapons, as defined in both theoretical and applied contexts, utilize electromagnetic waves or particles to disable or destroy adversary targets. Unlike traditional kinetic systems, DEWs engage at the speed of light and offer the potential for precise, scalable, and cost-effective operations. HELs, one of the most developed forms of DEWs, emit intensely focused beams capable of neutralizing aerial threats, such as UAVs and cruise missiles, or disabling optical sensors with precision (de Courcy Wheeler & Brehm, 2017). Similarly, HPMs disrupt electronic systems, offering non-kinetic alternatives to conventional explosives. These systems are increasingly recognized for their potential in layered defense architectures. For example, HEL systems integrated with naval platforms like the Aegis combat system provide a strategic advantage in maritime operations by defending against missile swarms while reducing reliance on kinetic (Mayfield et al., 2019). HPM systems, on the other hand, are effective in countering UAV swarms by disabling electronics without physical damage, highlighting their adaptability to evolving threats (Lyu & Zhan, 2021).

2. Evolution of DEWs: Historical Milestones

The development of DEWs has been shaped by decades of research and technological advancements. The Airborne Laser Laboratory, initiated in the mid-1970s, marked one of the earliest attempts to operationalize laser technologies for defense. This historical development of DEWs is well chronicled in the literature (Bernatskyi & Sokolovskyi, 2022). This program utilized gas dynamic CO₂ lasers mounted on airborne platforms to demonstrate the potential of high-energy beams in neutralizing aerial targets (Sabatini et al., 2015). Despite initial successes, early DEW programs faced challenges such as high energy demands and environmental sensitivity. For instance, chemical lasers, which dominated early research, required hazardous materials and extensive logistical support, limiting their practical application. Over time, advances in solid-state



laser technologies addressed many of these limitations, paving the way for more compact, reliable, and scalable systems suitable for modern military platforms (Sayler et al., 2024).

3. Modern Applications and Capabilities

Contemporary DEWs are characterized by their integration into existing combat systems and their ability to meet a wide range of operational requirements. For example, the U.S. Navy's High-Energy Laser and Integrated Optical-Dazzler with Surveillance (HELIOS) program has demonstrated the effectiveness of integrating HEL systems into naval defense strategies. HELIOS provides dual functionalities: targeting enemy assets and dazzling optical systems, thereby enhancing the versatility of naval operations (Mayfield et al., 2019). The adaptability of DEWs to different operational scenarios is further illustrated by the Directed Energy Counter-UAS program. This initiative highlights the use of high-energy lasers and microwaves in neutralizing UAV swarms, which represent a growing asymmetric threat. These technologies enable cost-effective engagements, reducing the dependency on expensive interceptors and offering continuous operational capability (Lyu & Zhan, 2021; Taylor, 2021).

4. Challenges in Technological Maturity

While DEWs offer unparalleled advantages, their deployment is constrained by several technological challenges. Beam control, power scaling, and energy efficiency remain critical areas of ongoing research. For instance, the effectiveness of HEL systems is often compromised in adverse atmospheric conditions, where factors like fog, smog, and dust can degrade beam quality. This sensitivity underscores the need for advancements in adaptive optics and environmental compensation technologies (Sabatini et al., 2019).

Another significant challenge lies in meeting the Size, Weight, Power, and Cooling (SWaP-C) requirements for airborne platforms (Blue et al., 2018). Solid-state lasers, while more compact than their predecessors, still demand significant power and cooling resources, limiting their integration into smaller aircraft. Research into superconducting



generators and energy storage systems aims to address these constraints, offering potential solutions for future applications (Tolliver et al., 2012; Sylvester, 2014).

5. Future Directions

Looking ahead, emerging technologies such as artificial intelligence, advanced beam control, and space-based DEW platforms represent exciting possibilities for overcoming current limitations. The integration of machine learning to optimize target prioritization, (Edwards, 2021), and the development of compact, lightweight laser systems (Michalska et al., 2024), offer pathways for advancing DEW capabilities. Artificial intelligence (AI) is poised to revolutionize the operational capabilities of DEWs by enabling real-time threat assessment, targeting, and decision-making. AI algorithms can process vast amounts of data from sensors and command systems, providing enhanced situational awareness and optimizing engagement strategies. For example, AI-driven beam management systems can dynamically prioritize targets based on threat levels, ensuring efficient resource allocation during high-intensity conflicts (Rassler, 2024). Furthermore, machine learning models can predict environmental variables and adjust beam parameters to maintain performance in complex operational environments. This integration of AI enhances the adaptability of DEWs, making them more resilient and effective in multi-domain operations (Weinberg, 2023). The application of DEWs in space-based platforms represents a significant frontier in defense technology. The unique characteristics of space—such as the absence of atmospheric interference and extended lines of sight—make it an ideal domain for deploying high-energy lasers and other DEWs. Space-based DEWs can be utilized for a variety of missions, including missile defense, satellite protection, and disabling adversary space assets (AFRL, 2021). For example, directed energy systems could intercept intercontinental ballistic missiles (ICBMs) during their boost phase, leveraging the clear conditions of the space environment to achieve precision targeting. Additionally, the deployment of DEWs in space aligns with the growing emphasis on space security as a critical component of national defense strategies (Williams et al., 2022).



C. ADVERSARIES DIRECTED ENERGY CAPABILITIES

China has made significant strides in DEWs, focusing on HEL and HPM systems to enhance its strategic capabilities. Notable advancements include the WB-1, a portable area-denial system, and applications targeting satellites, aircraft, and missiles. Reports indicate that China has operationalized DEWs on naval platforms like destroyers since 2018 and is leveraging its \$8.9 billion space program budget to address challenges in miniaturization and energy generation for space-based DEW systems. These innovations emphasize modularity, mobility, and asymmetric applications, allowing China to counter traditional military dominance in contested domains such as space and cyberspace.

Research also highlights China's focus on operational precision and adaptability in DEW deployment. Demonstration of the effectiveness of airborne laser weapon systems in cooperative combat through agent-based modeling was established (Shi et al., 2023), while other research (Shen et al., 2021) underscores the development of modular, vehicle-based HEL systems for rapid deployment in dynamic combat environments. Additionally, analyze the use of high-energy lasers in counter-unmanned aerial system (C-UAS) missions, showcasing their ability to neutralize threats like drones through sensor disruption and structural damage (Lyu & Zhan, 2021). These advancements reflect a robust commitment to leveraging DEWs as tools for countering superior adversarial forces. Collectively, China's progress offers valuable lessons for global stakeholders in adapting deployment strategies, overcoming technological challenges, and ensuring strategic stability in modern warfare efficiency (Wostenberg et al., 2024). See Table 1 for details.



Table 1. China Directed Energy Force Buildup Program. Source: National Defense Industrial Association (2024).

Program	Energy and Type	Description
LW-30 ¹⁹⁴	30 KW HEL ¹⁹⁵	C-UAS weapon ¹⁹⁶
Low Altitude Guardian ¹⁹⁷	10 KW HEL ¹⁹⁸	C-UAS weapon, 1-2 mile range ¹⁹⁹
Silent Hunter ²⁰⁰	30 KW HEL ²⁰¹	Truck-mounted C-UAS, 2½ mile range. ²⁰²
ZM-87 ²⁰³	15 mW HEL ²⁰⁴	Blinding device ²⁰⁵
BBQ-905 ²⁰⁶	200 mJ HEL ²⁰⁷	Handheld anti-ISR sensors ²⁰⁸
WB-1 ²⁰⁹	HPM ²¹⁰	Anti-personnel Area Denial, up to 1km range ²¹¹
Unknown name	1 MW Pulse Laser ²¹²	On-orbit ASAT

D. OPERATIONAL EFFECTIVENESS

The operational effectiveness of DEWs underscores their transformative potential in modern defense strategies. Leveraging the speed of light and precision targeting, DEWs address critical vulnerabilities in traditional kinetic systems, offering unparalleled advantages in engaging dynamic and high-volume threats. This subchapter explores their practical applications, performance metrics, and the operational challenges that shape their deployment across diverse scenarios.

1. Applications in Modern Defense

Directed Energy Weapons have demonstrated exceptional utility in addressing contemporary defense challenges, particularly where conventional systems fall short. One of the most prominent applications is in counter-unmanned aerial systems (C-UAS). The rising prevalence of UAV swarms has rendered traditional munitions-based defenses economically unsustainable and operationally limited.

Programs such as the U.S. military's Directed Energy Counter-UAS initiative showcase how HELs and HPMs are employed to disable UAVs without physical



munitions, providing a scalable and cost-effective solution (Lyu & Zhan, 2020). Similarly, HELWS (High Energy Laser Weapon System) program and THOR (Tactical High-power Operational Responder) program emphasize the increasing reliance on DEWs for neutralizing UAS threats, highlighting their efficiency and sustainability (Sayler, 2023). Naval applications further illustrate the versatility of DEWs. The HELIOS system not only neutralizes aerial and surface threats but also enhances situational awareness by dazzling enemy optical sensors (Mayfield et al., 2019). In addition, recently a research highlighted the integration of laser systems into European naval platforms, enhancing detection and countermeasures against UAVs (Steinvall, 2021). These examples demonstrate the adaptability of DEWs to evolving maritime security needs.

Beyond defense against UAVs, DEWs have shown adaptability to multi-domain operations. A snapshot of the DoD Directed Energy Roadmap is provided in Figure 5. For instance, they provide onboard defensive capabilities for aircraft, including counter-missile systems, while supporting ground operations with HPM systems to disrupt adversary electronics. The versatility of DEWs in naval, air, and ground operations emphasizes their role in layered, joint operations (Sabatini, 2015). Additionally, their applicability in space operations—such as counter-satellite strategies—further highlights their strategic significance.

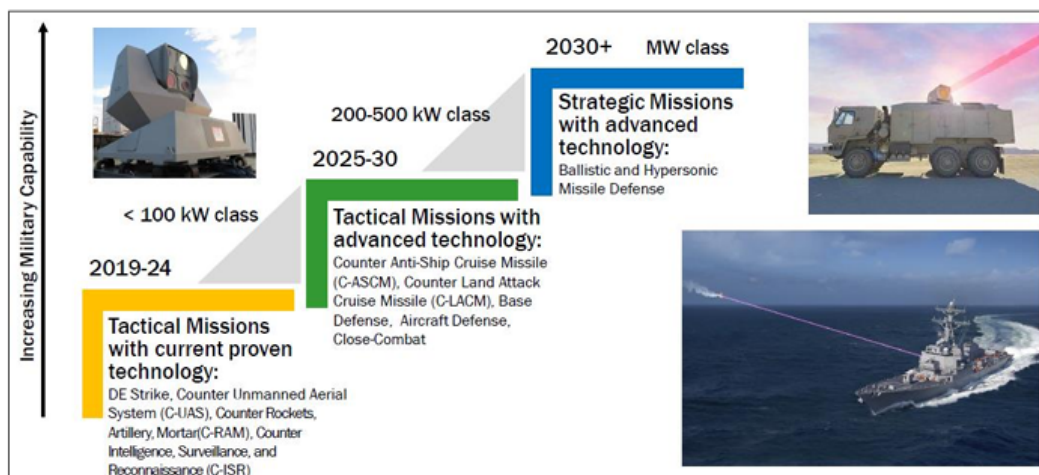


Figure 5. Summary of DoD Directed Energy Roadmap.
Source: Trebes (2020).

2. Performance Metrics and Comparisons

The effectiveness of DEWs is defined by performance metrics such as engagement speed, precision, and cost-efficiency. Unlike kinetic systems, which rely on physical interceptors with inherent time-of-flight limitations, DEWs engage targets instantaneously. This capability is particularly critical for countering fast-moving or maneuverable threats like hypersonic missiles and UAV swarms. HEL systems, for instance, can disable a UAV mid-flight by targeting its propulsion or control systems, ensuring precision engagement with minimal collateral damage (Weinberg, 2023; Yun et al., 2020).

Cost-effectiveness further amplifies the appeal of DEWs. The operational cost of a high-energy laser shot is typically measured in dollars, compared to the millions required for a missile engagement (Air Force Research Laboratory, 2021). The cost-benefit balance of using DEWs in counter-missile operations was explored (Ji et al., 2020), emphasizing their role in mitigating logistical constraints in high-intensity conflict scenarios. Additionally, a comprehensive review (Zhang et al., 2021) highlighted the material damage mechanisms caused by DEWs, offering insights into their operational efficiency against composite structures.

3. Laser Effect on Targets

The operational efficacy of tactical laser weapons hinges on several interrelated factors, including the precision and stability of the laser beam on the target, as well as the thermal and mechanical properties of the materials being engaged. Effective damage mechanisms for DEWs typically involve heating, melting, erosion, and in some cases, plasma generation (Nielsen, 2009; Zhang et al., 2020). Among these, the melting and erosion of target materials, such as polystyrene and carbon fiber reinforced composites, are particularly significant in counter-UAV operations. These materials, frequently used in UAV construction, exhibit relatively low thresholds for melting under sustained laser irradiation (Steinval, 2021). For instance, achieving effective damage to these materials often requires an irradiance level in the range of 1–10 kW/cm² over a duration of 1–10 seconds (See Figure 6). However, practical challenges arise due to factors such as heat dissipation through convection and radiation, as well as the target's movement, which



complicates maintaining consistent focus on the same surface area. We assume a typical damage limit for the carbon fiber composite to be about 100 W/cm^2 . Such a level can be achieved with a 1–10 kW laser at a distance of 1 km (Nielsen, 2009). Advances in laser systems, such as the Boeing Compact Laser Weapon System (CLWS), have demonstrated operational success, reportedly neutralizing over 300 UAVs during demonstrations, with an effective range of up to 3 km for UAVs and 7 km for optical sensors. These insights reinforce the significance of optimizing laser parameters and deployment strategies to enhance DEW effectiveness against a spectrum of aerial threats.

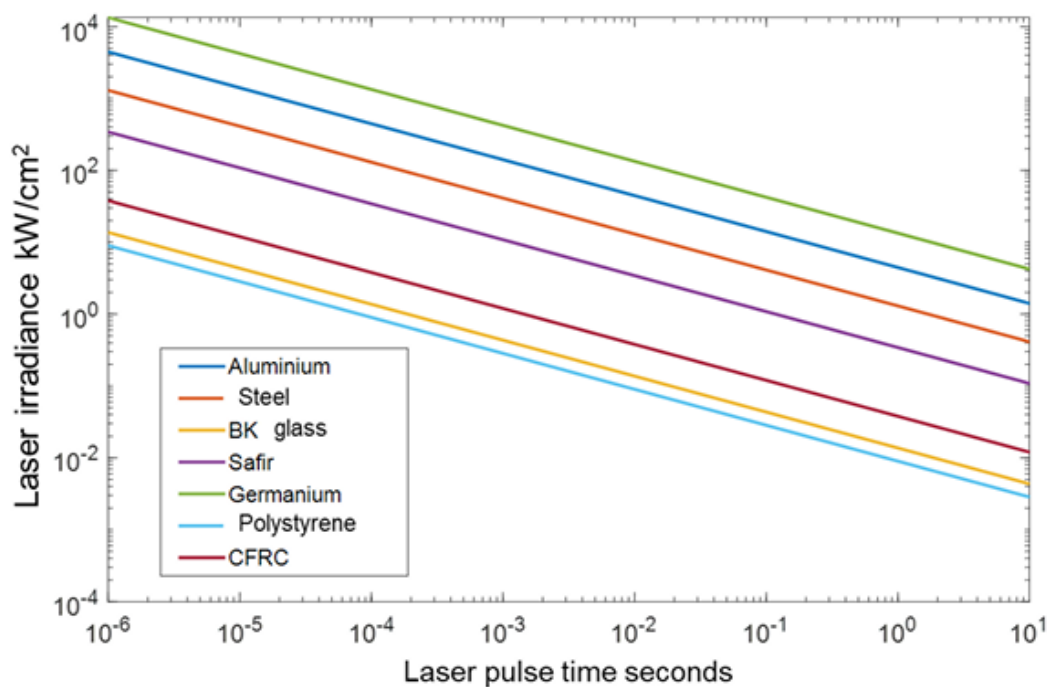


Figure 6. The Threshold Irradiance to Effect Melting of the Material as a Function of Pulse Time. Laser Wavelength 1.06 μm
Source: Steinvall (2021).

4. Integration into Layered Defense Strategies

The role of DEWs in layered defense strategies further demonstrates their operational flexibility. By complementing kinetic systems, DEWs optimize resource allocation and enhance overall defense efficacy. Naval combat systems, for instance, deploy HELs for short-range engagements while reserving interceptors for long-range or high-priority targets, reducing overall defense costs (Blau et al., 2018; Lyu & Zhan, 2021). The modular and mobile designs of DEWs further enhance their adaptability,

enabling integration across diverse platforms and scenarios (Shen et al., 2021). This strategy is further validated by HELIOS, which operates seamlessly alongside traditional defenses to enhance resilience and adaptability (Mayfield et al., 2019). Furthermore, an emphasis on the role of modular and mobile DEW systems in improving operational scalability and addressing emerging multi-domain threats was also presented (Shen et al., 2021).

Strategic adaptability in multi-domain operations is another advantage of DEWs. For example, HEL systems integrated into naval platforms can defend against aerial and surface threats while supporting ground operations. Similarly, HPM systems on land can neutralize adversary communications, creating a force-multiplier effect in complex engagements. These attributes highlight DEWs' ability to operate in contested environments, from littoral zones to space domains.

5. Operational Challenges

Despite their advantages, DEWs face significant operational Beacon Illumination Lasers challenges. A primary issue is the degradation of HEL system effectiveness under adverse atmospheric conditions such as fog, rain, and dust, which affect beam quality and engagement reliability. Atmospheric turbulence introduces beam jitter and scintillation effects, further reducing precision. Lidars have proven critical in addressing these issues by measuring aerosol distribution and turbulence along the beam path, enhancing real-time performance prediction (Steinvall, 2021). Beacon Illumination Lasers enable wavefront corrections, improving laser targeting in distorted environments.

Another major constraint involves the SWaP-C requirements of DEWs, particularly for airborne platforms. Compact, energy-efficient solutions such as superconducting generators and advanced thermal management systems offer potential solutions to this challenge (Tolliver et al., 2012). Further advancements in thulium-doped fiber amplifiers, as highlighted by Michalska et al. (2024), enhance beam quality and reduce thermal loads, enabling better performance in constrained deployment scenarios. Adaptive optics and beam control technologies, as noted by Sabatini et al. (2015), are also vital for maintaining beam quality under diverse operational conditions.



The detection and engagement of small, fast-moving UAV swarms present unique operational hurdles. UAVs' high velocities and unpredictable movements reduce engagement windows. Scanning laser radars and integrated electro-optical sensors provide precise target positioning, but their effectiveness diminishes under adverse weather conditions or when engaging multiple targets simultaneously. Smaller UAVs often require rapid multi-target tracking capabilities under compressed timelines, amplifying the challenge (Steinvall, 2021).

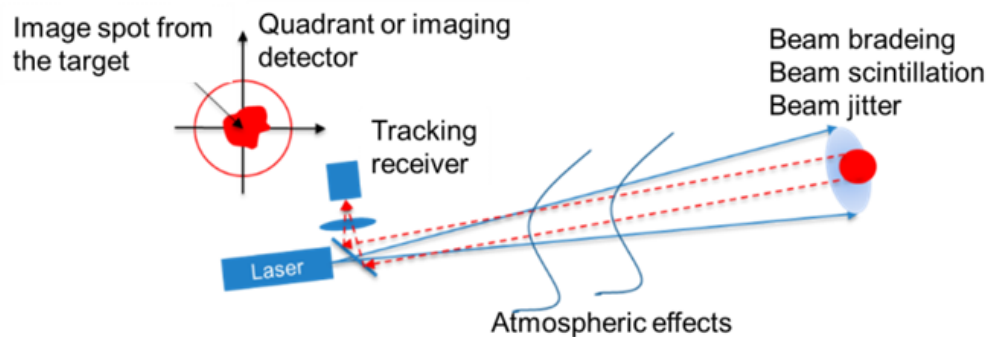


Figure 7. Example of a Laser Tracking Configuration and Associated Atmospheric and Platform Effects. Source: Steinvall (2021).

Ethical and regulatory dimensions compound these technical challenges. Non-lethal DEWs, such as optical dazzlers, must comply with international norms while minimizing unintended harm (Law, 2016). Furthermore, ensuring interoperability across multinational coalitions and military branches requires standardized communication protocols and leveraging machine learning for rapid target prioritization (Edwards, 2021). Overcoming these obstacles is essential for ensuring DEWs can operate effectively in complex and contested environments.

6. Case Studies and Real-World Validation

Real-world operations have validated the operational effectiveness of DEWs. The U.S. Navy's deployment of the Optical Dazzler Interdictor Navy (ODIN) system demonstrated the utility of HELs in countering UAV threats in maritime environments. Experimental deployments of HPM systems have shown promise in disabling adversarial drone electronics, solidifying their role in modern defense architectures (Ansley et al., 2020). Additionally, experimental evidence of laser effectiveness in neutralizing rogue

drones was provided (Chaari & Al-Maadeed, 2020), addressing critical factors like energy efficiency and targeting accuracy. The ongoing progress in C-UAS technology across multiple nations (Lyu & Zhan, 2020), further emphasizes the global significance of DEWs in defense strategies.

7. Strategic Implications

Beyond immediate operational capabilities, DEWs influence broader strategic considerations. By reducing reliance on kinetic munitions and enhancing engagement versatility, DEWs represent a paradigm shift in military defense strategies. Their ability to address asymmetric and high-end threats ensures relevance across a wide range of conflict scenarios, from localized skirmishes to large-scale campaigns (Lyu & Zhan, 2020; Saylor, 2023). Their adoption in NATO-aligned defense strategies, underscoring their growing importance in collective security frameworks was highlighted (Steinwall, 2021). Furthermore, the role of DEWs in countering long-range, stand-off attacks, highlighting their strategic value in neutralizing emerging aerial threats is well discussed in the literature (Rassler, 2024).

E. ECONOMIC FEASIBILITY

Economic feasibility is a critical factor influencing the adoption and scalability of DEWs within modern defense systems. Unlike traditional kinetic systems, DEWs offer the potential for significant cost savings in both procurement and operational contexts. However, these advantages are accompanied by challenges related to initial development costs, scalability, and long-term sustainability. This topic provides a detailed examination of the economic implications of integrating DEWs into defense architectures, supported by relevant examples and analysis.

1. Cost Per Engagement

One of the most compelling economic arguments for DEWs lies in their low cost per engagement. High-energy lasers (HELs) and high-power microwaves (HPMs) operate at a fraction of the cost of traditional interceptors, such as surface-to-air missiles. For instance, while a single missile can cost millions of dollars per shot, the operational cost of a laser engagement is measured in dollars, primarily accounting for the energy



required to power the system (Air Force Research Laboratory, 2021; Lyu & Zhan, 2020). This cost differential is particularly impactful in high-volume threat scenarios, such as defending against UAV swarms, where kinetic systems become economically unsustainable due to their high per-shot costs (Sayler et al., 2023). DEWs, in contrast, provide continuous operational capacity without the logistical burden of replenishing ammunition, making them ideal for asymmetric threat environments (Blau et al., 2018).

2. Initial Development and Integration Costs

While DEWs offer long-term operational savings, their initial development and integration costs are substantial. Research and development (R&D) phases require significant investments in advanced materials, beam control technologies, and energy systems. For instance, the U.S. Department of Defense has allocated billions of dollars to programs like HELIOS and ODIN, underscoring the complexity of bringing these systems to operational readiness (Mayfield et al., 2019). These expenses are indicative of the high technological barriers associated with DEW systems. Integrating DEWs into existing platforms presents additional financial challenges. The Size, Weight, Power, and Cooling (SWaP-C) requirements for these systems necessitate costly modifications to host platforms, such as ships, aircraft, or ground vehicles (Tolliver et al., 2012). Moreover, advancements in modular DEW designs (Shen et al., 2021), show promise for mitigating some integration costs by streamlining compatibility with multiple defense platforms.

3. Scalability and Production

The scalability of DEWs is another key economic consideration. Large-scale production demands a stable supply chain for advanced components, including rare-earth materials vital for laser systems (Wostenberg et al., 2024). The manufacturing processes' complexity and high precision requirements currently limit the scalability of DEWs, particularly in addressing rapid deployment needs. Additionally, dependence on international suppliers for critical components raises concerns about supply chain security, further complicating large-scale adoption (Ji et al., 2020).



Gallium is a critical material in both commercial and military applications, particularly for DEWs. It plays a pivotal role in semiconductor lasers and solid-state microwave emitters, with high-energy lasers (HELs) and high-power microwaves (HPMs) relying on gallium nitride (GaN) and gallium arsenide (GaA) for their construction and tuning. However, supply chain vulnerabilities are significant, as the U.S. lacks a domestic stockpile and relies heavily on imports, with 53% sourced from China, which controls 98% of global production. China's recent export restrictions have already caused price spikes, highlighting the potential for long-term disruptions. While this could incentivize alternative production globally, the immediate impacts pose challenges for DEW development and broader technology sectors reliant on gallium-based components. See Figure 8 and Figure 9 to illustrate to the world-wide vulnerability.

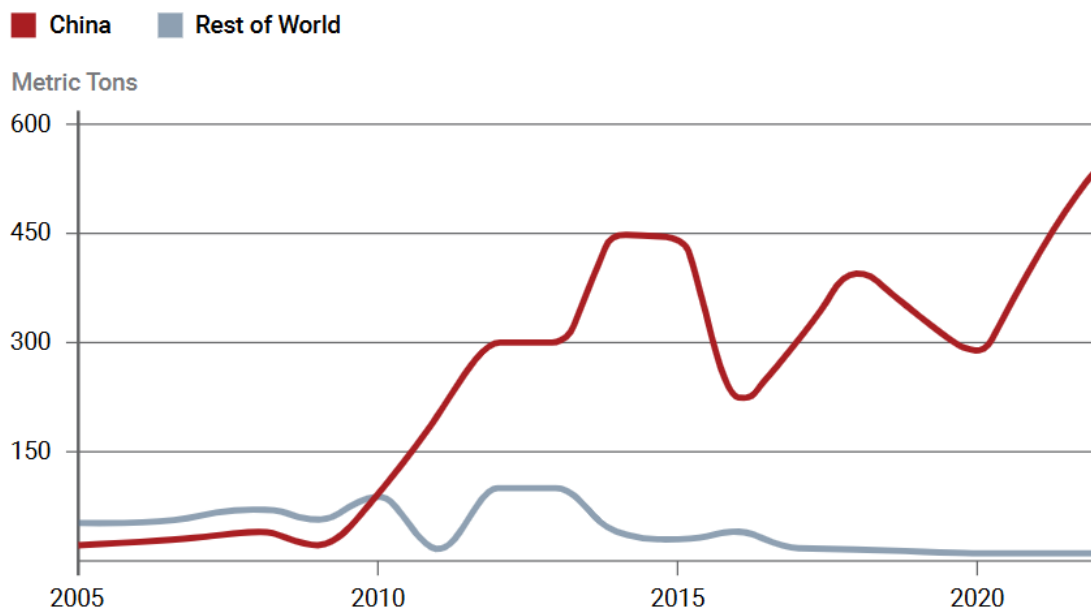


Figure 8. Global Primary Gallium Production.
Source: Funaiole et al. (2023).



Figure 9. Critical Minerals Commodity Supply Risk Assessment.
Source: Nassar et al. (2021).

Despite these challenges, advancements in manufacturing technologies offer potential solutions. For example, additive manufacturing processes have been proposed to reduce production costs and improve scalability, particularly for lightweight, high-efficiency components (Michalska et al., 2024). Modular design approaches, which allow for the reuse of components across various platforms, further enhance production efficiency and cost-effectiveness (Lyu & Zhan, 2021). These developments suggest that economies of scale could eventually make DEWs more accessible for widespread deployment.

4. Cost-Effectiveness in Layered Defense

DEWs contribute significantly to the cost-effectiveness of layered defense strategies by complementing kinetic systems. In these architectures, DEWs can address short-range threats, conserving munitions for long-range or high-priority targets (Blau et al., 2018). This hybrid approach reduces overall expenditures on traditional interceptors while maintaining robust defensive capabilities (Lyu & Zhan, 2020). Additionally, DEWs minimize logistical burdens by relying solely on power availability rather than physical

resupply of ammunition (Weinberg, 2023). This feature is especially advantageous in remote or contested environments, where maintaining supply chains is logistically challenging. For instance, naval platforms equipped with HEL systems have demonstrated enhanced operational flexibility due to reduced resupply requirements, further highlighting the economic efficiency of these systems (Shen et al., 2021).

Recent research from CSIS (Rumbaugh, 2024) critiques the reliance on cost-exchange ratios as an oversimplified metric for evaluating missile defense systems, arguing that it fails to account for the operational complexities and strategic value of defending high-value assets. He underscores the necessity of precision-guided and maneuverable interceptors, particularly in scenarios requiring rapid, area-wide protection, such as Red Sea escort missions. These missions illustrate how defensive decisions are shaped not only by the cost of munitions but also by the critical assets being protected and the economic stability tied to commercial shipping lanes. The analysis aligns with the broader perspective that DEWs offer a cost-effective and scalable solution to these challenges, bridging the gap between fiscal constraints and the need for rapid, flexible defense capabilities.

5. Economic Implications for Defense Policy

The economic feasibility of DEWs has broader implications for defense policy and budgeting. As defense budgets face increasing constraints, DEWs present a cost-efficient alternative to traditional systems, enabling long-term savings and enhanced strategic flexibility (U.S. Government Accountability Office, 2023). Policymakers must weigh the high initial investment costs against the potential for sustained operational savings and scalability. Furthermore, investments in DEWs align with global defense trends prioritizing rapid, adaptable solutions to emerging threats (Rassler, 2024). The strategic adoption of DEWs also positions nations to respond effectively to both asymmetric and state-level adversaries, ensuring technological parity or superiority in evolving conflict scenarios (Sayler et al., 2023). For instance, advances in HEL systems for missile and UAV interception have demonstrated not only tactical efficacy but also the potential for significant cost reductions over time, reinforcing their viability as a cornerstone of future defense architectures (Ji et al., 2020). Economic feasibility remains



a cornerstone of the argument for integrating DEWs into modern defense systems. While the initial costs are high, the operational savings, scalability, and logistical advantages position DEWs as a cost-effective solution to contemporary and future defense challenges. By addressing the economic barriers to production and deployment, the current research will be able to contribute to the broader adoption of DEWs in sustainable and efficient defense strategies.

F. INTEGRATION CHALLENGES

The integration of DEWs into existing military platforms presents a complex array of technical, logistical, and operational challenges. These challenges stem from the unique characteristics of DEWs, including their dependence on high-power systems, sensitivity to environmental conditions, and the need for seamless interoperability with existing defense architectures. Addressing these integration barriers is crucial for ensuring the successful deployment and operational efficacy of DEWs in diverse defense scenarios.

1. Size, Weight, Power, and Cooling (SWaP-C) Constraints

One of the most significant barriers to DEW integration lies in meeting the stringent SWaP-C requirements of modern platforms. DEWs, particularly HELs, demand substantial electrical power and advanced cooling systems to maintain operational stability. These requirements are especially challenging for airborne platforms, where weight and space are limited. For example, integrating HEL systems into fighter jets requires compact power generators and lightweight cooling systems to avoid compromising the aircraft's performance (Tolliver et al., 2012). Superconducting generators, offer a potential solution (Sylvester, 2014), providing lightweight, high-efficiency power delivery for airborne DEWs. Naval platforms have demonstrated more success in integrating DEWs due to their greater space and power capacity. The Navy's HELIOS program, which integrates HEL systems into the Aegis combat system, highlights the feasibility of addressing SWaP-C constraints in maritime applications (Mayfield et al., 2019). However, translating these successes to smaller platforms, such as UAVs or ground vehicles, remains a significant challenge (Blau et al., 2018).



Advances in modular designs for DEWs, are critical to overcoming these constraints (Shen et al., 2021), and achieving broader integration.

2. Environmental Sensitivity

DEWs, particularly HELs, are highly sensitive to environmental conditions such as fog, rain, and dust, which can degrade beam quality and reduce operational range. This sensitivity poses significant integration challenges, particularly for platforms operating in diverse and unpredictable environments. For instance, airborne DEWs must contend with atmospheric turbulence and variations in humidity, which can distort the beam and diminish its effectiveness (Sabatini et al., 2015). Beam control technologies, such as adaptive optics and turbulence compensation systems, have been developed to address these issues (Air Force Research Laboratory, 2021). The introduction of orbital angular momentum beams, offers an innovative approach to mitigating environmental sensitivity by increasing resilience to atmospheric disturbances (Kim, 2024). Additionally, advancements in beam propagation methods and enhanced atmospheric compensation systems, are essential for ensuring DEW performance in real-world conditions (Steinvall, 2021).

3. Interoperability with Existing Systems

The effective deployment of DEWs depends on their seamless integration with existing command and control (C2) systems. This requirement necessitates robust interoperability to ensure that DEWs can operate alongside kinetic weapons, sensors, and communication networks. For example, the Navy's Aegis combat system integrates HELs with radar and missile systems, enabling coordinated responses to multi-domain threats (Mayfield et al., 2019). However, achieving similar interoperability for airborne and ground-based platforms presents significant challenges (Blau et al., 2019). Joint operations further complicate interoperability. DEWs must be capable of functioning within multinational coalitions and across different branches of the military, each with its own systems and protocols. Standardizing communication interfaces and operational procedures is critical for enabling effective joint operations and maximizing the strategic value of DEWs (Ansley et al., 2020). Emerging technologies such as machine learning



for target prioritization, (Edwards, 2021), provide promising avenues for enhancing interoperability in dynamic combat scenarios.

4. Testing and Validation

The integration of DEWs into operational platforms requires rigorous testing and validation to ensure reliability and safety under real-world conditions. However, the complexity and high cost of testing DEWs present significant challenges. Simulating operational scenarios for HELs involves replicating environmental conditions, power demands, and target interactions, all of which require specialized facilities and equipment (Lyu & Zhan, 2021). Testing non-lethal DEWs, such as optical dazzlers, introduces additional complexities due to ethical considerations and compliance with international regulations. For instance, ensuring these systems can operate effectively without causing unintended harm requires careful design and evaluation (Law, 2016). Additionally, finite element modeling, offers innovative methods for predicting and optimizing DEW interactions with targets under various conditions (Rafols, 2024). Additionally, computational simulations in modeling laser lethality against complex geometries are critical for optimizing DEW integration (Shelander, 2023).

5. Strategic Implications of Integration Challenges

The challenges associated with integrating DEWs have broader implications for their strategic deployment. Delays in integration can hinder the operational readiness of DEWs, limiting their impact on defense capabilities. Furthermore, the high cost and complexity of integration may deter investments, particularly for smaller nations with limited defense budgets (U.S. Government Accountability Office, 2023). Addressing these challenges requires a coordinated approach that balances technological innovation with practical implementation. Collaborative efforts among defense contractors, research institutions, and military organizations are essential for developing scalable, interoperable, and cost-effective solutions for DEW integration. Future advancements in modular designs and adaptive technologies (Shen et al., 2021; Michalska et al., 2024), will play a pivotal role in overcoming these barriers. The integration of Directed Energy Weapons into defense platforms involves navigating a complex landscape of SWaP-C



constraints, environmental sensitivities, interoperability requirements, and testing challenges. By addressing these barriers, the defense community can unlock the full potential of DEWs, enabling their widespread deployment and operational effectiveness. This research seeks to contribute to these efforts by exploring innovative solutions to the integration challenges facing DEWs in modern and future defense scenarios.

G. GAPS IN THE LITERATURE

While DEWs represent a transformative leap in defense technology, several gaps persist in the existing body of research. These gaps not only underscore the need for further technological and operational studies but also highlight opportunities for innovation and development in the field. This section identifies key technological, operational, and strategic gaps, providing a foundation for the proposed research to address these shortcomings.

1. Technological Gaps

Beam Quality and Atmospheric Interference: Despite significant advancements, one of the persistent technological gaps is the degradation of beam quality due to environmental factors. Atmospheric conditions such as fog, smog, and rain adversely affect the performance of HELs, reducing their effectiveness in real-world operations. While adaptive optics and beam correction technologies show promise, they remain underdeveloped for large-scale deployment (Sabatini, 2015). For instance, current HEL systems are optimized for clear atmospheric conditions, but in contested environments, their effectiveness diminishes. Research into alternative beam propagation methods or environmental compensation systems is critical to bridge this gap (AFRL, 2021).

Power Generation and Energy Efficiency: The power requirements for DEWs, particularly those intended for airborne platforms, remain a significant challenge. Meeting the SWaP-C constraints requires innovations in power generation and thermal management. While high-temperature superconducting generators offer a potential solution, their scalability and reliability in operational contexts need further validation. Superconducting (Tolliver et al., 2012; Sylvester, 2014). Furthermore, advancements in energy storage systems, such as modular power units and regenerative energy cycles, are



essential to enhance the operational endurance of DEWs. *Current research has yet to fully address these power-related challenges, particularly for multi-role jetfighter air vehicle systems.*

2. Operational Gaps

Scalability Across Platforms: While DEWs have demonstrated efficacy in isolated deployments, their scalability across different platforms and operational scenarios remains limited. For instance, integrating HELs into airborne systems presents unique challenges compared to naval or ground-based platforms due to weight and cooling requirements (Canin, 2021). Additionally, fleet-wide deployment strategies have not been comprehensively studied (Lyu & Zhan, 2021; Michalska et al., 2024). Research into scalable DEW architectures capable of addressing localized skirmishes and strategic campaigns simultaneously is needed to maximize their operational impact.

Integration Challenges: Integrating DEWs with existing command and control systems poses a critical operational gap. Effective integration requires seamless communication between DEWs and traditional kinetic systems to enable layered defense strategies. However, the interoperability of these systems, especially in joint military operations, remains underexplored (Mayfield et al., 2019; Sayler 2024). For example, the HELIOS system successfully integrates HELs into the Aegis combat system, but *similar integration efforts for airborne platforms are still in experimental stages*. Addressing these integration challenges is crucial for DEWs to achieve widespread operational adoption.

3. Strategic Gaps

Scenario-Based Planning: Existing research lacks comprehensive scenario-based planning models for DEWs. While DEWs are well-suited for counter-UAV and missile defense missions, their adaptability to different conflict scales and domains—such as urban warfare or intercontinental missile campaigns—has not been thoroughly analyzed (Canin, 2021). Scenario modeling, such as fleet-wide deployment in high-intensity conflicts, would provide valuable insights into the operational feasibility and limitations



of DEWs. Incorporating these findings into systemic operational design frameworks could enhance strategic decision-making.

Regulatory and Ethical Considerations: The rapid advancement of DEWs has outpaced the development of regulatory and ethical guidelines. Issues such as collateral damage, unintended consequences, and compliance with international laws of war remain underexplored. For instance, non-lethal applications of DEWs, such as crowd control or disabling enemy electronics, require clear operational doctrines to prevent misuse (Law, 2016). Furthermore, the dual-use nature of DEW technology raises concerns about proliferation and the potential misuse by non-state actors. Addressing these regulatory and ethical gaps is imperative to ensure the responsible deployment of DEWs (AFRL, 2021).

These identified gaps highlight the critical areas where additional research and innovation are required to fully realize the potential of DEWs. Addressing these gaps will not only enhance the technological and operational capabilities of DEWs but also ensure their strategic integration into modern defense architectures. By bridging these gaps, the proposed research aims to contribute to the development of more effective, scalable, and ethical DEW systems capable of meeting contemporary and future defense challenges.

H. SUMMARY

The literature review provides an in-depth exploration of Directed Energy Weapons, emphasizing their technological, operational, economic, and strategic significance in modern defense. These weapons, including high-energy lasers (HELs), represent a paradigm shift by offering precision, cost-effectiveness, and rapid response capabilities against evolving threats like UAV swarms and cruise missiles.

Key insights include:

- **Technological Landscape:** DEWs leverage advances in HEL and HPM systems to overcome historical limitations, such as energy demands and environmental sensitivity. Solid-state lasers emerge as the most viable for rapid deployment due to their maturity and scalability.
- **Operational Effectiveness:** With their ability to deliver near-instantaneous, precise engagements at a fraction of the cost of traditional interceptors, DEWs



excel in countering high-volume threats. Their integration into naval, airborne, and space-based platforms demonstrates operational versatility.

- **Economic Feasibility:** DEWs promise significant cost savings through low operational costs and unlimited magazine depth. Challenges like high initial investments and SWaP-C constraints require targeted innovation to realize their full economic potential.
- **Integration Challenges:** Successfully incorporating DEWs into existing systems involves addressing SWaP-C constraints, enhancing interoperability, and improving beam quality to ensure effectiveness across diverse environments.
- **Strategic Implications:** DEWs contribute to a shift in defense paradigms by enabling multi-layered strategies that integrate kinetic and non-kinetic systems. Their adaptability to localized skirmishes and large-scale campaigns positions them as critical to maintaining strategic superiority. The study highlights the balance between technology-push innovations and requirement-pull demands, underlining the need for systemic operational design (SOD) and scenario-based planning.
- **Research Gaps:** The review identifies gaps in beam quality under adverse conditions, regulatory and ethical frameworks, scalability across platforms, and robust scenario-based strategic planning for DEWs' use in complex operational settings.

Following this comprehensive review, the **Methodology** chapter will detail how these strategic insights and identified research gaps are operationalized into a structured research framework. The methodology will incorporate **scenario-based modeling** to assess DEWs' effectiveness across different threat environments and strategic scenarios. Additionally, it will explore how systemic operational design principles guide the integration of DEWs within broader defense strategies. This chapter will also define key performance parameters (KPPs), establish evaluation frameworks, and align research objectives with strategic defense priorities, setting the stage for innovative, scalable, and cost-effective solutions to modern aerial threats.



IV. METHODOLOGIES FOR DEFINING THE AIRBORNE DIRECTED ENERGY WEAPONS ACQUISITION STRATEGY

The integration of Airborne DEWs into modern aerial defense represents a paradigm shift in addressing evolving threats like UAVs, swarm drones, and hypersonic missiles. This chapter explores strategies to achieve rapid DEW deployment within a three-year timeframe while balancing innovation with operational readiness. Drawing from Systemic Operational Design (SOD), Rogers’ Five Factors (Gourville, 2006), Danzig’s Ten Propositions (Danzig, 2011), and lessons from Public organizations (USPS, DARPA, FBI) and Private companies (Tesla) case studies, it outlines a comprehensive framework to navigate technical, organizational, and strategic challenges. The analysis emphasizes the interplay of “technology push” and “requirements pull,” institutional resistance, and the economic viability of DEWs in layered defense systems. Moreover, it highlights the critical role of leadership in guiding systemic change, fostering collaboration, and aligning technological innovation with strategic goals. By leveraging systemic thinking, adaptive strategies, and collaborative innovation, this chapter provides the acquisition strategy principles, with actionable insights for deploying DEWs as transformative assets, ensuring scalability, cost-efficiency, and sustained adaptability in modern aerial defense.

A. LESSONS LEARNED FROM PUBLIC AND PRIVATE ORGANIZATIONS CASE STUDIES

The following section examines selected cases from both public and private organizations to derive practical insights for shaping an acquisition strategy for airborne DEWs. Each case reflects a different aspect of innovation, including strategic vision, leveraging existing infrastructure, organizational adaptability, and systemic integration. Together, they provide a coherent perspective on how complex capabilities can be developed and fielded under conditions of uncertainty, time pressure, and institutional constraints.



1. Innovation and Strategic Balance - DARPA's Adaptive and Visionary Approach

DARPA is a great example of how an organization can balance **adaptive** and **visionary** strategies (Dew, 2013). It works on high-risk, high-reward projects, often experimenting and adjusting as new information becomes available (Gallo, 2021). This approach allows DARPA to innovate quickly while still aiming for long-term goals. DARPA's projects, such as stealth technology, the Internet, and autonomous systems, show how having a long-term **visionary strategy** can lead to significant changes in defense capabilities. However, DARPA also stays **adaptive** by adjusting its focus based on immediate military needs.

For the DEW project, DARPA's model demonstrates the importance of balancing a **long-term vision** with **short-term adaptability**. The disruptive potential of DEWs—energy-based weapons that respond quickly and cost very little per use—aligns with the **visionary strategy** of transforming defense systems. At the same time, by integrating DEWs with **legacy fighter jets**, the project ensures that deployment can happen quickly, making it more adaptable to current military needs. This mix of visionary and adaptive strategies ensures that DEWs not only represent the future of defense but are also relevant for today's battlefield.

Richard Rumelt's insights in *The Perils of Bad Strategy* (Rumelt, 2011) reinforce the need for clarity in strategic thinking. A common issue in defense projects is the failure to identify and address the real problem. In the DEW project, the focus on rapid deployment and addressing immediate military threats ensures that the project avoids becoming a case of "bad strategy." Rumelt emphasizes that good strategy focuses on clear objectives and actionable solutions, which the DEW project achieves by aligning disruptive technology with urgent defense requirements.

2. USPS's Strategy: Using Existing Infrastructure and Public-Private Partnerships

USPS operates in a very different space, but it also provides lessons on how to handle innovation by making the most of existing resources. As digital communication grew, USPS faced major challenges, especially with the decline of traditional mail. But



instead of being replaced, USPS used its **last-mile delivery network**—something competitors like FedEx and UPS didn't have—to remain relevant (Lewis et al., 2019). By partnering with these companies, USPS found a way to turn a potential weakness into a strength. Its partnerships with private carriers allowed USPS to stay in the logistics game without building new infrastructure from scratch.

For the DEW project, USPS's strategy of **leveraging existing infrastructure** offers an important lesson. Instead of focusing on developing completely new military platforms for DEWs, the project can use **existing fighter jets**. This approach reduces both the cost and time required for deployment, allowing the technology to be rolled out quickly. Just as USPS used its delivery network for last-mile services, the DEW project can use the military's existing assets to introduce new technologies faster and at a lower cost.

USPS's ability to form **public-private partnerships** with competitors like FedEx and UPS also shows how collaboration can lead to success (United States Department of the Treasury, 2018). USPS partnered with its competitors rather than trying to compete with them directly, which strengthened its position in the logistics industry. Similarly, the DEW project can form **public-private partnerships** with defense contractors and private firms to speed up development and deployment. By collaborating with the private sector, the DEW project can share risks, access advanced technology, and ensure the weapons are deployed quickly to meet military needs.

Max Boot's **What the Past Teaches About the Future** (Boot, 2007) emphasizes how military innovations from the past have reshaped warfare. Just as past innovations such as tanks and airplanes changed the battlefield, DEWs have the potential to revolutionize aerial defense. By learning from history, the DEW project ensures that it doesn't just develop new technology but integrates it into existing platforms, much like past technologies were adapted to fit with current military strategies.

3. Tesla: Visionary Strategy and Systemic Thinking

Tesla's systemic approach to innovation showcases the power of aligning visionary strategies with practical execution. The company's ability to disrupt the



automotive industry stems from its focus on technological superiority, operational efficiency, and market alignment.

Tesla's ability to demonstrate the **relative advantage** of electric vehicles (EVs) over internal combustion engines offers a clear parallel for DEWs in defense (Shipley, 2020). DEWs can redefine aerial defense by addressing threats at a fraction of the cost per engagement compared to traditional missile systems, which can cost hundreds of thousands of dollars per interception. Integrating DEWs into layered defense systems—neutralizing low-cost UAV swarms and preserving kinetic systems for higher-value targets—not only enhances operational efficiency and economic sustainability but also reinforces their value proposition as transformative and cost-effective solutions in modern defense strategies.

Tesla's **systemic integration** through centralized production, exemplified by its Gigafactories, underscores the importance of manufacturing agility (Van den Steen et al., 2024). For the DoD, establishing modular DEW production facilities can standardize manufacturing processes while enabling adaptability to evolving requirements. These facilities could incorporate scalable designs, ensuring DEWs remain relevant as threats and technologies advance.

Additionally, Tesla's commitment to **iterative development** highlights the value of incremental innovation. By testing prototypes in real-world scenarios, Tesla refined its products to align with consumer needs. Similarly, the DoD could deploy DEWs on existing platforms like the C-130 Hercules for pilot programs. These programs would refine targeting, power management, and maintenance protocols before scaling to advanced platforms such as unmanned aerial vehicles or fighter jets. Tesla's experience highlights the importance of demonstrating relative advantage, adopting modular production models, and committing to iterative development. However, disruptive innovation alone is insufficient. Addressing institutional and organizational barriers is equally critical—a challenge where the lessons from the FBI's transformation become invaluable.



4. **FBI: Adaptive Strategy and Overcoming Resistance**

The FBI's transformation after 9/11 exemplifies how adaptability and systemic change can address emerging challenges while overcoming institutional inertia. By shifting from reactive law enforcement to proactive intelligence-driven operations, the FBI effectively redefined its mission to tackle threats such as global terrorism, cyberattacks, and digital espionage (Rivkin et al., 2010). This transformation demonstrates the value of cognitive agility, strategic collaboration, and reframing success metrics—lessons directly applicable to the deployment of Directed Energy Weapons (DEWs).

Cognitive agility was pivotal in the FBI's ability to anticipate and adapt to emerging threats. The creation of the Cyber Division in 2002 and its subsequent expansion in 2009 showcased how real-time analytics and advanced technologies could enhance the FBI's ability to counter digital and physical threats. Similarly, DEWs require flexibility to address evolving challenges like UAV swarms, hypersonic missiles, and coordinated drone attacks. Integrating real-time data analytics into DEW systems could allow operators to dynamically assess threats, optimize power usage, and refine targeting in complex, fluid environments. For example, a DEW equipped with predictive algorithms could analyze a swarm's flight patterns and prioritize critical targets, ensuring efficient energy allocation and engagement success.

Managing resistance to change is another critical lesson. The FBI overcame institutional inertia by reframing its mission to emphasize the urgency of new approaches to combat emerging threats. Similarly, the Department of Defense (DoD) must position DEWs as enhancements to existing defense systems rather than replacements. Presenting DEWs as the first line of defense in a multi-layered architecture can demonstrate how they preserve kinetic systems for higher-value threats, such as advanced missiles or adversary aircraft. This strategy can foster acceptance among operators and decision-makers while emphasizing DEWs' role in enhancing overall mission efficiency.

The FBI's success with **interagency collaboration** further highlights the importance of partnerships in accelerating innovation and addressing complex challenges. Initiatives like the Joint Terrorism Task Forces (JTTFs) and the establishment of the



National Security Branch (NSB) demonstrated the FBI's ability to coordinate efforts across federal, state, and local agencies, as well as with international partners. For DEWs, similar collaboration with industry leaders, allied forces, and academic institutions can advance critical areas like power systems, beam control, and cooling technologies.

Partnerships with private-sector leaders such as Lockheed Martin or Raytheon could expedite technological development, while ensuring interoperability with allied forces would enhance joint operations. The F-35 program, which successfully combined multinational cooperation and resource sharing, offers a proven model for such collaborative efforts.

Additionally, the FBI's ability to **redefine success metrics** was critical to its transformation. Moving from traditional crime-solving metrics to intelligence-driven outcomes allowed the agency to focus on threat prevention rather than reaction. Similarly, DEWs require a shift in evaluation criteria to highlight their unique capabilities, such as the number of threats neutralized per sortie or energy efficiency per engagement. Redefining metrics demonstrates how DEWs complement kinetic systems while offering scalable and cost-effective solutions for modern aerial defense.

By combining Tesla's visionary strategy and systemic thinking with the FBI's adaptive approach and collaborative frameworks, the DEW program can achieve both innovation and operational readiness. Tesla's focus on relative advantage, iterative development, and scalable production provides a roadmap for positioning DEWs as cost-effective and adaptable solutions within a multi-layered defense system. Meanwhile, the FBI's cognitive agility, success in overcoming institutional resistance, and ability to foster interagency collaboration demonstrate how DEWs can navigate organizational challenges and drive strategic alignment. Together, these lessons emphasize the importance of integrating advanced analytics, modular designs, and public-private partnerships to ensure DEWs are not only technologically superior but also seamlessly integrated into existing defense frameworks. By adopting these strategies, the DEW program can establish itself as a transformative pillar of modern defense, capable of addressing today's threats while preparing for those of the future.



B. UNPACKING AIRBORNE DIRECTED ENERGY WEAPONS STRATEGY THROUGH SYSTEMIC OPERATIONAL DESIGN

Systemic Operational Design (SOD) offers a dynamic framework for addressing complex challenges in defense strategy (Sorrells et al., 2005 ; Delacruz, 2007), particularly when applied to transformative technologies like Airborne Directed Energy Weapons. By combining systems thinking, operational art, and design praxis, SOD redefines how military organizations can navigate the uncertainties of modern warfare (Graicer, 2017). Insights from the previously gathered case studies will guide our exploration of how SOD principles can be applied to analyze and optimize the integration of DEWs into aerial defense systems, see Figure 10:

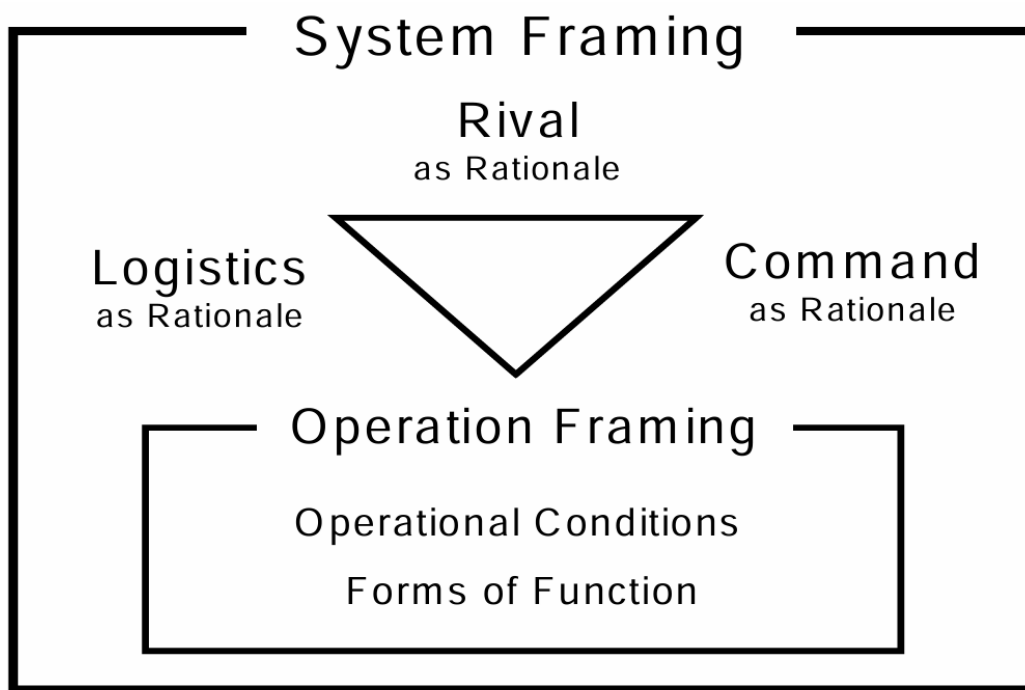


Figure 10. Systemic Operational Design (SOD) Framework.
Source: Sorrells et al. (2005).

1. Framing the System

The process begins with framing, which is not merely defining the problem but questioning the boundaries of understanding and context. The advent of low-cost, high-capability threats such as UAV swarms and hypersonic missiles has exposed the inefficiency of traditional kinetic interceptors. DEWs emerge as a promising solution, offering scalability and cost efficiency. However, their integration demands an

understanding of the operational environment that transcends technical considerations. This includes mapping interactions between DEWs, existing platforms like the C-130 Hercules, Fighter Jets, and broader command and logistical systems.

System framing also involves identifying critical tensions: the trade-offs between innovation and integration, the urgency of deployment versus technological maturity, and the resistance of institutional inertia against the necessity for adaptation. SOD posits that these tensions are not obstacles but opportunities to explore the systemic relationships that underpin the challenge.

2. Rival as Rationale

The adversary's strategies and capabilities serve as a rationale for operational design. Rivals exploit the cost asymmetry inherent in missile-based defense systems by deploying inexpensive aerial platforms to overwhelm defenses. The integration of DEWs alters this calculus, reducing cost-per-engagement while forcing adversaries to adapt. This disruption shifts the strategic advantage, compelling rivals to redirect resources into countermeasures such as reflective materials or electronic interference. In SOD, analyzing the rival extends beyond technological considerations to include their operational and strategic responses. Understanding these dynamics enables the creation of a strategy that not only counters the immediate threat but anticipates and influences the adversary's long-term behavior.

3. Command as Rationale

Effective implementation of DEWs requires a reevaluation of command structures. The rapid engagement cycles of DEWs necessitate decentralized decision-making systems capable of real-time adaptation. Operators must be trained not only in the technical aspects of DEW use but also in the strategic implications of their deployment. Commanders, in turn, must integrate DEWs into multi-domain operations, ensuring coherence across air, land, and cyber theaters. The Government Accountability Office emphasizes that while DEWs offer significant operational potential, the Department of Defense (DoD) must prioritize transition strategies that address logistical, training, and



support challenges as DEWs move from development to active deployment (GAO, 2023).

Command as rationale also addresses the doctrinal shift needed to position DEWs as integral components of layered defense systems. This involves reconciling their capabilities with those of kinetic interceptors and electronic warfare systems, fostering an ecosystem where each element complements the others.

4. Logistics as Rationale

The logistical challenges of deploying DEWs are central to their feasibility. High-energy laser systems demand robust power generation and cooling, which must be adapted to airborne platforms. One of the main challenges with integrating Directed Energy Weapons onto current military platforms is dealing with Size, Weight, Power, and Cooling (SWaP-C) limitations. SWaP-C issues make it hard to add high-energy lasers to existing ships and aircraft since these weapons need high power and cooling systems to function. SOD emphasizes modularity in design, allowing for scalable integration that can evolve alongside technological advancements (Blau et al., 2018). Partnerships with defense contractors and research institutions are vital for addressing these challenges. Collaborative innovation can streamline production and maintenance while accelerating the development of supporting technologies such as advanced power management systems.

5. Operational Framing

Operational framing translates strategic insights into actionable concepts. For DEWs, this involves identifying scenarios where their unique capabilities provide the greatest impact. Pilot programs on platforms like the C-130 Hercules offer an initial proving ground for testing power systems, targeting algorithms, and engagement protocols prior their integration on Jet Fighters. These scenarios serve as laboratories for iterative learning, refining the deployment strategy based on real-world feedback. The framing also encompasses the broader integration of DEWs into existing defense architectures. This includes their role in layered defense strategies, where they neutralize



low-cost threats to preserve high-value kinetic interceptors for more advanced adversarial platforms.

6. Operational Effects

The success of DEWs must be measured by their operational effects. Metrics such as cost-per-engagement, energy efficiency, and targets neutralized per sortie provide a quantitative basis for evaluating their impact. However, the strategic implications of their deployment—such as altering the adversary’s calculus and enhancing force multiplier effects—are equally critical. By focusing on these effects, SOD ensures that the integration of DEWs is aligned with broader defense objectives, balancing immediate tactical needs with long-term strategic imperatives.

7. Forms of Function

The final stage of SOD operationalizes the insights gained through systemic inquiry. Pilot programs transition into full-scale deployment, guided by doctrines that integrate DEWs with other defense systems. Feedback loops enable continuous refinement, ensuring that each iteration informs the next. In this phase, SOD emphasizes the importance of adaptability. As adversaries respond to DEW deployments, the system must evolve to counter emerging challenges. This iterative process transforms DEWs from experimental technologies into cornerstone assets of modern aerial defense.

C. EVOLUTION OF THE SYSTEMIC OPERATIONAL DESIGN (SOD) INTO SYSTEMIC INQUIRY IN OPERATIONAL MEDIATION (SIOM)

The evolution of Systemic Operational Design (SOD) into Systemic Inquiry in Operational Mediation (SIOM) marks a transformative shift in addressing the complex challenges of modern defense strategies (Graicer et al., 2022). While SOD emphasized structured problem framing and design processes, SIOM advances this methodology by focusing on the mediation of systemic tensions and fostering cognitive agility to adapt to dynamic environments. Central to this evolution is the Z-Model (see Figure 11), which integrates perplexity, systemic framing, and iterative refinement, enabling leaders to navigate uncertainty and capitalize on emerging opportunities by incorporating the principle of self-disruption - challenging ingrained assumptions and fostering continuous



innovation (Graicer, 2017). This shift reflects a recognition that modern challenges, such as integrating DEWs, require not only operational solutions but also a continuous process of redefining boundaries, testing assumptions, and harmonizing innovation with existing structures. SIOM’s emphasis on iterative learning and cross-functional coherence provides the ideal framework for addressing the complexities of DEW integration, setting the stage for a strategic and adaptive implementation process.

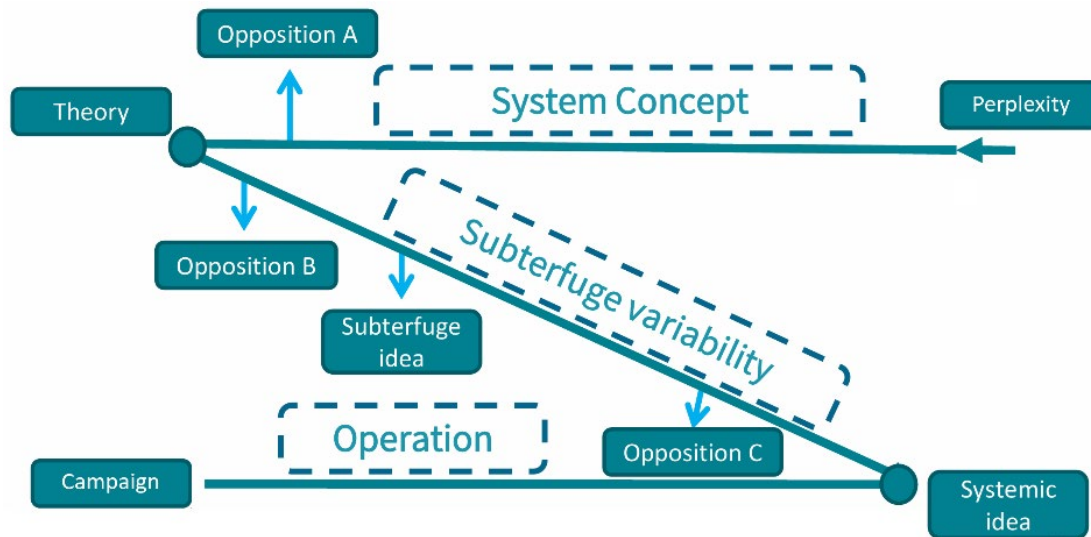


Figure 11. Systemic Inquiry in Operational Mediation Framework (Z-Model)
Source: Graicer (2017).

In the context of Airborne DEWs, the Z-Model provides a robust extension to the SOD framework by offering a stepwise methodology for addressing systemic tensions and aligning innovation with operational readiness:

1. Perplexity as a Driver

The Z-Model begins with perplexity, a recognition of the gap between the current state (traditional kinetic systems struggling with UAV swarms) and the desired future state (cost-effective, scalable DEWs). This step formalizes the discomfort or “basic surprise” driving the need for DEW integration. For DEWs, perplexity helps frame the economic and operational inefficiencies of missile interceptors as critical motivators for disruptive innovation.

2. Systemic Framing

Building on SOD's systemic framing, the Z-Model explicitly organizes the strategic environment into entities, players, and interactions, identifying potential tensions (Graicer, 2017) such as “technology push vs. requirements pull” or “institutional inertia vs. innovation urgency.” This step provides clarity on how DEWs interact with existing defense architectures (e.g., layered defense systems) and adversarial tactics (e.g., cost asymmetries).

3. Subterfuge

Subterfuge introduces a dynamic layer of strategic adaptation, incorporating logic, opposition, and imagination to overcome barriers. It reflects the iterative process of testing, adjusting, and refining DEW strategies based on systemic feedback. For example, **pilot programs on Jetfighters in a constrained three year timeframe represent a form of subterfuge**, where insights from operational trials refine engagement protocols and address logistical challenges like power management.

Systemic Idea: This stage bridges abstract insights into actionable concepts. For DEWs, it involves formulating modular designs, scalable deployment strategies, and phased integration plans that align with broader defense goals. By distilling systemic understanding into operationally relevant frameworks, the systemic idea ensures that DEWs complement existing kinetic systems and enhance overall mission efficiency.

4. Campaign/Operation

The Z-Model leads into the execution of a campaign or operation, informed by the systemic idea and continuously refined through feedback. For DEWs, this involves deploying prototypes in layered defense systems, where their capabilities are demonstrated alongside kinetic systems to foster institutional acceptance. The iterative nature of the Z-Model ensures that operational outcomes (e.g., cost-per-engagement, energy efficiency) inform strategic adjustments and further innovation.

To ensure the effective implementation and evaluation of DEWs deployment, the Department of Defense should adopt the S.M.A.R.T. framework, as presented by Braun and Latham's workshops for business success, specifically in chapter 10, which provides



a structured approach to setting clear, actionable objectives (Braun & Latham, 2014). Specifically, DEWs pilot programs can benefit from defining **Specific** objectives such as “achieve a neutralization rate of 85% for UAV swarms within designated test environments.” This clarity avoids ambiguity and aligns all stakeholders on expected outcomes. The objectives should also be **Measurable**, using metrics like the energy efficiency of laser engagements, cost-per-engagement comparisons with kinetic systems, and the number of successful neutralizations per sortie. To ensure accountability, the framework requires objectives to be **Assignable**, meaning that specific units or teams, such as engineering divisions or operational testers, are responsible for achieving these goals. The **Realistic** dimension is vital for maintaining feasibility; for instance, rather than targeting full operational capability on all platforms within three years, the objective could focus on demonstrating successful integration on one platform, such as the F-16. Finally, objectives must be **Time-bound**, with deadlines for each phase of development, testing, and evaluation—for example, setting milestones for prototype testing within 12 months and operational trials within 24 months. By adopting the S.M.A.R.T. framework, the DoD can ensure that DEW initiatives are not only ambitious but also actionable, fostering strategic alignment and measurable progress.

5. Fundamental Strategic Takeaway from Integration of SOD, SIOM and the Z-model

The application of SOD and its enhancement of SIOM to airborne DEWs offers a structured yet flexible approach to addressing the complexities of their integration. By reframing problems, mediating tensions, and iterating solutions, they transform the conceptual into the operational. These methodologies not only accelerate deployment but ensure that DEWs are positioned as transformative elements of defense strategy, capable of meeting the demands of a rapidly evolving threat landscape.

In this context, the three-year constraint is not merely an operational deadline but a **deliberate strategic decision** informed by the Z-Model process. By embracing self-disruption, the framework forces decision-makers to confront systemic tensions—such as balancing innovation with operational readiness—and use them as a catalyst for prioritization and action. The iterative mediation process embedded in the Z-Model



ensures that this constraint becomes a productive tension point, driving urgency in aligning resources, refining technologies, and overcoming resistance.

The result is a dynamic and adaptive strategy where the three-year timeline is treated as a **transformational lever**, pushing for accelerated innovation and operational integration while remaining flexible enough to respond to evolving threats and institutional challenges. This self-disruptive approach ensures that DEWs are not just developed and deployed within the defined timeframe but are positioned as scalable, strategic assets capable of reshaping modern defense frameworks.

D. ROGERS' FIVE FACTORS IN AIRBORNE DIRECTED ENERGY WEAPONS ADOPTION

Building on the insights from SOD, which emphasize the importance of understanding systemic tensions and operational dynamics, Rogers' Five Factors provide a complementary framework focused on overcoming adoption challenges. The literature shows how these factors offer practical strategies to reduce complexity, enhance observability, and ensure that systemic solutions are translated into actionable outcomes (Gourville, 2006). By addressing factors strategically, the DoD can balance the challenges of innovation with the demands of operational readiness. To anchor this analysis, the following subsection outlines Rogers' Five Factors as the conceptual basis for evaluating DEW adoption:

1. Relative Advantage

DEWs offer transformative benefits over traditional kinetic defense systems:

- **Cost Efficiency:** DEWs drastically reduce the cost-per-engagement compared to interceptors, making them economically viable for countering low-cost threats like UAV swarms.
- **Operational Superiority:** Unlimited engagements without the need for reloading and minimal collateral damage highlight DEWs' scalability and precision.

However, the relative advantage depends on perception as well as performance. To solidify their value, the DoD must demonstrate DEWs' advantages through pilot programs and high-visibility successes. A key trade-off is balancing innovation with



reliability—prioritizing proven capabilities over untested advancements to mitigate operational risks.

2. Compatibility

Compatibility ensures DEWs integrate seamlessly with existing defense systems and align with stakeholder expectations:

- **Legacy Platform Integration:** DEWs can initially be deployed on platforms like the Jetfighters minimizing disruptions while leveraging existing infrastructure.
- **Modular designs and scalable production** can ensure compatibility, reducing the need for entirely new supply chain frameworks.
- **Alignment with Strategic Goals:** Their ability to complement kinetic systems in layered defense strategies supports broader DoD objectives of cost-efficiency and force multiplier effects.

A critical consideration is the risk of overreliance on legacy platforms, which may constrain DEW performance due to power and cooling limitations. Modular designs and phased deployments can address these challenges, ensuring DEWs' compatibility with evolving mission needs.

3. Complexity

DEWs' advanced technologies pose challenges in perception and usability:

- **Perceived Complexity:** Sophisticated targeting systems and power management might deter adoption among operators unfamiliar with such systems.
- **Mitigation Strategies:** Simplified interfaces, comprehensive training programs, and technical support systems can reduce the learning curve and foster trust among stakeholders.

Trade-offs involve balancing usability with advanced capabilities. Simplifying systems to enhance operator adoption must not come at the cost of operational performance, necessitating iterative refinements based on user feedback.

4. Trialability

Trialability is a critical enabler of adoption, particularly for disruptive technologies like DEWs:



- **Prototype Testing:** Deploying DEWs on test platforms such as the C-130 provides real-world data on power usage, targeting algorithms, and engagement protocols.
- **Incremental Rollouts:** Limited trials in specific theaters of operation allow the DoD to refine deployment strategies while addressing operational feedback.

While trialability reduces uncertainty, a potential risk is stakeholder impatience if early trials do not immediately demonstrate significant results. Transparent communication of long-term goals and iterative successes can manage expectations effectively.

5. Observability

The observability of DEWs' results enhances their credibility and accelerates diffusion:

- **Demonstrated Effectiveness:** Showcasing DEWs in high-profile exercises highlights their operational impact, fostering confidence among policymakers and operators.
- **Interoperability Successes:** Collaborative demonstrations with allied forces emphasize DEWs' role in joint defense strategies, strengthening international partnerships.

A risk here lies in premature public exposure. Negative outcomes in early trials could undermine confidence. Careful selection of demonstration scenarios and proactive risk management can ensure positive observability.

E. PORTER'S FIVE FORCES APPLIED TO DIRECTED ENERGY WEAPONS

To understand how the DEW project fits into the competitive defense landscape, we can apply **Porter's Five Forces** (Porter, 1979). This framework helps identify competitive pressures, supplier power, buyer influence, and the risk of substitutes, all of which are important for positioning DEWs as a disruptive yet essential technology.

1. Competitive Rivalry

In the defense industry, DEWs face competition from traditional kinetic systems like missile interceptors. However, DEWs offer unique advantages, such as scalability, lower cost, and quick response times. Instead of replacing traditional systems, the DEW



strategy focuses on **complementing existing defense systems**, positioning DEWs as a necessary addition rather than a competitor. This reduces direct competition because DEWs can handle threats—like drone swarms—that traditional systems struggle with, filling a gap in defense capabilities.

2. Threat of New Entrants

Entering the defense industry is difficult due to high costs, technological barriers, and the need for strong relationships with the military. The DEW project raises these barriers even higher by focusing on integrating with **legacy platforms**. New entrants would need both the advanced technology and the military partnerships to compete, making the threat of new competitors low.

3. Bargaining Power of Suppliers

DEWs rely on specialized components such as laser systems, power management, and cooling technology, giving suppliers some influence. However, the DEW project can mitigate this risk by working with multiple suppliers and forming **public-private partnerships**. DARPA's model of collaboration shows how working with many partners can reduce dependency on any single supplier, maintaining flexibility in the supply chain.

4. Bargaining Power of Buyers

The Department of Defense (DoD) is the primary buyer, and it holds a lot of bargaining power. However, DEWs offer unique capabilities, like lower operational costs and scalability, which make them highly valuable to the DoD. By aligning DEWs with the military's **immediate needs (requirements pull)** while pushing forward with **innovative technologies (technology push)**, the DEW project ensures that the DoD sees these weapons as essential.

5. Threat of Substitutes

The threat of substitutes for DEWs is relatively low. Traditional kinetic systems, like missile interceptors, are costly and less scalable, while DEWs offer the ability to engage multiple threats at a lower cost per use. DEWs fill a gap in defense capabilities,



particularly when it comes to handling high-volume, low-cost threats like drone swarms, which existing systems cannot address as efficiently.

In summary of the Porter's Five Forces analysis, DEWs are strategically positioned in the defense sector by adding unique value to existing missile systems rather than competing head-to-head. High barriers to entry—like advanced technology requirements and strong airborne military foundations—limit new competition. By building diverse partnerships, DEWs reduce supplier power, while DoD's influence as the main buyer is balanced by DEWs' cost-effectiveness and practicality. The low threat of substitutes strengthens DEWs' position, especially since they handle high-volume threats like drone swarms that traditional systems struggle with. Altogether, these forces make DEWs a game-changer in aerial defense, solidifying their role as a valuable, essential tool in modern military strategy.

F. CORE STRATEGIC TRADE-OFFS IN AIRBORNE DIRECTED ENERGY WEAPONS ACQUISITION

From an acquisition perspective, the previously identified tensions translate into key strategic trade-offs that shape decision-making. The first and most critical is the balance between innovation and operational readiness.

1. Balancing Innovation and Readiness

Rogers' Five Factors reveal not only the pathways for accelerating DEWs' adoption but also the strategic trade-offs and risks inherent in the process. The DoD must navigate these challenges by aligning DEW deployment with the overarching theme of balancing innovation with operational readiness. Researchers argue that while prediction is unavoidable in national security planning, its failure is equally inevitable (Danzig, 2011). This necessitates strategies that prioritize adaptability and responsiveness over rigid, long-term predictions. For DEWs, this could mean designing modular systems and iterative deployment frameworks that allow for mid-course corrections as new threats emerge. By leveraging legacy platforms while investing in modular upgrades, addressing complexity with focused training, and ensuring trialability and observability through phased rollouts, DEWs can evolve from experimental technologies into indispensable assets of modern aerial defense.



2. Balancing Technology Push and Requirements Pull

The core strategy of the DEW project is finding the balance between **technology push and requirements pull**. On one hand, the **technology push** comes from the innovative capabilities of DEWs, which provide a scalable, cost-effective solution for dealing with new threats like UAVs and cruise missiles. On the other hand, the **requirements pull** is the immediate need to integrate this technology with existing military platforms to address today's defense challenges.

Much like USPS used its infrastructure for last-mile delivery, the DEW project avoids the high costs and delays of creating new military platforms by focusing on **integrating DEWs with legacy fighter jets and reducing its Laser power requirements as part of a realistic "SWAP-C" constraints solution**. This balance between innovation and practicality allows for the rapid deployment of DEWs, ensuring they meet the military's current needs while still pushing the boundaries of defense technology.

According to the GAO (U.S. Government Accountability Office, 2023), one of the significant hurdles for DEWs' effective deployment is not solely the innovation itself but the transition planning that ensures these systems integrate smoothly into current defense structures. The Government Accountability Office (GAO) emphasizes that while DEWs present immense operational potential, the Department of Defense (DoD) must prioritize transition strategies that mitigate logistical, training, and support challenges as DEWs move from development to active deployment. This report underscores the importance of synchronizing technology push with robust, proactive transition planning to align DEWs effectively with operational readiness and sustainment needs.

3. Understanding Strategy Synergies

The strategy synergies emerge from the integration of multiple analytical frameworks applied throughout this chapter. Systemic Operational Design (SOD) defines the structure of the problem and identifies the key tensions shaping DEW integration. The evolution to SIOM provides the mechanism for continuous adaptation, enabling iterative refinement under conditions of uncertainty and time pressure. Rogers' Five Factors



address the organizational dimension, ensuring that the technology is not only developed but also accepted and operationalized. Porter's Five Forces situate the DEW project within the broader defense ecosystem, highlighting constraints related to suppliers, competition, and industrial capacity.

The integration of these perspectives transforms the strategy from a set of independent considerations into a coherent decision-making framework. For example, the use of legacy platforms simultaneously addresses the need for rapid deployment (SOD), reduces adoption barriers (Rogers), and strengthens competitive positioning by increasing entry barriers (Porter). Similarly, modular design enables both technological adaptability (SIOM) and operational readiness, while phased pilot programs support trialability and reduce implementation risk.

In this sense, the strategy is not defined by a single approach but by the alignment of multiple logics—systemic, organizational, and competitive—into a unified acquisition model. This integrated approach ensures that DEWs are not only technologically viable but also operationally relevant, economically sustainable, and strategically positioned within the defense ecosystem.

This integrated logic is operationalized in Figure 12, which illustrates how the key strategic elements interact to support rapid deployment and long-term capability development.



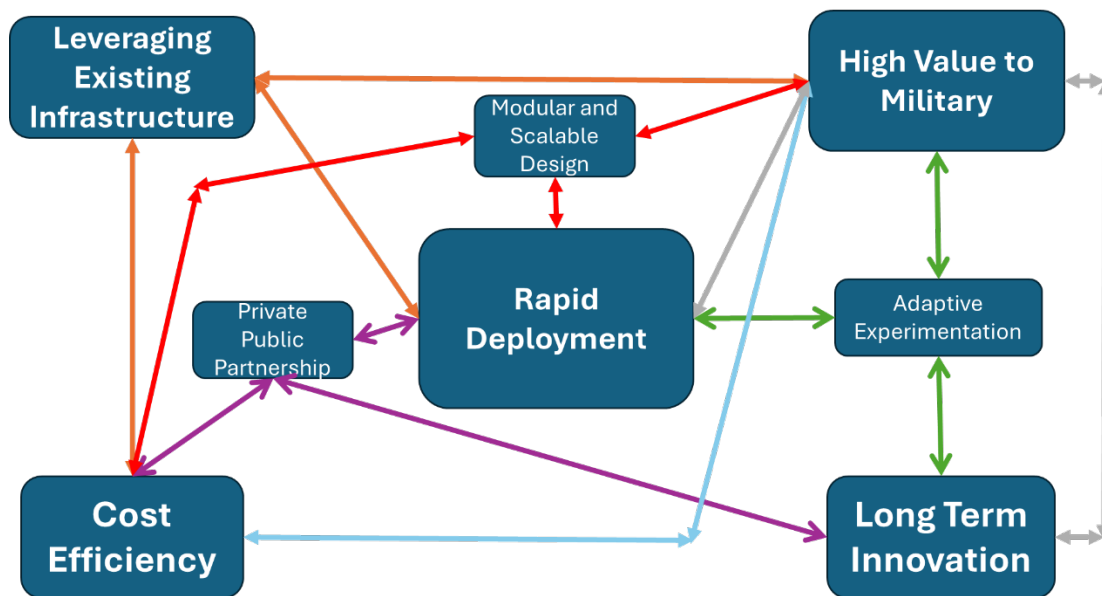


Figure 12. Integrated Strategy for Rapid Deployment and Cost-Effective Defense of DEWs.

At the core of the model is the objective of **rapid deployment**, which serves as the central organizing principle. Surrounding it are several mutually reinforcing elements. Leveraging existing infrastructure, such as legacy fighter jets, directly enables rapid deployment by reducing integration time and cost, while also contributing to overall cost efficiency. In turn, cost efficiency strengthens the value proposition of DEWs and supports their broader adoption.

The introduction of **modular and scalable design** acts as a critical bridge between competing requirements. It enables technological adaptability, consistent with the SIOM framework, while simultaneously supporting operational readiness through incremental upgrades. This approach connects short-term deployment needs with long-term innovation, ensuring that immediate implementation does not constrain future capability development.

Adaptive experimentation, reflected in pilot programs and iterative testing, further strengthens the system by enabling continuous learning and refinement. This process reduces uncertainty, improves system performance, and reinforces the perceived and actual value of DEWs to the military, which is essential for adoption according to Rogers' framework.

The role of **public-private partnerships** links multiple components of the model. These partnerships reduce supplier dependency, accelerate development, and enhance flexibility within the industrial base, addressing key insights from Porter’s Five Forces. At the same time, they contribute to both cost efficiency and long-term innovation, creating reinforcing feedback loops within the system.

The model also highlights that **high value to the military** emerges from the interaction of these elements rather than from any single factor. Similarly, **long-term innovation** is sustained through continuous interaction with adaptive experimentation and modular design, ensuring ongoing relevance in a dynamic threat environment.

Overall, the strategy is defined not by isolated decisions but by the interaction of interconnected elements that simultaneously address multiple constraints and objectives. This integrated acquisition framework enables the DEW program to balance speed, cost, innovation, and operational effectiveness, while maintaining the flexibility required to adapt to evolving technological and strategic conditions

G. LEADERSHIP ROLE AND STRATEGY FOR DIRECTED ENERGY WEAPONS

The integration of DEWs into national defense demands visionary leadership, systemic thinking, and a competitive strategy that adapts to modern challenges. Drawing from the insights of leaders such as Robert Gates, Robert McNamara, Michael Porter, and Cynthia Montgomery’s research, the narrative of DEWs becomes not just about technology but about leadership guiding a dynamic, purpose-driven transformation of defense capabilities. Strategic innovation requires selecting approaches that align with the specific challenges of the environment, emphasizing the need for tailored strategies in complex and dynamic settings (Reeves, 2015).

Robert Gates exemplified the balance between immediate operational needs and long-term strategic vision during his tenure as Secretary of Defense (Gates, 2014). He understood that reforming the Pentagon required pragmatism and persistence, redirecting resources to address pressing conflicts while fostering readiness for emerging threats. For DEWs, this balance is critical. Starting with pilot programs on legacy aerial platforms like the C-130 Hercules and Jetfighters provides a practical approach to test and refine



capabilities, ensuring their success in real-world scenarios. Gates' **pragmatic leadership** demonstrates how DEWs can be framed as complements to existing kinetic systems, showing how they conserve traditional resources while addressing low-cost threats like UAV swarms.

Robert McNamara's legacy of **systemic thinking and data-driven strategies** offers another crucial perspective (Shapley, 1987). His Planning, Programming, and Budgeting System (PPBS) redefined how resources were aligned with strategic goals. For DEWs, a systemic approach ensures that they are integrated not just as standalone technologies but as elements of a cohesive defense ecosystem. McNamara's emphasis on iteration and adaptability is also instructive; by starting with modular designs and incremental deployments, DEWs can evolve over time to address power, targeting, and scalability challenges.

Michael Porter's theories of national competitiveness (Porter, 1990), highlight the importance of innovation and collaboration. DEWs, as scalable and cost-effective solutions, disrupt traditional cost dynamics in defense. Porter's concept of **industrial clusters**—where sectors like aerospace and semiconductors collaborate—can accelerate advancements in DEW technologies such as beam control and power efficiency. Moreover, Porter underscores the value of **international alliances**. By positioning DEWs as integral to joint defense strategies, the U.S. can enhance its leadership role while sharing costs and knowledge with allies.

Cynthia Montgomery in her paper: "Putting leadership back into strategy" completes the narrative by focusing on **leadership's central role in strategy** (Montgomery, 2008). She argues that purpose should guide every decision, ensuring that strategy remains dynamic and aligned with evolving realities. DEWs must be seen as more than technical innovations; they are symbols of a forward-thinking defense strategy. Leadership must continually reassess their role, aligning them with the broader mission of cost efficiency and operational adaptability, much like Lou Gerstner redefined IBM's purpose to deliver integrated solutions.

The integration of DEWs is not just a challenge of technology; it is a test of leadership. Gates' pragmatism, McNamara's systemic frameworks, Porter's emphasis on



competitiveness, and Montgomery's focus on purpose all converge to illuminate a path forward. DEWs represent the opportunity to redefine the future of defense, blending innovation with adaptability and ensuring the U.S. remains at the forefront of global security. Through strategic leadership and a living strategy, DEWs can achieve their transformative potential, addressing today's threats while preparing for those of tomorrow.

Strategic innovation demands selecting approaches that fit the specific challenges of the environment, which underscores the need for tailored strategy in complex and changing settings (Reeves, 2015).

1. Visionary Strategy

The DEW project is guided by a **visionary strategy**, which focuses on transforming aerial defense by introducing energy-based weapons. Like DARPA's revolutionary work on stealth technology and the Internet, the DEW project seeks to disrupt traditional defense systems by offering a new way to neutralize multiple aerial threats. This long-term vision is crucial in defense, where technological leadership determines future success.

2. Adaptive Strategy

While the project is forward-looking, it also uses an **adaptive strategy** to ensure rapid deployment. By focusing on **integrating DEWs with legacy platforms**, such as existing fighter jets, the project avoids the high costs and delays of developing new systems from scratch. This approach allows DEWs to be deployed faster, ensuring they meet today's defense needs while still evolving for the future.

3. Shaping Strategy

The DEW project actively uses a shaping strategy by building strong partnerships across the defense ecosystem. **Collaborating closely** with military units, defense companies, and research bodies, it aims to shape the future of aerial defense. These partnerships aren't just for show—they make sure DEWs address the real needs of all involved, boosting the project's chances of success. DARPA's approach to working



together on strategic goals is a useful example, ensuring the DEW project stays in line with the broader defense community's priorities.

This multi-faceted approach enhances flexibility, drives innovation, and builds strong alliances, ensuring the Airborne Directed Energy Laser project is both responsive to current demands and resilient in facing the complexities of tomorrow's battlefield.

H. SUMMARY

This chapter explores the principles of the acquisition strategy for **Airborne Directed Energy Weapons (DEWs)** in modern aerial defense systems, emphasizing the balance between **rapid innovation** and **operational readiness**. DEWs address emerging threats such as UAV swarms, hypersonic missiles, and drone attacks by offering **scalable, cost-effective solutions** that complement existing kinetic systems. Drawing from **Systemic Operational Design (SOD)**, **Rogers' Five Factors**, and lessons from the **Tesla, FBI, DARPA, and USPS case studies**, the chapter outlines strategies to overcome technical, organizational, and logistical barriers.

The key to the project's success lies in balancing **technology push** with **requirements pull**, ensuring that DEWs are integrated quickly and efficiently into existing defense systems. With the right mix of strategies, the DEW project has the potential to **transform aerial defense** and offer a scalable, cost-effective solution to modern threats, maintaining the critical balance between innovation and readiness.

Strategic lessons from **DARPA** and **USPS** provide valuable insights. DARPA's use of **visionary, adaptive, and shaping strategies** illustrates how to drive innovation while addressing immediate operational needs. USPS demonstrates how **leveraging existing infrastructure** and forming **public-private partnerships** can accelerate deployment and increase efficiency by optimizing resources and fostering collaboration.

Similarly, the **FBI** case highlights the importance of **organizational transformation** to overcome institutional resistance and embrace new capabilities. By employing systemic planning and leadership-driven change, the FBI successfully modernized its operations—a model applicable to the cultural and bureaucratic hurdles in DEW adoption. The **Tesla** case underscores the value of **disruptive innovation**,



showcasing how modular, scalable designs and a commitment to reliability can drive adoption of emerging technologies. These principles align with the need for **trialability** and **compatibility** in DEWs, ensuring seamless integration with existing defense platforms.

Leadership emerges as a **critical enabler** in this transformative process. Drawing on the leadership philosophies of **Gates, McNamara, Porter, and Montgomery**, the chapter underscores the role of leaders in guiding the development and deployment of DEWs. Leadership characteristics such as **pragmatism, system planning, competitiveness, and purpose-driven vision** ensure alignment with evolving strategic imperatives.

The **three-year execution timeframe** is framed as a **deliberate strategic leverage point**, driving disruptive innovation and prioritization by fostering urgency and aligning resources with rapid deployment goals. **Rogers' Five Factors—relative advantage, compatibility, complexity, trialability, and observability**—are applied to assess and mitigate risks, ensuring that the project's challenges are effectively addressed.

By integrating systemic thinking, risk assessment, and a disruption-focused strategy, the chapter provides actionable recommendations for deploying DEWs as **transformative, scalable assets** capable of countering evolving threats while ensuring **cost-efficiency and institutional acceptance**.



V. LEVERAGING THE MIDDLE TIER OF ACQUISITION FOR RAPID PROTOTYPING AND RAPID FIELDING OF AIRBORNE DIRECTED ENERGY LASERS

The integration of airborne Directed Energy Weapons (DEWs) into modern military capabilities represents a critical leap in countering evolving threats such as unmanned aerial systems (UAS), cruise missiles, and high-speed surveillance platforms. These advanced systems promise significant advantages, including precision engagement, reduced collateral damage, and cost-effective scalability. However, as we have seen in the previous chapter, the complexity and urgency of their development demand innovative acquisition strategies that transcend the limitations of traditional frameworks.

The Middle Tier of Acquisition (MTA) framework, introduced under Section 804 of the National Defense Authorization Act (NDAA) for FY2016, was designed to address delays and inefficiencies in defense acquisition by providing a streamlined approach to rapidly prototype and field advanced technologies. For programs like DEWs, where timelines are constrained by rapidly advancing threats, MTA provides an ideal mechanism for accelerating capability delivery. Unlike traditional acquisition pathways, which prioritize comprehensive documentation and deliberative decision-making, MTA emphasizes speed, adaptability, and iterative development—qualities essential for integrating high-risk, high-complexity systems like DEWs (Department of the Navy, 2022).

The MTA framework offers two primary pathways: Rapid Prototyping, which focuses on demonstrating new capabilities to operational users within five years, and Rapid Fielding, which ensures the deployment of proven technologies with minimal additional development within the same timeframe (GAO, 2022). Both pathways are critical for addressing the technical and operational challenges of airborne DEWs, including size, weight, power, and cooling (SWaP-C) constraints, as well as the need for compatibility with existing platforms and joint force operations (GAO, 2023).

This chapter explores how the MTA framework can be leveraged to enable the rapid development and deployment of airborne DEWs. Building on the foundational



methodologies and principles outlined in Chapter IV, it highlights the specific challenges and opportunities associated with applying MTA to DEW programs. The discussion draws extensively from lessons learned in similar acquisition efforts, as well as from the documents and case studies examined throughout this research.

In this chapter we will first examine the limitations of conventional acquisition frameworks and their implications for DEWs. After providing a detailed overview of MTA principles, focusing on its applicability to high-risk technologies, we will discuss specific adjustments required to align MTA with DEW program goals. Then, we will explore the implementation strategies, exploring the pathways of rapid prototyping and rapid fielding, highlighting key activities and case studies. We will also try to balance and to address the challenges of managing risks in the MTA framework and propose enhancements tailored to DEWs in the MTA framework.

By addressing these aspects, this chapter aims to demonstrate how the MTA framework can bridge the gap between technological feasibility and operational readiness for airborne DEWs. It underscores the importance of adapting acquisition processes to meet the unique demands of disruptive technologies, ensuring that the military remains equipped to counter emerging threats effectively and efficiently.

A. CHALLENGES IN TRADITIONAL ACQUISITION PROCESSES

The development and deployment of DEWs, such as high-energy lasers and high-power microwave systems, present unique challenges that expose the limitations of traditional defense acquisition frameworks. Conventional acquisition pathways, structured around the DoD 5000 series, emphasize comprehensive planning, documentation, and milestone reviews. While this approach ensures rigor, it often leads to delays, cost overruns, and inefficiencies—factors that are particularly problematic for high-risk, rapidly evolving technologies like DEWs (Department of the Navy, 2022). We will explore here the shortcomings of traditional acquisition methods and their implications for airborne DEWs, highlighting the urgency of adopting more adaptive and streamlined frameworks such as the MTA. The structure of the Department of Defense Adaptive Acquisition Framework, which underpins traditional acquisition pathways, is illustrated in Figure 13.



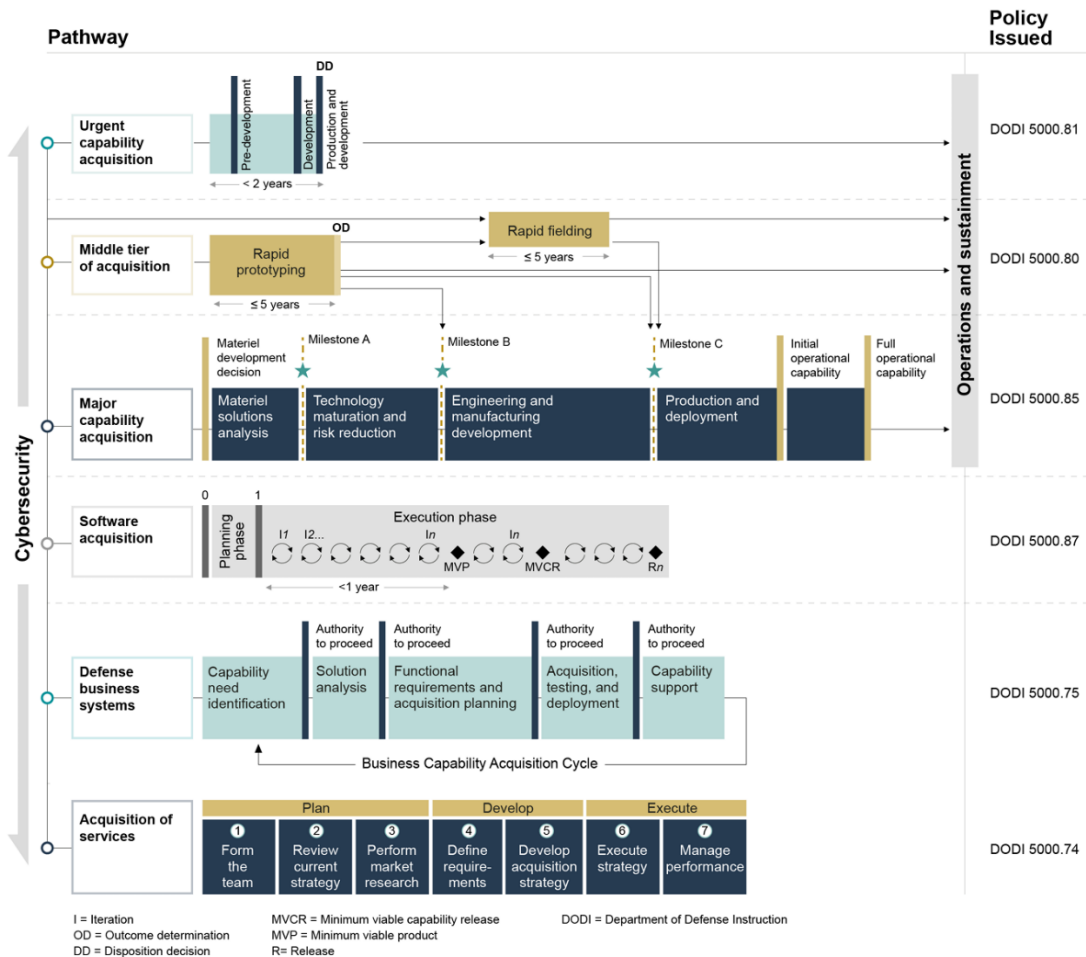


Figure 13. DoD Adaptive Acquisition Framework.
Source: GAO (2023).

1. Lengthy Development Timelines

Traditional acquisition processes prioritize risk reduction through exhaustive planning and phased development cycles. While this ensures robust systems, it also results in timelines that often exceed a decade from concept to deployment. For technologies like DEWs, such delays are untenable due to the rapid evolution of aerial threats, including advanced UAS and hypersonic weapons (GAO, 2023), and the need for operational systems that can keep pace with adversaries' innovations. Historically, the Airborne Laser Program, initiated in the 1990s, aimed to deploy high-energy lasers for missile defense. Despite substantial investments, the program was canceled after decades of development due to technical and operational challenges, underscoring the risks of extended timelines (Lamberson et al., 2006).

2. Rigid Requirements and Oversight

The Joint Capabilities Integration and Development System (JCIDS) process, a cornerstone of traditional acquisition, often emphasizes fixed requirements that are difficult to adapt as technologies and operational needs evolve. This rigidity limits flexibility in addressing emerging threats and creates bottlenecks when new requirements necessitate revisions to existing plans. We have seen that traditional oversight mechanisms can lead to delays in decision-making, as seen in several legacy programs where approval cycles extended project timelines by years (GAO, 2023).

3. High Costs and Budgetary Constraints

DEWs require substantial investments in research, development, testing, and evaluation (RDT&E). Traditional acquisition often struggles to balance these costs with the need for affordability, leading to frequent budget overruns due to unforeseen technical challenges and difficulty in securing sustained funding for long-term programs.

Example: The Free Electron Laser (FEL) program demonstrated promise as a high-power DEW system but was ultimately discontinued due to escalating costs and shifting priorities (National Research Council, 2009; Socol, 2013).

4. Integration Challenges

Integrating DEWs into existing platforms, such as fighter jets and UAVs, involves addressing stringent SWaP-C constraints. Traditional acquisition frameworks often lack the flexibility to address these integration challenges dynamically, resulting in delays and redesigns. The Advanced Tactical Laser (ATL) program faced significant SWaP-C issues, weighing 12,000 pounds, limiting its operational utility despite successful demonstrations of laser capabilities (Burke & Sailor, 2008).

5. Insufficient Iterative Testing

Traditional acquisition pathways emphasize linear development processes with distinct phases for developmental testing (DT&E) and operational testing (OT&E). For DEWs, which require iterative design improvements to address technical complexities, this approach is suboptimal. Key issues include limited opportunities for feedback during



early development phases, and delayed identification and resolution of critical design flaws. (DoD, 2022). Programs such as the Airborne Laser Program failed to incorporate iterative testing, resulting in late-stage design changes that significantly increased costs and delayed deployment.

6. Lack of Rapid Adaptation

In rapidly changing operational environments, the inability to quickly adapt systems to new threats or technologies is a critical limitation of traditional acquisition. DEWs, being inherently modular and evolving technologies, require flexible frameworks that can accommodate updates and enhancements. Adversaries' rapid deployment of swarming UAVs demonstrates the need for DEWs capable of adapting to shifting threat profiles. Traditional acquisition pathways often lack mechanisms to respond with the necessary speed (GAO, 2023).

7. Limited Stakeholder Engagement

Traditional acquisition frameworks often operate in silos, with limited collaboration between key stakeholders such as operational units, industry partners, and international allies. This fragmented approach can hinder innovation and slow down the integration of critical feedback into system development. Stakeholder collaboration in the Angry Kitten Combat Pod Program, developed outside traditional acquisition, showcased how early user involvement can accelerate capability delivery (MacGregor et al., 2022).

8. Conclusion

The limitations of traditional acquisition processes underscore the need for alternative frameworks capable of addressing the unique challenges posed by airborne DEWs. Lengthy timelines, rigid requirements, high costs, and insufficient testing methodologies all highlight the inadequacy of conventional pathways for rapidly evolving, high-risk technologies. These challenges reinforce the relevance of the MTA as a flexible, streamlined approach to ensure that DEWs are developed and deployed at the speed of relevance. The next section will provide the core principles and pathways of the MTA framework, illustrating how it can overcome these limitations.



B. OVERVIEW OF THE MIDDLE TIER OF ACQUISITION FRAMEWORK

The MTA framework represents a transformative approach to defense acquisition, designed to address the persistent inefficiencies of traditional processes. Established under Section 804 of the NDAA for Fiscal Year 2016, the MTA framework facilitates the accelerated development and deployment of warfighting capabilities by prioritizing flexibility and speed over the extensive documentation and oversight characteristic of traditional frameworks. This approach is particularly relevant for programs involving DEWs, which require rapid technological advancement and deployment to counter emerging threats effectively (Department of the Navy, 2022; Webster, 2024). This part examines the foundational principles of MTA, its pathways for rapid prototyping and rapid fielding, and its relevance to DEWs. It also highlights the trade-offs between speed and rigor inherent in the MTA framework, drawing insights from existing studies and examples to contextualize its application to high-risk, high-complexity technologies such as airborne DEWs.

1. Origins and Objectives of the MTA Framework

The MTA framework was introduced as an alternative to the traditional DoD 5000 series acquisition pathways, which often involve lengthy timelines and excessive bureaucratic processes. While the traditional frameworks ensure rigor and mitigate risks, they have been criticized for their inability to respond effectively to rapidly evolving threats. The MTA framework addresses these shortcomings by providing two key acquisition pathways:

Rapid Prototyping: Aimed at demonstrating new capabilities through operational prototypes within five years.

Rapid Fielding: Designed to deploy proven capabilities with minimal additional development within five years.

These pathways align closely with the operational requirements for DEWs, which demand rapid development cycles to meet the evolving threat landscape, such as the proliferation of UAS and advanced missile technologies (GAO, 2023). The primary objectives of the MTA framework are as follows:



- **Accelerated Capability Delivery:** Ensuring that critical capabilities are developed and delivered within a timeframe that aligns with operational needs.
- **Flexibility in Execution:** Enabling acquisition strategies that adapt to the specific requirements of each program.
- **Operational Relevance:** Ensuring that technologies developed under MTA address immediate and high-priority defense needs.

2. Principles of the MTA Framework

The MTA framework is underpinned by three fundamental principles: speed, iterative development, and operational relevance. These principles are particularly relevant to the development and deployment of DEWs, which face significant technical and operational challenges.

a. *Speed Over Bureaucracy*

The MTA framework prioritizes rapid delivery over bureaucratic rigor, allowing programs to bypass traditional milestones and documentation requirements. This emphasis on speed is critical for technologies like DEWs, which must counter rapidly advancing adversarial threats. The U.S. Army's Long-Range Hypersonic Weapon (LRHW) program achieved initial operational capability (IOC) within five years, demonstrating how MTA enables accelerated timelines without compromising operational needs (DOT&E, 2023).

b. *Iterative Development*

The iterative development approach embedded within MTA allows programs to refine technologies through continuous prototyping and testing. This iterative process is essential for high-complexity systems like DEWs, which require extensive validation of components such as power management, beam control, and thermal regulation. Airborne Directed Energy Weapons necessitate modular designs and iterative testing to address SWaP-C constraints. Iterative development minimizes risks by identifying and resolving technical flaws early in the acquisition cycle (DoD, 2022).



c. Operational Relevance

MTA ensures that all program activities align with high-priority operational needs, enabling rapid response to emerging threats. The Air Force’s “Angry Kitten” Combat Pod program exemplifies the focus on operational relevance, providing advanced electronic warfare training capabilities through rapid prototyping.

3. The Two Pathways of MTA

The MTA framework consists of two complementary pathways—rapid prototyping and rapid fielding—each tailored to different stages of technology readiness and operational priorities.

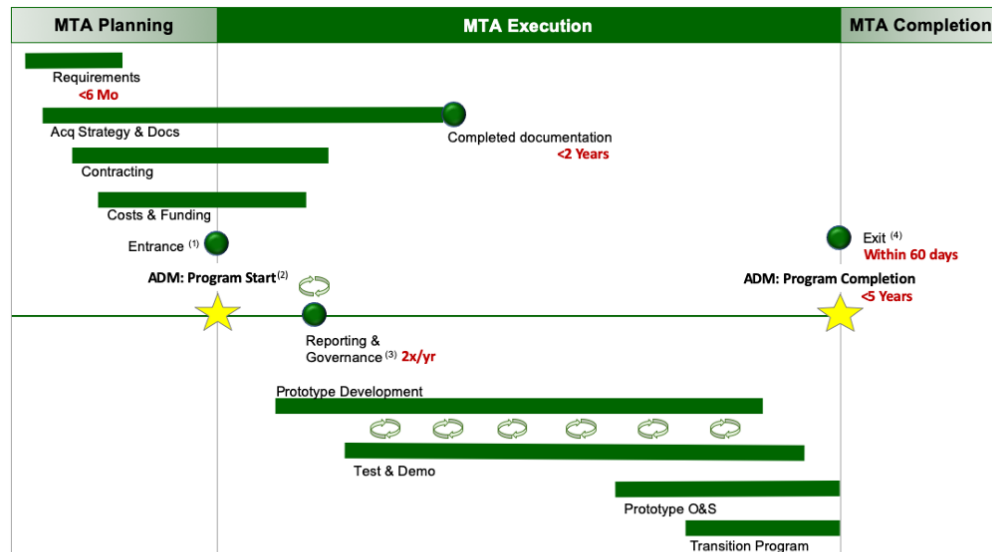
a. Rapid Prototyping

Rapid prototyping is designed to evaluate and demonstrate the feasibility of new capabilities within five years, making it an ideal pathway for complex systems like DEWs that require extensive testing before deployment. Key Activities are as follows:

- **Development of Modular Prototypes:** Creating flexible designs that can be tested across multiple platforms.
- **Operational Testing:** Conducting live-fire demonstrations in realistic threat scenarios to validate performance metrics such as targeting accuracy and energy efficiency.
- **Feedback Integration:** Incorporating input from operational users to refine prototypes.

Example: The Next Generation Squad Weapons Program demonstrated the feasibility to replace the rifle, automatic rifle, and fire control in the Army’s effort to modernize weapon systems through rapid prototyping, showcasing the effectiveness of this pathway for fire control (Department of Defense Office of Inspector General, 2021). The structure and key stages of the MTA rapid prototyping pathway, which supports the iterative development and validation of emerging capabilities, are illustrated in Figure 14.





- (1) **Major Systems:** Acquisition Decision Memorandum(ADM) signed by the Decision Authority (DA), Acquisition Strategy (which includes [1] Security, Schedule & Production Risks; [2] Test Strategy/Results; and [3] Transition Plan), and Program Identification Data (PID)
- Non-Major Systems:** ADM signed by the DA, PID
- (2) Major Defense Acquisition Programs (MDAPs) require Under Secretary of Defense for Acquisition & Sustainment (USD(A&S)) Prior Written Approval
- (3) Updated PID submitted twice a year with President's Budget and Program Objective Memorandum submissions to Office of Secretary of Defense (OSD)
- (4) Signed Outcome ADM, Final PID, Assessment of Test Results

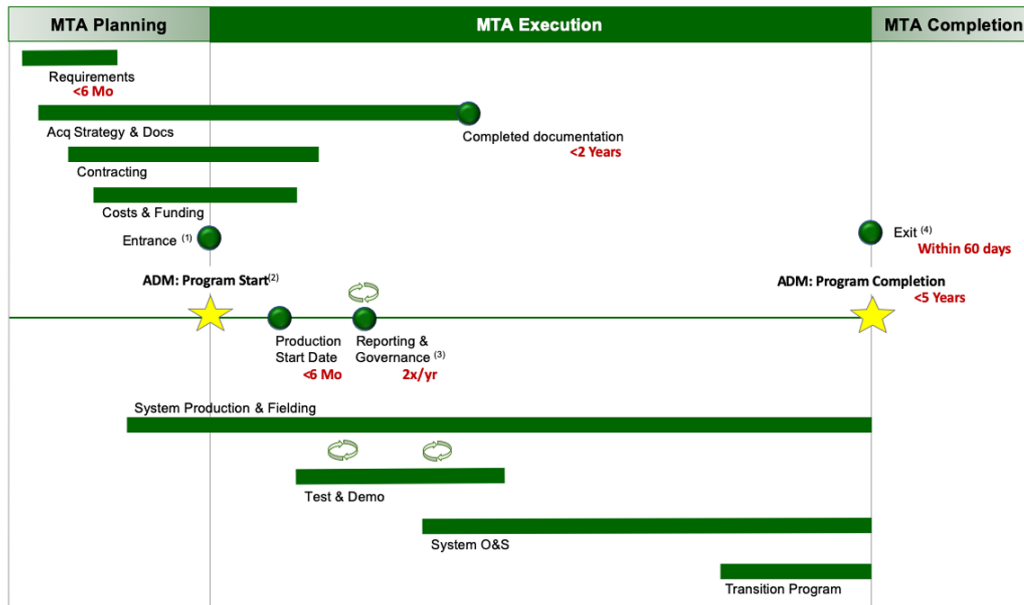
Figure 14. Middle Tier of Acquisition Rapid Prototyping Pathway Model.
Source: DAU (2024).

b. Rapid Fielding

Rapid fielding focuses on deploying technologies that are already mature or require minimal development. This pathway ensures quick delivery of operational capabilities to the field, addressing urgent mission needs. Key Activities are as follows:

- **Production Qualification Testing:** Verifying system reliability and readiness for production.
- **Sustainment Planning:** Establishing logistics and support infrastructure for deployed systems.
- **Deployment of Initial Operational Capability (IOC):** Fielding systems while continuing to refine performance.

Example: The U.S. Marine Corps Wideband Satellite Expeditionary combines commercial off-the-shelf and DoD hardware utilizing rapid fielding, instead of developing a new one. The procurement of the latest mature and supported technology enables the program to focus on reduction of size, weight and power from legacy equipment (Department of Defense Office of Inspector General, 2021). The structure and key stages of the MTA rapid fielding pathway, which focuses on the accelerated deployment of mature capabilities, are presented in Figure 15.



- (1) Major Systems: Acquisition Decision Memorandum(ADM) signed by the Decision Authority (DA), Acquisition Strategy (which includes [1] Security, Schedule & Production Risks; [2] Test Strategy/Results; and [3] Transition Plan), and Program Identification Data (PID)
 Non-Major Systems: ADM signed by the DA, PID
 (2) Major Defense Acquisition Programs (MDAPs) require Under Secretary of Defense for Acquisition & Sustainment (USD(A&S)) Prior Written Approval
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 (4) Signed Outcome ADM, Final PID, Assessment of Test Results

Figure 15. Middle Tier of Acquisition Rapid Fielding Pathway Model
 Source: DAU (2024).

4. Balancing Speed and Rigor in MTA

While MTA excels in accelerating capability delivery, it also presents challenges in maintaining rigor and managing risks. The recent research “The Middle Tier of Acquisition: Speed vs. Rigor” highlights several key trade-offs (Webster, 2024):

Requirements Ambiguity: Streamlined processes can dilute the rigor of requirement definition, leading to potential misalignments between system capabilities and operational needs. Recommendation: For DEWs, ensure that performance metrics such as beam quality and power output are clearly defined and validated during prototyping phases.

Workforce Expertise: The success of MTA programs depends on skilled acquisition professionals capable of navigating nontraditional pathways. However, gaps in workforce expertise can hinder program execution. Recommendation: Invest in training programs to equip acquisition professionals with the tools to manage rapid prototyping and fielding initiatives.



Oversight Challenges: Accelerated timelines can reduce oversight, increasing the risk of quality degradation or integration failures. In a recent study (Bub, 2023), “Analysis of Rapid Prototyping within the DoD,” it is stated that one of the reasons for massive rapid growth in the use of MTA authorities may be the significant reduction in reporting requirements. Recommendation: Establish robust governance structures to monitor program progress and address technical risks proactively (GAO, 2023).

5. Conclusion

The MTA framework provides a flexible and accelerated pathway for developing and deploying DEWs, offering a much-needed alternative to traditional acquisition processes. By prioritizing speed, iterative development, and operational relevance, MTA enables programs to address urgent mission needs while managing the complexities of disruptive technologies. However, balancing speed with rigor remains a critical challenge, necessitating targeted adjustments to optimize the application of MTA for airborne DEWs. The next section explores how MTA can be tailored further to meet the specific requirements of DEWs, ensuring alignment with both technical feasibility and strategic priorities.

C. ADDRESSING GAPS IN THE MIDDLE TIER OF ACQUISITION FORMAL GUIDANCE FOR AIRBORNE DIRECTED ENERGY WEAPONS

The MTA framework, while an excellent mechanism for accelerating the development and deployment of technologies like airborne DEWs, has several gaps in its formal guidance that need to be addressed for better alignment with your thesis objectives. Based on the documents you provided and discussions, here are the specific gaps and their implications for airborne DEWs.

1. Lack of Detailed Guidance for High-Risk, High-Complexity Technologies

MTA’s formal guidance does not explicitly address the unique challenges posed by high-risk, high-complexity technologies like DEWs. Specifically:



Technical Maturity: MTA lacks clear requirements for evaluating the readiness of advanced technologies like solid-state lasers or free electron lasers.

Integration Complexity: There is limited guidance on managing SWaP-C constraints during the rapid prototyping phase.

The Government Accountability Office (GAO, 2023) Highlights the importance of rigorous testing for emerging technologies but notes that MTA often overlooks comprehensive risk assessments in the rush to field capabilities. We should develop formal criteria for assessing technology readiness in MTA programs, including specific TRL benchmarks and integration feasibility studies for DEWs.

2. Insufficient Emphasis on Iterative Testing and Evaluation

MTA guidance does not mandate iterative testing cycles before transitioning from prototyping to fielding. This can lead to rushed deployments with unresolved technical risks. Current MTA guidance assumes a linear transition from rapid prototyping to rapid fielding, which is not ideal for technologies requiring iterative design improvements.

It is worthwhile to mention that the Testing and Evaluation (T&E) Enterprise Guidebook (DoD, 2022) emphasizes the need for iterative developmental and operational testing for complex systems but notes that this is not explicitly embedded in MTA guidance. Incorporating iterative T&E requirements into MTA formal guidance, with milestones for validating performance metrics like energy efficiency, beam control, and targeting accuracy, would be highly beneficial.

3. Gaps in Risk Management Framework

MTA guidance does not provide robust risk management frameworks for programs with high uncertainty, such as DEWs. Risks associated with power generation, beam stability, and adversarial countermeasures are often underestimated in MTA programs. The Government Accountability Office (GAO, 2022) Notes that risk management practices in MTA programs are often ad hoc, leading to unforeseen delays and cost overruns.

We recommend that a formal risk management process within MTA that includes early



identification of technical and operational risks be included, followed by mitigation plans, such as modular designs to allow iterative upgrades.

4. Lack of Focus on Digital Engineering and Modeling

MTA formal guidance does not prioritize the use of digital engineering and modeling tools to streamline design, testing, and integration processes. DEWs require extensive modeling to validate their effectiveness under varied operational scenarios. T&E Enterprise Guidebook (DoD, 2022) Discusses the benefits of digital engineering in reducing development timelines but notes that MTA guidance does not require its use. The Undersecretary of Defense for R&E published a DEWs MOSA (Modular Open System Architecture) reference architecture in 2022, emphasizing the guidelines as a tool to enable rapid fielding, extended service life of systems through incremental upgrades and reuse across programs and Services (DoD, 2022). We recommend embedding digital engineering tools in MTA programs to simulate Airborne DEW performance, including power requirements, thermal management, and beam stability.

5. Weak Guidelines for Stakeholder Collaboration

MTA guidance provides limited direction on engaging stakeholders like operational units, industry partners, and allied nations. For DEWs, early collaboration is essential to ensure operational relevance and compatibility with existing platforms. The Navy instructions on adaptive acquisition framework (Department of the Navy, 2022) highlights the need for stakeholder engagement in rapid acquisition programs but notes gaps in formal guidance for collaboration strategies. We recommend to develop lines of communications for engaging stakeholders during the prototyping and fielding phases, such as: Joint testing exercises with Combatant Commands, and Industry-government partnerships to accelerate development.

6. Insufficient Emphasis on Sustainment Planning

MTA formal guidance does not adequately address sustainment and life cycle considerations for rapidly fielded technologies. DEWs require specialized maintenance, spare parts, and training programs, which are often overlooked during rapid fielding. The Government Accountability Office (GAO, 2023) notes that many MTA programs fail to



account for long-term sustainment during the acquisition process. We recommend including sustainment a mandatory component of MTA guidance of the Services, with requirements for training programs for operators and maintainers and pre-positioned logistics hubs for spare parts and repair tools. The scope could be varied, to fit the accurate rapid fielded capability. It is interesting to note that only in November 2024, the DoD added to DoDI 5000.80 (Operation of the Middle Tier of Acquisition Change 1) requirements for sustainment metrics, exportability considerations, and transition plan requirements (DoD, 2024).

7. Ambiguity in Transition Planning

MTA guidance lacks detailed instructions for transitioning successful prototypes to full production and sustainment phases. For DEWs, this ambiguity can result in delays or inefficiencies during the fielding phase. It is worthwhile to mention that the T&E Enterprise Guidebook (DoD, 2022) stresses the importance of transition planning but notes inconsistencies in how it is applied across MTA programs. We recommend requiring a detailed transition planning to include criteria for moving from prototyping to fielding and plans for scaling production and addressing bottlenecks.

8. Limited Guidelines on Cybersecurity

MTA guidance does not emphasize cybersecurity testing for advanced systems like DEWs, which are vulnerable to electronic warfare and hacking. DEWs, relying on sophisticated electronics and data links, are particularly susceptible to cyber threats. Even within rapid fielding of capabilities, one should understand the cyber risks and apply a mitigation plan, or notify stakeholders the risks associated with the mission assurance. The T&E Enterprise Guidebook (DoD, 2022) emphasizes Cybersecurity Testing. Therefore, we recommend testing DEWs' resilience to jamming and spoofing during developmental phases, where simulation of adversarial cyber-attacks could support the effort to ensure DEWs maintain functionality in contested environments, such as penetration testing.



9. Weak Oversight Mechanisms

MTA programs often suffer from limited oversight, leading to inconsistencies in execution and outcomes. The benefit for utilizing that for DEWs, the absence of robust oversight could result in unaddressed performance issues or delays. The Inspector General audit report, titled *Audit of Department of Defense Middle Tier of Acquisition Rapid Prototyping and Rapid Fielding Programs* (Department of Defense Office of Inspector General, 2021) notes that oversight mechanisms in MTA programs are often less stringent than in traditional acquisition programs. It also mentions that “While the requirement of component commands to create their own processes was straightforward, the documentation and reporting of projects to their oversight authorities was not clearly defined.” However, it is well understood that the real challenge is to restrain from overburdening the MTA pathway with reporting and regulations. It was well written in published research as well as DAU report (Bub, 2023 ; Webster, 2024) that one of the reasons for the rapid growth in the use of MTA authorities could be the significant reduction in reporting requirements. We recommend establishing dedicated oversight bodies for MTA for clear and lean reporting requirements with relevant performance benchmarks.

D. INTEGRATING GAO’S FOUR LEADING PRINCIPLES INTO AIRBORNE DIRECTED ENERGY WEAPONS DEVELOPMENT UNDER THE MTA FRAMEWORK

The Government Accountability Office reports from 2022 and 2023 highlight four leading principles that are essential for guiding defense acquisition programs, particularly those leveraging the MTA framework (GAO, 2022; GAO, 2023). These principles—attaining a sound business case, employing an iterative design approach, prioritizing schedule through off-ramping capabilities, and collecting customer feedback—offer a structured foundation for managing high-risk, high-complexity projects such as airborne DEWs. This part explores how these principles can be integrated into the DEW development process, enhancing both technical feasibility and operational effectiveness. The four leading principles that underpin successful product development within the MTA framework are illustrated in Figure 16.



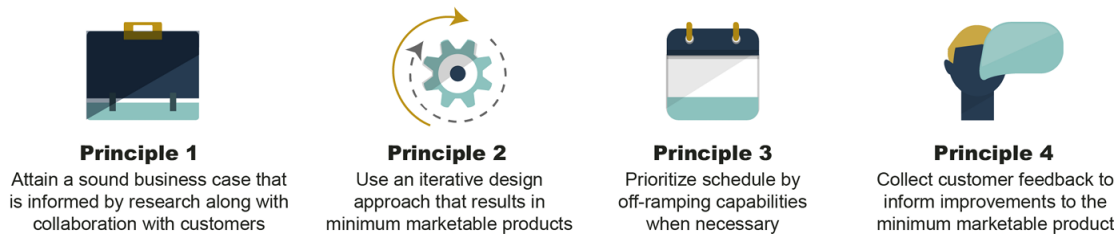


Figure 16. Four Principles to Enable Successful Product Development.
Source: GAO (2023).

1. Principle 1 – Attaining a Sound Business Case

A sound business case ensures that the DEW program is grounded in realistic objectives, resources, and timelines. It involves clearly defined requirements, cost assessments, and alignment with strategic priorities. Application to DEWs:

Clear Operational Requirements: Define precise performance parameters for DEWs, such as energy output, beam stability, and engagement range, ensuring alignment with mission-critical needs. For example, specify the ability to neutralize UAV swarms within a 5 km radius under contested conditions.

Cost-Benefit Analysis: Conduct life cycle cost analyses to evaluate the affordability and long-term value of DEWs compared to kinetic systems. Highlight the cost-effectiveness of DEWs in terms of engagement costs versus missile-based interceptors.

Risk-Adjusted Planning: Develop risk mitigation strategies for technical and operational uncertainties, such as power scalability and platform integration.

2. Principle 2 – Employing an Iterative Design Approach

The GAO emphasizes the importance of iterative design to identify and address technical challenges early in the development process. For DEWs, this principle is particularly critical given the complexity of high-energy laser systems.

Prototyping and Testing Cycles: Implement multiple iterations of developmental testing (DT&E) to validate system performance, focusing on beam alignment, thermal management, and SWaP-C constraints. For Example, use modular

prototypes for incremental testing on multiple platforms, such as the legacy F-15/F-16 and C-130.

Integration of Operator Feedback: Incorporate input from pilots and tactical commanders during prototype evaluations to refine system usability and operational concepts.

Modular Design Flexibility: Develop modular DEW architectures that allow for iterative upgrades without requiring complete redesigns, such as Agile development practices for hardware and software integration, ensuring flexibility in addressing unforeseen technical challenges.

3. **Principle 3 – Prioritizing Schedule Through Off-Ramping Capabilities**

To meet the accelerated timelines of the MTA framework, the GAO advocates focusing on core functionalities while off-ramping less critical capabilities for future iterations. This approach ensures timely delivery without compromising essential performance. Application to DEWs:

Minimum Viable Product (MVP): Deliver a basic DEW system capable of neutralizing single targets or small UAV swarms, deferring multi-target engagement or extended range capabilities for subsequent versions. For example, field a pod-mounted DEW prototype on transport aircraft while refining advanced targeting algorithms for future integration.

Incremental Capability Enhancements: Prioritize features that address immediate operational threats, allowing additional capabilities to be phased in through software or hardware updates.

Streamlined Decision Points: Establish clear criteria for determining which features can be deferred without jeopardizing mission effectiveness.



4. Principle 4 – Collecting Customer Feedback

Customer feedback ensures that DEWs align with end-user needs and operational realities. The GAO highlights the importance of structured feedback loops to refine systems throughout development and deployment. Application to DEWs:

Operational Feedback Mechanisms: Conduct field trials with combat units to gather insights on DEW performance, user interfaces, and maintainability. For example, pilot testing on Group 5 UAVs (such as MQ-9 Reapers) in contested environments to validate targeting and engagement accuracy prior to fielding Jetfighters capability.

Iterative Updates: Use operator feedback to inform iterative improvements, focusing on usability enhancements and reliability issues identified during testing.

Continuous Learning Framework: Establish a continuous feedback loop between developers, operators, and acquisition professionals to adapt DEWs to evolving threats.

5. Conclusion

Integrating the GAO's four leading principles into the airborne Directed Energy Weapons program under the MTA framework ensures a balanced approach to accelerated development and operational effectiveness. By emphasizing sound business cases, iterative design, schedule prioritization, and customer feedback, these principles address both technical and strategic challenges, providing a pathway for delivering DEWs that meet mission-critical needs. The application of these principles not only aligns with the goals of the MTA framework but also mitigates risks and enhances the likelihood of program success.

E. ACQUISITION STRATEGY PRINCIPLES RECOMMENDATIONS FOR AIRBORNE DIRECTED ENERGY WEAPONS

The development of airborne DEWs under the MTA framework necessitates a structured and academically rigorous approach to acquisition strategy. This section outlines the proposed acquisition strategy for Airborne DEWs, incorporating insights from SECNAV 5000.2G Instructions (Department of the Navy, 2022), directives from Dr. William B. Roper's memorandum of "7 Steps for Incorporating Rapid Prototyping



into Acquisition” (Department of the Air Force, 2018), and key findings from Government Accountability Office (GAO) reports. The strategy is tailored to address the acquisition approach, benefit analysis, business strategy, contracting framework, cooperative opportunities, industrial base considerations, and valuation of general equipment, ensuring alignment with operational priorities and rapid deployment goals. The acquisition strategy emphasizes achieving the rapid prototyping and fielding of DEWs to counter emerging threats effectively. It leverages established guidelines and lessons learned from other programs, aiming to deliver innovative, operationally relevant capabilities within an accelerated timeline.

1. Acquisition Approach

The Airborne DEW acquisition strategy is designed to deliver operational capabilities within three years, leveraging the MTA framework to balance speed, innovation, and technical rigor. The strategy is implemented through two primary pathways: rapid prototyping and rapid fielding. The prototyping phase will introduce and test transformative “X-factors,” such as advanced beam control or modular integration, with a focus on discovery and iterative improvement. The prototyping phase focuses on validating the feasibility of high-energy laser systems in operationally relevant environments, addressing critical challenges such as beam stability, power scaling, and integration with airborne platforms. Testing is conducted iteratively to refine designs and mitigate technical risks. By bounding risks—ensuring only one high-risk factor is introduced per prototype iteration—the acquisition strategy prioritizes manageable challenges to deliver fieldable capabilities. The transition from rapid prototyping to rapid fielding will ensure the deployment of mature systems within five years, maintaining flexibility for future capability enhancements. Once prototypes meet key performance parameters (KPPs), the fielding phase transitions systems to low-rate initial production (LRIP) and operational deployment. The modular design approach ensures scalability across multiple platforms, including transport aircraft such as C-130, using Group 5 UAV for sub components risk reduction, followed by integration on legacy Jetfighters (F-16, F-15). This phased approach reduces development timelines while ensuring alignment with operational needs and combat readiness.



2. Business Strategy

The acquisition strategy prioritizes agile program management and innovative funding mechanisms to support the rapid development and deployment of DEWs. A dedicated Program Management Office (PMO) will oversee all acquisition activities, ensuring adherence to timelines, budgets, and performance objectives. Quarterly program reviews will be conducted to monitor progress and address potential risks.

Funding for the DEW program will be secured through the Department of Defense's Planning, Programming, Budgeting, and Execution (PPBE) system, supplemented by Other Transaction Authority (OTA) agreements to streamline contracting processes. These mechanisms enable flexibility in resource allocation, allowing the program to adapt to evolving technical and operational requirements.

The strategy also emphasizes resource allocation for modular design and iterative testing to support multi-platform integration. Sustainment planning is integrated from the outset, ensuring the availability of spare parts, diagnostic tools, and operator training programs to maintain long-term operational readiness.

3. Contracting Strategy

The contracting framework for the DEW program is designed to align with the iterative nature of rapid prototyping and fielding. During the prototyping phase, cost-plus-fixed-fee (CPFF) contracts will incentivize innovation and flexibility in research and development. These contracts are tailored to reflect Roper's recommendation for minimizing administrative burdens while fostering agility and rapid decision-making. As the program transitions to fielding, fixed-price incentive (FPI) contracts will be implemented to control production costs and maximize value for money. Sustainment and logistical operations will be supported by indefinite delivery/indefinite quantity (IDIQ) contracts, facilitating the procurement of spare parts and maintenance services. Performance-based incentives will ensure that contractor payments are linked to milestone achievements, such as successful testing and delivery of operational units. To maintain speed and efficiency, the contracting framework enforces strict time and budget constraints during the prototyping phase, prioritizing progress over comprehensive



compliance with traditional acquisition standards. This approach reflects a commitment to Roper's principle of constraining time and budget rather than prematurely optimizing performance.

4. Cooperative Opportunities

The Airborne DEW program will leverage cooperative opportunities with international allies, industry leaders, and academic institutions to enhance innovation, reduce costs, and improve interoperability. Partnerships with allied nations will focus on co-developing DEW technologies and standardizing systems for joint operations. This collaborative approach aligns with the U.S. military's multi-domain operational objectives, ensuring seamless integration across allied forces.

Public-private partnerships will be established with industry leaders such as Lockheed Martin and Northrop Grumman to leverage their expertise in high-energy lasers and thermal management systems. Academic institutions will contribute to advanced research in areas such as beam control, power scaling, and cooling technologies, fostering innovation and accelerating development timelines.

5. Industrial Base Capability Considerations

The success of the Airborne DEW program depends on the strength and resilience of the industrial base. Key considerations include supplier engagement, workforce development, and infrastructure investment. Critical suppliers for components such as laser diodes, beam control systems, and thermal management units will be identified and supported to mitigate supply chain risks. Contingency plans will address potential disruptions, ensuring continuity in production and sustainment operations.

Workforce development initiatives will focus on training skilled personnel to support the production, integration, and maintenance of DEWs. Partnerships with technical schools and universities will foster the next generation of engineers and technicians specializing in laser and power systems.

Infrastructure investments will include the upgrade of manufacturing facilities to accommodate DEW production and the establishment of test ranges for live-fire



validation exercises. These investments ensure the industrial base is prepared to meet the demands of the DEW program while supporting broader defense objectives.

6. Conclusion

This acquisition strategy for airborne Directed Energy Weapons leverages the Middle Tier of Acquisition framework to deliver advanced capabilities efficiently and effectively. By integrating modular prototyping, iterative testing, and cooperative partnerships, the strategy addresses the unique challenges of DEW development while ensuring alignment with operational priorities. Robust contracting frameworks, sustainment planning, and industrial base considerations further enhance the program's viability, ensuring the successful deployment of DEWs to counter emerging threats and maintain U.S. military superiority.

F. TAILORING THE MIDDLE TIER OF ACQUISITION FRAMEWORK FOR AIRBORNE DIRECTED ENERGY WEAPONS

The MTA framework, while offering significant advantages for rapidly developing and deploying advanced defense technologies, requires tailored adjustments to effectively address the unique challenges posed by airborne DEWs. These systems, including HEL and HPM systems, introduce complexities in terms of technological readiness, integration constraints, and operational relevance. This subchapter explores how the MTA framework can be optimized specifically for DEWs by addressing their development, testing, and deployment needs. The discussion builds on insights from existing MTA programs, case studies, and key findings from the literature and the 4 leading principles of the 2022 and 2023 GAO reports.

1. Challenges Unique to Airborne DEWs

DEWs present a distinct set of challenges that make their development and deployment fundamentally different from conventional weapon systems:

Technological Maturity: Many DEW technologies, such as free electron lasers, remain at lower TRLs compared to solid-state lasers, which have achieved TRL 7–8 (GAO, 2022). Rapidly transitioning these systems from research to operational use requires careful consideration.



Integration Constraints: SWaP-C requirements are particularly stringent for airborne platforms. These constraints often necessitate extensive redesigns or modular approaches to ensure compatibility with host platforms like the F-35 or C-130 (Department of the Navy, 2022).

Iterative Development Needs: DEWs require iterative testing and refinement to address challenges such as beam stability, energy efficiency, and targeting precision. Traditional linear acquisition processes do not adequately support such iterative cycles (DoD, 2022).

Operational Uncertainty: The rapidly evolving nature of aerial threats, such as swarming UAVs and hypersonic missiles, demands flexible systems capable of adapting to diverse and unpredictable scenarios (GAO, 2023).

2. Tailoring Rapid Prototyping for Airborne DEWs

The Rapid Prototyping pathway under MTA provides an ideal mechanism for developing and testing new DEW capabilities. However, to optimize this pathway for DEWs, the following adjustments are recommended:

Modular Prototyping: Develop modular DEW prototypes that can be integrated across multiple airborne platforms, allowing for scalability and adaptability. Example: A pod-mounted DEW system for the F-35 can serve as a prototype for integration onto other platforms like UAVs or ground vehicles.

Iterative Testing and Feedback Loops: Implement iterative testing cycles to refine prototypes based on performance data and operator feedback. These cycles should include: Lab-based testing for beam quality and thermal management and field testing in operationally relevant scenarios, such as live-fire exercises against UAV swarms (DoD, 2022). Example: The HELIOS program's iterative testing approach demonstrated the feasibility of integrating laser systems into shipboard platforms, providing a model for airborne DEWs (GAO, 2022).

Early Stakeholder Involvement: Engage operational units, industry partners, and allied nations early in the prototyping phase to ensure that system designs align with mission needs. Example: The collaboration between the Air Force and DARPA on the



Self-Protect High Energy Laser Demonstrator (SHiELD) illustrates the value of early stakeholder engagement in refining system capabilities (AFRL, 2020).

3. Tailoring Rapid Fielding for Airborne DEWs

The Rapid Fielding pathway under MTA is designed to transition mature technologies to operational use with minimal additional development. To optimize this pathway for airborne DEWs, the following adjustments are proposed:

Scalable Production and Deployment: Establish scalable production processes that allow for phased deployment of DEWs while maintaining the flexibility to incorporate design improvements. Example: Begin low-rate initial production (LRIP) of pod-mounted DEWs for transport aircraft like the C-130, followed by full-scale production for fighter platforms.

Operational Readiness Validation: Conduct rigorous testing to ensure that fielded DEWs meet key performance parameters (KPPs) such as power output, targeting accuracy, and system reliability. Recommendation: Use production qualification testing and first article testing (FAT) to validate system readiness before full deployment (Department of the Navy, 2022).

Comprehensive Sustainment Planning: Develop sustainment plans to address maintenance, logistics, and training requirements for DEW systems. These plans should include: Pre-positioned logistics hubs for spare parts and repair tools and training programs for operators and maintainers to ensure operational proficiency. Example: Sustainment planning was a critical factor in the success of the Integrated Air and Missile Defense Battle Command System (IBCS), providing lessons for DEW fielding (Urness, 2024).

4. Enhancing Tailored Oversight and Governance

To ensure the success of DEW programs under the MTA framework, robust oversight and governance structures must be established. These should focus on:



Performance Metrics: Define clear metrics for evaluating the success of rapid prototyping and fielding efforts, such as time-to-capability, energy efficiency, and operational reliability (GAO, 2023).

Program Reviews: Conduct regular program reviews to assess progress and address potential risks. Recommendation: Incorporate digital engineering tools, such as model-based systems engineering (MBSE), to provide real-time insights into program status (DoD, 2022).

Risk Management Frameworks: Implement comprehensive risk management strategies to address technical, operational, and schedule risks. These frameworks should include: Early identification of integration challenges and mitigation plans for power and cooling system failures (GAO, 2023).

5. Incorporating Digital Engineering

Digital engineering tools can significantly enhance the development and deployment of DEWs under the MTA framework. These tools enable:

Virtual Prototyping: Simulate DEW performance under various operational scenarios, reducing the need for physical testing. Example: Use modeling and simulation to evaluate beam stability and power distribution in contested environments.

Streamlined Integration: Identify and resolve integration challenges early in the design phase.

The Undersecretary of Defense for R&E published a DEWs MOSA (Modular Open System Architecture) Reference Architecture in 2022, emphasizing the guidelines as a tool to enable rapid fielding, extended service life of systems through incremental upgrades and reuse across programs and Services (DoD, 2022).

6. Conclusion

Tailoring the Middle Tier of Acquisition framework to the unique requirements of airborne Directed Energy Weapons involves a deliberate focus on modular prototyping, iterative testing, scalable deployment, and robust governance. By addressing the technical and operational complexities of DEWs, these adjustments ensure that the MTA



framework can deliver advanced capabilities at the speed of relevance while maintaining the rigor needed for mission success. These implementation strategies for rapid prototyping and fielding, provides a roadmap for integrating DEWs into operational units.

G. SUMMARY

The integration of airborne DEWs under the MTA framework offers a transformative approach to counter modern aerial threats such as UAV swarms and cruise missiles. This Chapter delineates how the MTA framework facilitates the rapid prototyping and fielding of DEWs by leveraging innovative acquisition principles, addressing technical challenges, and aligning with operational priorities. The chapter underscores the inadequacies of traditional acquisition pathways, particularly their lengthy timelines, rigid requirements, and insufficient adaptability to emerging threats. It highlights the benefits of the MTA framework, which prioritizes speed, iterative development, and operational relevance, enabling faster capability delivery and agile responses to dynamic threat landscapes.

1. Key Themes and Findings

The chapter introduces the dual pathways of the MTA framework—rapid prototyping and rapid fielding—tailored to address the unique complexities of DEWs. The prototyping pathway emphasizes the iterative development of modular designs to validate critical performance metrics, including power scaling, beam stability, and SWaP-C constraints. Rapid fielding, in turn, focuses on transitioning validated prototypes into operational deployment within constrained timelines, ensuring immediate mission impact.

To overcome gaps in the formal MTA guidance, the chapter proposes specific enhancements, including the integration of iterative testing cycles, robust risk management frameworks, and advanced digital engineering tools. These adjustments address the technical and operational uncertainties associated with DEWs while ensuring their compatibility with legacy platforms such as C-130 transport aircraft and jet fighters like the F-16 and F-15.



The chapter further explores the strategic integration of the GAO's four leading principles for defense acquisition: sound business case development, iterative design approaches, off-ramping non-critical features, and the incorporation of user feedback. These principles serve as foundational elements for ensuring the alignment of DEWs with mission-critical needs and their scalability across diverse operational scenarios.

2. Contributions and Implications

This analysis provides actionable insights into balancing speed and rigor within the MTA framework. The chapter highlights how leveraging public-private partnerships, modular production strategies, and international cooperation can accelerate innovation while mitigating supply chain risks. It also emphasizes the importance of sustainment planning and workforce development to ensure long-term operational readiness.

By aligning acquisition strategies with systemic operational design principles and scenario-based planning, the chapter establishes a roadmap for integrating DEWs as a cornerstone of modern defense architectures. It positions the MTA framework as not only a mechanism for rapid deployment but also a model for addressing the broader challenges of defense acquisition in an era of disruptive technological advancements.

3. Conclusion

The findings in this chapter underscore the transformative potential of applying the MTA framework to airborne DEWs. By addressing gaps in current acquisition guidance and aligning development efforts with operational imperatives, it provides a comprehensive strategy for deploying DEWs as scalable, adaptable, and cost-effective solutions to modern threats. This approach ensures that DEWs not only meet today's challenges but also lay the groundwork for sustained technological superiority in an evolving global security landscape.



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VI. MODELING THE BATTLEFIELD: THE THREAT AND THE AIRBORNE DIRECTED ENERGY WEAPON SOLUTION

The transformation of modern warfare has led to the emergence of increasingly complex and dynamic threats that challenge traditional defense strategies. The proliferation of UAVs, cruise missiles, ballistic missiles, and hypersonic weapons has significantly altered the strategic landscape, creating an urgent need for more cost-effective, precise, and scalable defense solutions. Existing kinetic-based air defense systems, while highly capable, suffer from inherent economic and operational limitations, particularly in scenarios where adversaries rely on low-cost, high-volume attacks designed to overwhelm conventional interceptors. DEWs, particularly high-energy laser systems, represent a fundamental shift in defensive capabilities, providing a means to engage threats at the speed of light, with significantly reduced cost-per-engagement compared to traditional kinetic systems. By leveraging continuous-wave laser beams, DEWs offer the potential to counter UAV swarms, missile barrages, and hypersonic threats in a sustainable and economically viable manner.

This chapter presents a detailed battlefield modeling framework, structured into two main sections:

- Analysis of the evolving threat landscape – focusing on both short-range and long-range threat scenarios, as observed in recent conflicts and technological advancements.
- Mathematical modeling of airborne DEWs – developing an analytical framework to evaluate their performance, efficiency, and feasibility as an alternative to traditional missile-based interceptors.

This modeling will serve as the operational research foundation for subsequent analytical chapters, where the integration, strategic impact, and cost-benefit analysis of airborne DEWs will be assessed.

A. UAV SWARMS AND MISSILE BARRAGES THREAT SCENARIO

In order to ground the analysis in a realistic operational context, this section introduces a representative threat scenario based on the combined use of UAV swarms and missile barrages. This scenario reflects current trends in asymmetric warfare and



provides a practical framework for examining the challenges faced by conventional air defense systems, as well as the potential advantages of airborne DEWs.

1. Qualitative Description

The short-range battlefield environment is increasingly defined by asymmetric threats, where adversaries leverage cheap, expendable aerial assets to exhaust advanced air defense systems. One of the most notable examples of this tactic is Hezbollah's extensive use of UAVs and short-range missiles in conflicts against Israel, **a model that could be replicated by other state and non-state actors.**

It is important to note that between September 2024 and November 2024, there was an ongoing high-intensity conflict between Israel and Hezbollah. This conflict began with the well-known "Pagers attack" and ended with a fragile ceasefire. During this period, Israel was able to significantly reduce Hezbollah's weaponry and threat along the Israeli border, despite continued hostilities between the parties. Still, the scenario presented here serves as a strong model for evaluating airborne DEWs as a test case.

2. Nature of the Threat

- UAV Swarms: Hezbollah and similar militant groups operate fleets exceeding 2,000 UAVs, including Shahed-101, Mirsad, and Ababil drones. These drones vary in function from intelligence gathering and electronic warfare to precision-guided suicide attacks.
- Short-Range Rockets & Missiles: The organization's missile arsenal includes: Fajr-3 (40 km range), Zelzal-2 (210 km range), Fateh-110 (300 km range). These missiles are low-cost, mass-produced, and intended to saturate air defense systems.
- Tactics and Operational Complexity: Attacks often combine multiple vectors (UAVs, rockets, and guided munitions) to strain defensive responses. UAVs are deployed to suppress air defenses, while larger missiles target critical infrastructure and military bases.

3. Challenges to Conventional Defenses

- Cost-Exchange Disparity: Kinetic interceptors such as Iron Dome's Tamir missiles cost between \$40,000 and \$100,000 per shot, while UAVs and short-range rockets cost as little as \$1,000 to \$10,000 per unit.



- Saturation Attacks: Continuous daily barrages (often exceeding 100 rockets per day) force expensive interceptors to engage low-cost threats, creating an economically unsustainable defense posture
- System Overload & Ammunition Constraints: Defending against continuous UAV and missile attacks depletes interceptor stockpiles faster than they can be replenished. Interceptors require reloading after a fixed number of engagements, unlike DEWs, which only require power.

4. Quantitative Description

Here's the detailed comparison table for the July and October 2024 Hezbollah daily attacks on Israel, with references linked to their web addresses:

Table 2. Quantitative Description of July/October 2024 UAV Swarms and Missile Barrages Threat Scenario

Aspect	July 2024 Attacks	October 2024 Attacks
Scale of Attack (Daily)	Approx. Combined 20–50 drones and missiles launched daily from southern Lebanon, targeting IDF bases and northern civilian areas	More than 100 missiles and 20–30 UAVs launched daily from southern Lebanon, focusing on cities and critical infrastructure
Attack Codename	None reported	Operation Support for Gaza
Primary Targets (Daily)	IDF bases in northern Israel, border towns such as Kiryat Shmona, Metula, Galilee, Golan Heights	Israeli military bases, key cities (Tel Aviv, Haifa), and critical infrastructure like gas platforms
Drones Used	Shahed-101 (900 km range, 8 kg warhead), Shahed-136 (~2,000 km range)	Shahed-136, Mirsad-1 and 2, Ababil (Iranian-made, ~120 km range), Shahed 107 (for Central Israel)
Missiles Used	Fajr-3 (40 km), few Zelzal-2 (210 km)	Fateh-110 (~300 km), Zelzal-1 (125 km), Falaq Rockets
Hezbollah's UAV Arsenal	Estimated 2,000 UAVs, including kamikaze and surveillance drones	Over 2,000 drones, including kamikaze UAVs and loitering munitions
Interception Systems	Iron Dome, David's Sling	Iron Dome, David's Sling
Interception Rate	~90% success rate, but multiple drones and missiles bypass defenses daily	~85% success rate, higher impact from UAVs causing more damage

Aspect	July 2024 Attacks	October 2024 Attacks
Damage (Daily)	Moderate damage to IDF bases, disruption to northern civilian life; daily evacuations	civilian infrastructure, significant disruptions to economic activity in northern Israel
Casualties (Daily)	Total of 5 soldiers and civilians killed or wounded in a month by scattered attacks	Total of 15 soldiers and civilians killed or wounded in a month
Stated Motivation	Retaliation for Israeli strikes on Hezbollah commanders	Escalation in response to the Gaza conflict, retaliation for Israeli airstrikes on Hezbollah leadership
International Response	UN urged de-escalation, U.S. provided increased military aid	Strong condemnation from the U.S., calls for EU and UN intervention
Strategic Observations	Combination of UAVs and rockets overwhelms Israeli defenses; growing sophistication in UAV precision strikes	UAV swarms, precision missiles overwhelm air defenses, causing extensive damage to military and economic targets
Operational Impact	Temporary disruption to northern defense positions and civilian evacuations	Serious disruption of operations in northern Israel up to Haifa, civilian morale impacted both sides (Waiting for Hezbollah defeat, economic pressure)
Diplomatic Impact	Increased international tensions, more calls for ceasefire, pressure on Lebanese government	Heightened diplomatic tensions, risk of broader regional conflict, increased support for Israeli defenses from international allies

5. Short Range Scenario public domain references:

- Wikipedia (2024 Odaiseh clashes and Hezbollah-Israel conflict):
https://en.wikipedia.org/wiki/2024_Odaiseh_clashes
- Jerusalem Post (articles on Hezbollah's drone capabilities):
<https://www.jpost.com/middle-east/article-825216>
- Times of Israel (reports on Hezbollah attacks):
<https://www.timesofisrael.com/liveblog-october-2024/> ,
<https://www.timesofisrael.com/hezbollah-drone-attacks>
- Iran Primer (Hezbollah's Iranian Arms):
<https://iranprimer.usip.org/blog/2024/jul/31/hezbollah's-iranian-arms>



- Alma Research Center (Hezbollah missile and UAV capabilities):
<https://israel-alma.org/hezbollahs-missiles-and-uavs> ,
<https://israel-alma.org/wp-content/uploads/2021/12/Irans-UAV-Army-%E2%80%93-A-Global-Threat.pdf>
- Haaretz Newspaper:
<https://www.haaretz.com/israel-news/security-aviation/2023-10-23/ty-article-magazine/150-000-rockets-and-missiles-the-weapons-israel-would-encounter-in-a-war-with-hezbollah/0000018b-573d-d2b2-addf-777df6210000>

A comprehensive understanding of the contemporary threat environment requires both quantitative and spatial analysis of adversarial capabilities. The visual representation of Hezbollah's missile and rocket arsenal, as illustrated in Figure 17, provides crucial insights that enhance the battlefield modeling framework for this study. We will now integrate the data extracted from the figure into the analytical model, establishing key parameters for evaluating the feasibility and effectiveness of airborne Directed Energy Weapons (DEWs) in countering Hezbollah's growing missile and UAV threat.



150,000 missiles and rockets: Hezbollah's arsenal

Rockets			
	Range	Warhead	Number (estimate)
Katyusha (Grad)	40 km	20 kg	Tens of thousands
Fajr-1	10 km	8 kg	Unknown
Falak-1	10 km	50 kg	Unknown
Shaheen-1	15 km	190 kg	Unknown
Fajr-3	40 km	45 kg	Tens of thousands
Fajr-5	75 km	90 kg	Tens of thousands
Ra'ad-3	70 km	50 kg	Unknown
Khaibar-1 (M-302)	100 km	150 kg	Thousands
Missiles			
	Range	Warhead	Number (estimate)
Zelzal-1	160 km	600 kg	Tens of thousands
Zelzal-2	210 km	600 kg	Tens of thousands
Fateh-110 (M-600)	300 km	500 kg	Thousands
Scud	Up to 700 km	800 kg	*
Anti-ship missiles			
	Range	Warhead	Number (estimate)
C-802	120 km	160 kg	Unknown
Yakhont	300 km	200 kg	Dozens
Anti-tank missiles			
	Range	Warhead	Number (estimate)
Kornet	5 km	armor-piercing	Thousands
Sagger	3 km	armor piercing	Thousands
Surface-to-air missiles			
	Range	Number (estimate)	
SA-8	Short-range, distance of 10 km and altitude of 5 km	Thousands of interceptors	
SA-14/16/18	Shoulder-launched, heat-guided missile with an altitude range of up to 3.5 km	Hundreds	
SA-17	Medium-range, distance of up to 50 km and altitude of 24 km	A handful	
Pantsir-S1	Short-to-medium range, altitude of up to 15 km	Unknown	

* Whether Syria has provided Hezbollah with this type of missile is unknown

* Whether Syria has provided Hezbollah with this type of missile is unknown



Source: CSIS, INSS

Figure 17. Hezbollah's Deadly Arsenal Reach
Source: Yaron (2023).

6. Short Range Scenario Analysis

Hezbollah's missile and rocket arsenal, estimated at **150,000 projectiles**, constitutes a significant strategic and operational challenge. The dataset categorizes threats into various classes based on their **range, warhead size, and estimated inventory**, with key figures including:

- **Short-Range Rockets** (Katyusha, Fajr-1, Falak-1) – **Ranges up to 40 km**, warheads between **10–50 kg**, and available in **tens of thousands**.
- **Medium-Range Rockets** (Shaheen-1, Fajr-3, Fajr-5, Khaibar-1) – Ranges up to 100 km, warheads ranging from 45 kg to 150 kg, stockpiled in thousands to tens of thousands.
- **Long-Range Missiles** (Zelzal-1, Zelzal-2, Fateh-110, Scud) – **Ranges from 160 km to 700 km**, warheads between **500–800 kg**, and inventory in **thousands**.

- **Anti-Ship Missiles** (C-802, Yakhont) – **Ranges of 120 km and 300 km**, designed for precision strikes against naval and coastal infrastructure.
- **Surface-to-Air Missiles (SAMs)** – Includes SA-8, SA-14, SA-16, SA-18, SA-17, and Pantsir-S1, with interception capabilities extending to 50 km altitude.

The presence of **advanced air-defense systems** among Hezbollah’s arsenal introduces additional operational constraints, as airborne DEW platforms will likely have to engage in contested airspace.

7. Establishing Engagement Zones for DEWs

The spatial distribution of Hezbollah’s missile arsenal, as mapped in **Figure 17**, delineates specific **engagement zones** that must be addressed when considering the operational parameters of airborne DEWs. The figure provides a visual representation of **range rings** extending from Hezbollah’s launch sites deep within Lebanon to strategic locations across Israel, including:

- **50 km Range** – Immediate threat zone covering northern Israel, including **Kiryat Shmona and Haifa**. This is where **short-range Katyusha and Fajr-1 rockets** present a frequent and persistent challenge.
- **100 km Range** – Threat zone extending toward **central Israel**, affecting **Tel Aviv metropolitan area**, targeted primarily by **Fajr-5 and Khaibar-1 rockets**, and Kamikaze Drones.
- **150–200 km Range** – Critical area encompassing Jerusalem and Be’er Sheva, susceptible to Zelzal and Fateh-110 ballistic missile attacks.
- **Beyond 250 km** – Represents the long-range missile engagement spectrum, where Scud and Iranian-supplied ballistic missiles can target strategic military installations and airbases in southern Israel.

These engagement zones directly impact the operational requirements for DEWs, particularly in terms of **platform positioning, power levels, and engagement times**.

B. FULL-SCALE MISSILE AND UAV CAMPAIGN THREAT SCENARIO

While the previous section focused on short-range, asymmetric engagements, the following scenario expands the analysis to a broader strategic level. It examines a full-scale campaign characterized by long-range missile strikes and coordinated UAV operations, reflecting the capabilities of a state-level adversary. This scenario provides a



complementary framework for assessing how airborne DEWs may perform under high-intensity, long-range conditions.

1. Qualitative Description

The rapid evolution of Iran's missile and UAV capabilities presents a growing challenge for regional and global security. Iran has demonstrated an ability to conduct large-scale, long-range missile strikes and UAV operations, posing direct threats not only to Israel but also to U.S. and allied forces in the Middle East and beyond. Recent events, such as **Operation True Promise (April 2024)** and **Operation True Promise 2 (October 2024)**, have highlighted the extent of Iran's strategic missile and UAV arsenal. These attacks, involving hundreds of projectiles in coordinated waves, showcased Iran's increasing reliance on long-range ballistic missiles and precision-strike capabilities.

The scenario under examination involves a **full-scale Iranian offensive** utilizing long-range missiles and UAVs in a strategic campaign aimed at overwhelming air defense systems and striking key military and critical infrastructure targets. Unlike short-range conflicts where UAV swarms serve as primary offensive tools, the long-range scenario focuses on **ballistic missile saturation**, with UAVs playing a supporting role in surveillance, decoy operations, and electronic warfare.

2. Nature of the Threat

Iran's missile doctrine relies on a mix of precision-strike ballistic missiles, cruise missiles, and kamikaze drones to create a layered offensive. The attack profile in this scenario includes:

Long-Range Ballistic Missiles (LRBMs):

- Khaibar Shekan (range: 1,450 km) – Used for high-impact strikes on airbases and command centers.
- Emad (range: 2,000 km) – Precision-strike capable, targeting strategic assets.
- Fattah-1 (hypersonic, range: 1,400 km) – A high-speed, maneuverable missile designed to evade interceptors.



Cruise Missiles:

- Paveh (range: 1,650 km) – Low-altitude attack missile used against Israeli and U.S. regional bases.

Kamikaze UAVs:

- Shahed-136 – Long-range drone with autonomous targeting capabilities, deployed in large numbers (See Figure 19).
- Mohajer-6 – ISR (Intelligence, Surveillance, and Reconnaissance) drone supporting missile targeting and real-time battlefield assessment.

Iranian forces employ a multi-phase saturation attack, combining missile barrages with UAV-led disruption operations. UAVs are used to probe enemy air defenses, deplete interceptor stockpiles, and target vulnerable radar systems, while missile salvos follow in rapid succession to maximize damage.

3. Challenges to Conventional Defenses

- Overwhelming Israel's Multi-Layered Air Defense:
The attack aims to saturate Israel's Iron Dome, David's Sling, and Arrow missile defense systems. The goal is to deplete interceptor stockpiles and expose vulnerabilities in missile defense coverage.
- Targeting Key Military Installations and Infrastructure:
High-value targets include **Nevatim and Tel Nof Airbases**, key logistical hubs, and early-warning radar sites. Critical infrastructure, including **power plants, defense industries, and transportation hubs**, are secondary targets.
- Deterring U.S. and Allied Forces in the Region:
Iran seeks to demonstrate its ability to strike U.S. regional bases (such as Al Udeid Air Base in Qatar and Al Dhafra Air Base in the UAE) to deter potential intervention. The deployment of hypersonic missiles signals Iran's capability to challenge U.S. and NATO air superiority.

4. Quantitative Description

Here's the detailed comparison table for the April and October 2024 Iranian attacks on Israel, with references linked to their web addresses:



Table 3. Quantitative Description of July/October 2024
Full Scale Missile and UAV Campaign Scenario Threat

Aspect	April 2024 Attack	October 2024 Attack
Scale of Attack	Approx. 320 projectiles, including drones, cruise missiles, and ballistic missiles	Approx. 200 ballistic missiles launched in 2 waves , with 15 minutes between them
Attack Codename	Operation True Promise	Operation True Promise 2
Primary Targets	Military installations, critical infrastructure, Israeli-occupied Golan Heights	Nevatim and Tel Nof Airbases, areas around Tel Aviv
Drones Used	- Shahed-131 : ~70 units - Shahed-136 : ~100 units	None reported
Cruise Missiles Used	- Paveh cruise missiles : ~30 units	None reported
Ballistic Missiles Used	- Emad missiles : ~50 units - Ghadr-1 missiles : ~40 units - Khaibar Shekan : ~30 units	- Fattah-1 missiles : ~80 units - Khaibar Shekan missiles : ~120 units
Iranian Proxies Involved	Hezbollah, Houthis, and other regional allies	No proxies; attack directly conducted by Iran
Interception Systems	Iron Dome, Arrow 3, and David's Sling, with support from U.S., British, French, and Jordanian forces	Primarily Israeli air defense systems, including Iron Dome and Arrow, with U.S. support
Interception Rate	Approx. 99% interception rate with help from allied forces	High interception rate; majority of missiles intercepted, with minimal damage
Damage	Minor infrastructure damage, minor injuries reported	Structural damage to airbases, some civilian areas impacted, minor injuries, and two fatalities
Casualties	Minimal; minor injuries reported	Two fatalities (one Israeli, One Palestinian), with a few injuries among civilians
Stated Motivation	Retaliation for Israeli airstrike on the Iranian embassy in Damascus	Retaliation for assassinations of key Iranian, Hezbollah, and Hamas leaders by Israel

Aspect	April 2024 Attack	October 2024 Attack
International Response	U.S. condemned attack, reinforced support for Israel; heightened military readiness in the region	U.S. and allies condemned attack, pledged support, and warned Iran of potential consequences
Strategic Observations	Showcased Iran's capacity for coordinated, multi-platform attacks, including drone swarms	Demonstrated Iran's focus on direct ballistic missile barrages as a means of overwhelming Israel's defenses
Key Technologies and Weapons	Kamikaze drones (Shahed series), Paveh cruise missiles, long-range ballistic missiles (Emad, Ghadr-1)	Long-range ballistic missiles (Fattah-1, Khaibar Shekan)
Operational Impact	Limited operational impact on Israel's military capacity; infrastructure repairs needed in some locations	Temporary disruption of operations at airbases; no significant long-term impact on Israel's military capabilities
Diplomatic Impact	Increased international condemnation of Iran; calls for restraint from the UN	Heightened diplomatic tensions; U.S. promised severe repercussions if Iran continued escalations

5. Long-Range Iran-Driven Scenario public domain references:

- <https://theaviationist.com/2024/10/01/iran-massive-ballistic-missile-attack-on-israel/>
- <https://iranprimer.usip.org/blog/2021/feb/17/iran%E2%80%99s-missiles-timeline-attacks>
- https://en.wikipedia.org/wiki/October_2024_Iranian_strikes_against_Israel
- https://en.wikipedia.org/wiki/April_2024_Iranian_strikes_against_Israel
- <https://www.rferl.org/a/iran-shahed-drones-israel-attack/32904882.html>
- <https://iranprimer.usip.org/blog/2024/apr/15/iran%E2%80%99s-unprecedented-attack-israel>
- <https://www.timesofisrael.com/liveblog-april-13-2024/>



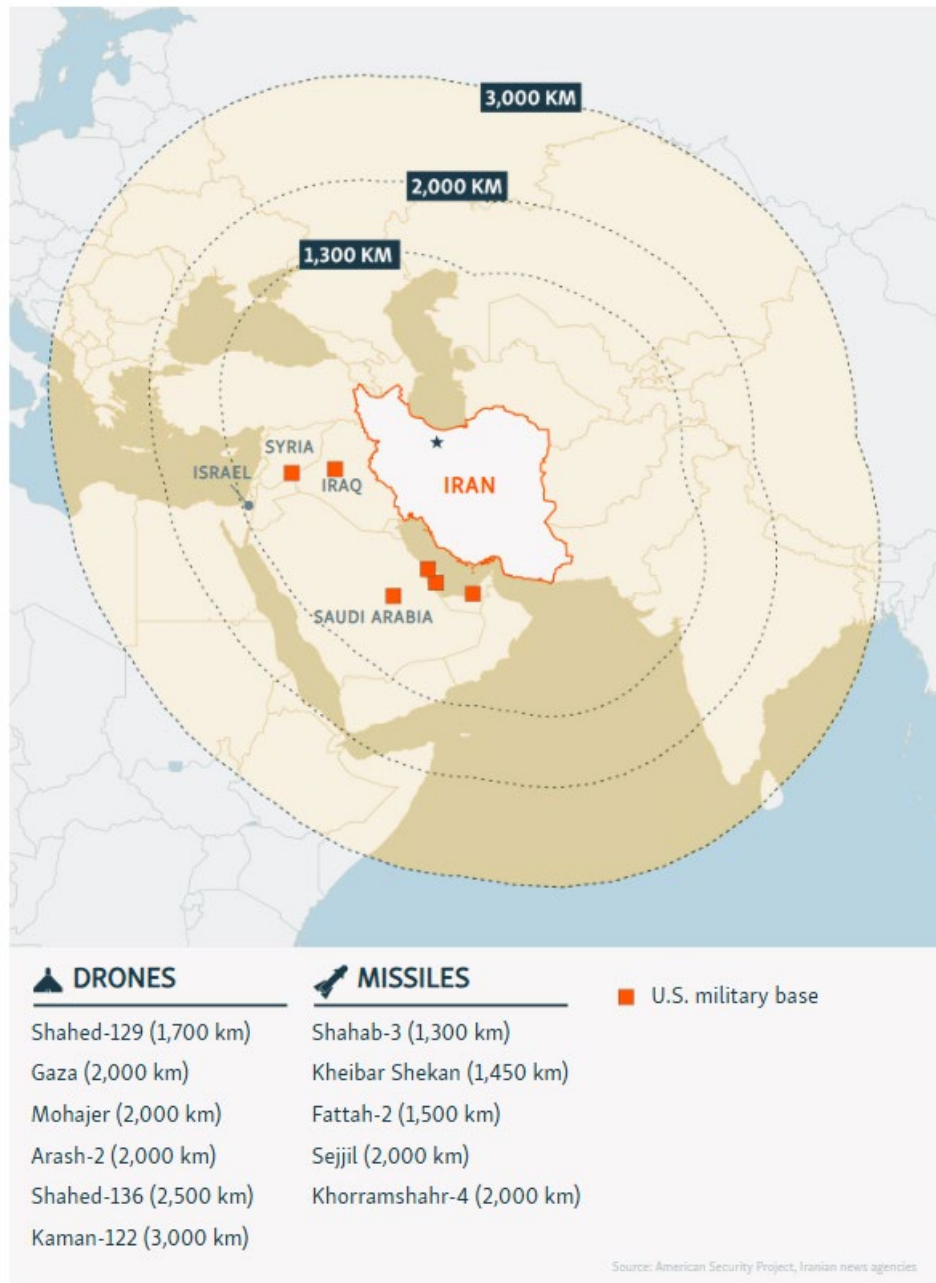


Figure 18. Iran Deadly Arsenal Reach
Source: Ruhe & Cicurel (2026).

Shahed-136 Drone ("Geran-2")

An Iranian-made suicide drone imported by Russia for use in its invasion of Ukraine. Rebranded as "Geran-2," or Geranium-2.

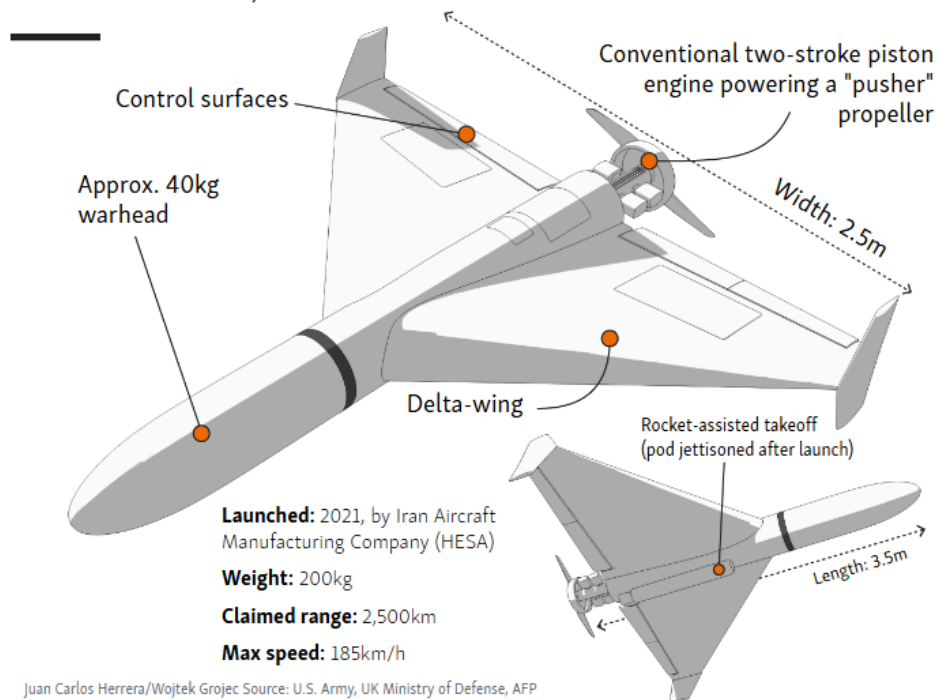


Figure 19. Iran Shahed 136 Key Performance Parameters. Source: Army Technology (2026).

6. Long-Range Scenario Analysis

The effectiveness of Israel's missile defense systems, bolstered by U.S. and allied support, is projected to intercept a majority of incoming threats. However, the challenge lies in managing sustained attacks over multiple days, as interceptor stockpiles become depleted. In a prolonged engagement, Iran could leverage additional waves of missile and UAV strikes, further straining defensive assets.

Key Analysis Points: High-volume attacks require multi-tiered defense solutions to balance engagement costs and efficiency. UAVs play a critical role in degrading air defense capabilities before missile waves arrive. Saturation tactics expose interceptor stockpile vulnerabilities, emphasizing the need for scalable, cost-effective defense solutions.

DEWs as a Countermeasure: The integration of airborne DEWs offers a game-changing capability to counter long-range missile and UAV threats. Unlike kinetic

interceptors, which are limited by ammunition stockpiles and launch constraints, DEWs provide a scalable and cost-effective solution to high-volume aerial threats.

Missile Engagement Strategy with DEWs: DEWs are deployed on airborne platforms (such as modified C-130 transport aircraft, UAVs or Jetfighters) to intercept ballistic and cruise missiles before they enter densely populated areas. High-powered lasers (30–50 kW) can disable missile guidance systems and detonate warheads mid-air, reducing impact damage.

UAV Neutralization with DEWs: Airborne DEWs can engage UAVs at extended ranges (5–10 km), disrupting their electronic controls and rendering them inoperable. Targeting ISR drones (Mohajer-6) early in the conflict disrupts Iranian real-time strike coordination, reducing overall attack effectiveness.

Defensive Coordination with Kinetic Systems: DEWs complement kinetic air defense by handling low-altitude threats (UAVs and cruise missiles) while traditional systems focus on high-speed ballistic missiles. This layered defense approach extends interceptor endurance, ensuring sustained defensive capabilities over prolonged conflicts.

C. ANALYTICAL MODELING OF AIRBORNE LASER POD

The successful deployment of airborne DEWs requires a rigorous analytical modeling framework that defines their operational effectiveness, physical constraints, and performance optimization in real-world combat scenarios. Unlike traditional kinetic interceptors, DEWs rely on electromagnetic energy propagation, where engagement success depends on multiple factors, including laser power output, beam quality, atmospheric attenuation, and target vulnerability. The integration of airborne DEWs within modern air defense architectures presents both opportunities and challenges. On one hand, they provide instantaneous target engagement, infinite ammunition (limited only by onboard power supply), and cost-effectiveness compared to expensive kinetic interceptors. On the other hand, their performance is constrained by atmospheric conditions, power availability, beam divergence, and laser-material interactions at varying ranges.



To establish a robust mathematical foundation for airborne DEWs, this foundational section systematically develops an analytical modeling approach based on fundamental optical physics, energy transfer equations, and probability-based target engagement models. These models aim to:

- Quantify laser energy propagation and effectiveness over varying engagement distances.
- Determine required engagement times to neutralize UAVs, cruise missiles, and ballistic threats.
- Establish operational constraints, such as aircraft power supply limitations and atmospheric degradation.
- Compare cost-effectiveness and engagement efficiency relative to traditional kinetic interceptors.

The following sections develop the analytical model step by step, beginning with the fundamental equations governing laser energy transmission and progressing toward probability-based target neutralization under realistic combat conditions. A baseline model is established to support the SWAP-C analysis of the airborne DEW, incorporating key assumptions that enable sensitivity analysis of the notional design.

1. Material Properties

$$\text{Density: } \rho = 2700 \text{ kg/m}^3 \quad (1)$$

$$\text{Specific Heat Capacity: } C_p = 900 \text{ J/kg} \cdot \text{K} \quad (2)$$

$$\text{Melting Point: } T_m = 660^\circ\text{C} \quad (3)$$

$$\text{Latent Heat of Fusion: } L = 397,000 \text{ J/kg} \quad (4)$$

$$\text{Thickness of Target: } d = 3\text{mm} = 0.003 \text{ m} \quad (5)$$

2. Energy Required to Heat Target

$$\text{Laser Power: } P = 30,000 \text{ W (30 kW)} \quad (1)$$

$$\text{Beam Diameter: } D = 0.10 \text{ m (10 cm)} \quad (2)$$

$$\text{Beam Area (m}^2\text{): } A = \pi \cdot D^2 / 4 = (3.1416 / 4) \cdot (0.10)^2 = 0.00785 \text{ m}^2 \quad (3)$$



$$\text{Volume Affected: } V=A \times d=0.00785 \times 0.003=2.35 \times 10^{-5} \text{ m}^3 \quad (4)$$

$$\text{Mass of Aluminum: } m=\rho \times V=2700 \times 2.35 \times 10^{-5}=0.0636 \text{ kg} \quad (5)$$

$$\text{Energy to Heat to Melting Point: } E_{\text{heat}}=m \times c_p \times \Delta T \quad (6)$$

$$E_{\text{heat}}=0.0636 \times 900 \times (660-20) \quad (7)$$

$$E_{\text{heat}}=36,636 \text{ J}=36.63 \text{ kJ} \quad (8)$$

3. Energy Required to Melt Aluminum

$$E_{\text{melt}}=m \times L=0.0636 \times 397,000=25,251 \text{ J}=25.25 \text{ kJ} \quad (1)$$

4. Total Energy Required

$$E_{\text{req}}=E_{\text{heat}}+E_{\text{melt}}=36.63+25.25=61.88 \text{ kJ} \quad (1)$$

5. Atmospheric Attenuation

Lasers lose power as they travel through the atmosphere due to absorption and scattering.

$$\text{Attenuation Coefficient: } \alpha=0.15 \text{ per km (assumed for clear air)} \quad (1)$$

$$\text{Target Range} = 5 \text{ km} \quad (2)$$

$$\text{Transmission Factor: } T=5^{(-\alpha R)}=5^{-(0.15 \times 5)}=5^{-0.75}=0.1778 \quad (3)$$

$$P = \text{Laser power (Watts = Joules/second)} \quad (4)$$

$$I_{\text{initial}}=P / A_{\text{cm}}^2=30,000/78.530=382.0 \text{ W/cm}^2 \quad (5)$$

$$\text{Attenuated Intensity (W/cm}^2\text{): } I_{\text{attenuated}}=I_{\text{initial}} \times T=382.2 \times 0.1778=67.9 \text{ W/cm}^2 \quad (6)$$

6. Formula for Dwell Time

Dwell time (t_d) is the amount of time the laser must stay on a target to achieve the desired effect (e.g., material penetration, thermal damage).

$$t_d=E_{\text{req}}/(P \times T) \quad (1)$$



where t_d is Dwell time in seconds.

$$E_{req} = \text{Energy required to disable/destroy the target (Joules)} \quad (2)$$

$$T = \text{Transmission Factor} \quad (3)$$

In the case example,

$$t_d = 61880 \text{ (Joule)} / (30000 \text{ (Watt)} * 0.1778) = 11.601 \text{ (sec)} \quad (4)$$

7. How Does Beam Diameter Grow with Distance?

A laser beam is not perfectly parallel—it naturally expands as it travels due to diffraction:

$$D_{spot} = D_0 + \theta_{diff} \times R \quad (1)$$

where:

$$D_{spot} = \text{Beam diameter at distance } R \quad (2)$$

$$D_0 = \text{Initial beam diameter (e.g., 5 cm = 0.05 m)} \quad (3)$$

$$\theta_{diff} = \text{Beam divergence angle (e.g., 0.1 milliradians (mrad))} \quad (4)$$

$$R = \text{Distance to target (meters)} \quad (5)$$

Example at 5 km Range:

If beam divergence is 0.1 mrad:

$$D_{spot} = 0.05 + (0.0001 \times 5,000) = 0.05 + 0.5 = 0.55 \text{ meter} \quad (6)$$

8. How Does Jitter Move the Beam?

While the beam expands due to diffraction, aircraft movement (jitter) shifts the entire beam off-target.

$$D_{jitter} = R \times \theta_{jitter} \quad (1)$$

where:



$$D_{\text{jitter}} = \text{Beam displacement due to jitter} \quad (2)$$

$$\theta_{\text{jitter}} = \text{Angular jitter (assumed } \mathbf{1 \text{ mrad}} \text{ at high speeds)} \quad (3)$$

$$R = \text{Target distance} \quad (4)$$

High-speed flight can introduce beam jitter due to aerodynamic turbulence and mechanical vibrations.

Jitter Angle (θ_{jitter}) Increases with speed; for instance, at 300 m/s, jitter might be around 1 milliradian (mrad), so the impact on Beam Spot Size at Range (R):

$$\text{Spot Displacement : For } R=5 \text{ km, } \theta_{\text{jitter}}=0.001; D_{\text{jitter}}=5,000 \times 0.001=5\text{m} \quad (5)$$

9. Energy Per shot

The Energy per shot is constrained by the pre-calculated Dwell time.

$$\text{Energy Per shot} = P \cdot t_{\text{dwell}} = 30000 \cdot 11.608 = 348021.2 \text{ (Joule)} \quad (1)$$

We assume would be able to have at least 2 shot per threat,

$$\text{Total Energy per Threat: Number of shots} * \text{Energy Per Shot} \quad (2)$$

$$\text{Total Energy per Threat} = 696042.5 \text{ (Joul)} \quad (3)$$

10. Flight Time Budget

We would take a nominal Jet Fighter sortie average time, and calculate eventually how much net time the operational pilots could have for performing the Directed Energy Weapon Mission, taking into account the time to area of interest, time to home base runway, tracking and cooling times for the pod.

Integrating all datapoints, would provide us the practical excess capacity for utilizing the DEWs, as well as a notional planning about number of enemy aircraft to be engaged.

$$\text{Sortie Flight Time: 1 hour} = 60 \text{ Minutes} \quad (1)$$

$$\text{Air to Air Mission Tracking time per Threat: 1 min} \quad (2)$$



Cooling Time after each Threat: 1 Minutes (3)

Flight Time to Area of Interest: 15 Minutes (4)

Flight Time back to base: 15 Minutes (5)

Usable Time: $60 - 15 - 15 = 30$ Minutes (6)

Planned Number of Threats to be Engaged = (7)

Usable Time / (A/A Tracking time per Threat+ Cooling Time after each Threat) =

$= 30 / (1+1) = 15$ Enemy Aircraft

Lasing Energy Required per Sortie= Total Energy per Threat * Enemy Aircraft (8)

$696042.5 \text{ (Joul)} * 15 = 10440638.5 \text{ (Joul)}$ (9)

11. Aerial Platform Analysis

Critical parameter out of this nominal simulation would be calculating the Lasing energy required per sortie, including the electrical to optical low efficiency.

Laser Diode Efficiency: Converts electrical to optical energy – 70%

Solid-State Laser Efficiency: Converts optical energy into laser output → ~20%

Overall System Efficiency = Laser Diode Efficiency* Solid-State Laser Efficiency (1)

$70\% * 20\% = 14\%$ (2)

Energy Required by POD Electrical System is calculated taking into account the overall system efficiency, which is equal to Lasing Energy Required per Sortie / Overall System.

$10440638.5 \text{ (Joul)} / (14\%) = 74575989.3 \text{ (Joul)} = 74.57 \text{ (MJoul)}$ (3)



12. Aerial Cooling Requirements

As a ground rule, we would establish an aerial cooling system , that would eventually need excess capacity of the electrical system, based on batteries.

$$\text{Power for Pod Cooling for 1 shot} \approx 5000\text{W} \quad (1)$$

$$\text{Energy Required for Cooling} = \quad (2)$$

$$= \text{Power for Pod Cooling for 1 shot} * \text{Planned Number of Threats to be Engaged} *$$

$$* \text{Dwell Time} * \text{How many shots per Threat} =$$

$$= 5000 * 15 * 11.6 * 2 = 1740106.4 \text{ (Joul)} = 1.74 \text{ (MJoul)}$$

$$\text{Total Energy Required for System} = \quad (3)$$

$$= \text{Energy Required for Cooling} + \text{Energy Required by POD Electrical System} =$$

$$= 74.57 \text{ (MJoul)} + 1.74 \text{ (MJoul)} = 75.31 \text{ (MJoul)}$$

$$\text{Total Energy Required For System in KWh} = \text{MJoul} / 3.6 = 21.19 \text{ KWh} \quad (4)$$

13. Battery Sizing

It is not easy to achieve a high C-rate capability and a high energy density. They somehow strike a balance between being too high and too low for Directed Energy Weapons (DEWs) since they would require quick bursts of power right at the moment and also keeping enough energy to operate over the time such as firing at a certain target. In fact, high energy densities require thick electrodes, wherein they can have more space to store energy, but they slow down the movement of ions and make it difficult to discharge maximum power as the demand of DEW. High C-rate capability needs thin electrodes and specialized materials to permit quick discharge, which significantly decreases battery energy storage. DEWs emit heat while firing, so high C-rate batteries will need thermal management systems that all add weight and bulk, thus further reducing energy density. The significance of this compromise is especially for DEWs, which operate in airspace confined by weight and volume. The challenge in designing a



system is to deliver quick high-power pulses without depriving energy reserve needed for sustained engagements. Therefore, we would provide a trade-off on the Battery Energy Mass and Volume Density. The nominal values for the Energy Mass Density and Energy Volume Density are taken as averaged low number, as part of the need to have a Battery with high C-Rate value.

$$\text{Battery Energy Mass Density} = 80 \text{ Wh/Kg} = 288,000 \text{ (Joul/Kg)} \quad (1)$$

$$\text{Lithium-ion Energy Volume Density} = 210 \text{ Wh/L} = 756,000 \text{ (Joul/L)} \quad (2)$$

$$\text{POD Maximum Volume} = 600 \text{ Galon, by similarity to certified External Fuel Tanks} \quad (3)$$

$$\text{POD Maximum Weight} = 4020 \text{ Lb, by similarity to certified External Fuel Tanks} \quad (4)$$

$$\text{Weight of Battery Required} = W_{ES} = \quad (5)$$

$$= \text{Total Energy Required for System in KWh} / \text{Battery Energy Mass Density} =$$

$$= 21.19 \text{ (KW* h)} / 80 \text{ (W/Kg)} = 264.98 \text{ Kg}$$

$$\text{Volume of Battery Required} = 21.19 \text{ (KW* h)} / 210 \text{ (W/L)} = 100.94 \text{ Liter} \quad (6)$$

14. Laser Sizing

Ratio of Kg/KW in Laser Design is a parametric design, which could be found in several demonstration programs, in USAF/NAVY and research activities. For simplicity and conservatism, we could utilize the suggested ratio in literature (Yun et al., 2020),

$$\text{Ratio of Kg/KW in Laser Design} = 5 \text{ Kg/KW} \quad (1)$$

Weight of the Laser system, W_L , would be equal to:

$$W_L = \text{Laser KW} * \text{Ratio of Kg / KW in Laser Design} \quad (2)$$

$$W_L = 30 * 5 = 150 \text{ Kg} \quad (3)$$

$$\text{Heat Waster of the Laser Source} = \text{Laser Power} * (1 / \text{Solid-State Laser Efficiency} - 1) \quad (4)$$

$$\text{Heat Waster of the Laser Source} = 30 * (1 / (0.2) - 1) = 120 \text{ KW} \quad (5)$$



Thermal Energy Storage Weight Ratio would be taken as 1.685 (590/350), following by sources in the literature. Thus, the Thermal Energy Storage Weight (W_T) would be equal to :

$$W_T = \text{Heat Waster of the Laser Source} * \text{Thermal Energy Storage Weight Ratio} \quad (6)$$

which follows into :

$$W_T = 120 * 1.685 = 202.28 \text{ Kg} \quad (7)$$

The weight estimation of the beam delivery subsystem (W_{BD}) is based on DEWs that were developed, in the area of 50 – 100 KW. From the literature, where we took earlier the Thermal Energy Storage Weight Ratio, it is recommended to estimate a 225 Kg for such system in the realms of 50–100 KW Laser source Power.

The out of the pod, would be made of Aluminium. Taking the 600 G tank as an envelope and a weight estimate; of 300 [Lb], is which 132 Kg. One could calculate that (W_{CASE}) as follows:

$$\text{Surface area of a cylindrical tank with hemispherical ends: } A=2\pi rL+4\pi r^2 \quad (8)$$

$$\text{Radius (r): } \sim 0.5 \text{ m (half the diameter)} \quad (9)$$

$$\text{Length of cylindrical section (L): } \sim 3 \text{ m (total length minus hemispherical ends)} \quad (10)$$

$$A=2\pi*(0.5)*(3)+4\pi*(0.5)^2=9.42+3.14\approx 12.56 \text{ m}^2 \quad (11)$$

$$\text{Volume} = A * \text{Thickness, Assuming thickness is 3 mm;} \quad (12)$$

$$V= 12.56*0.003=0.377\text{m}^3$$

$$\text{Weight}=0.377*2,700\approx 101.8 \text{ Kg;} \quad (13)$$

adding to it 30% uncertainty, it equals to 132 Kg

When we sum up all the sub systems, we would get:

$$\text{Total Weight} = W_{ES} + W_L + W_T + W_{BD} + W_{CASE} \quad (14)$$



In the current calculation, that follows into:

$$264.98 + 150 + 202.28 + 225 + 132 = 974.27 \text{ [Kg]} = \mathbf{2147.9 \text{ [Lb]}} \quad (15)$$

D. SENSITIVITY ANALYSIS OF AIRBORNE LASER POD SIZING

This section analyzes how variations in key parameters affect the feasibility and performance of the airborne laser pod design by analytical methods.

1. Introduction

Sensitivity analysis is essential for understanding whether the airborne laser pod is practical and capable of performing as intended. This isn't just a technical exercise—it's about ensuring the system can handle the challenges it will face in real operations. With so many interconnected parameters—like power output, range, battery capacity, and platform constraints—even a small change in one factor can create a domino effect on the entire system. The goal here is to identify the key sensitivities, so we know where to focus our efforts to optimize the design and manage risks. We're focusing on the factors that matter most:

- **Power and Range Sensitivity:** How do changes in laser power or the operational range affect the pod's ability to deliver effective engagements?
- **Battery Capacity and Weight Sensitivity:** Can we find the right balance between the battery's weight and its ability to support sustained operations? What trade-offs are needed to ensure the platform isn't overloaded but still meets mission requirements?
- **Number of Shots Per Sortie:** How many threats can we realistically engage in a single sortie? This is a critical question for mission planning and operational effectiveness.

The purpose of this section is straightforward: to understand the trade-offs and limitations that come with deploying such a system. This is about more than just the numbers—it's about creating a system that can succeed in the unpredictable conditions of real-world combat. Each section ahead will break down these sensitivities in detail, helping to ensure that the design is both robust and operationally viable. To support this analysis, the relationship between operational range, laser power, number of threats, and resulting system weight is presented in Figure 20.



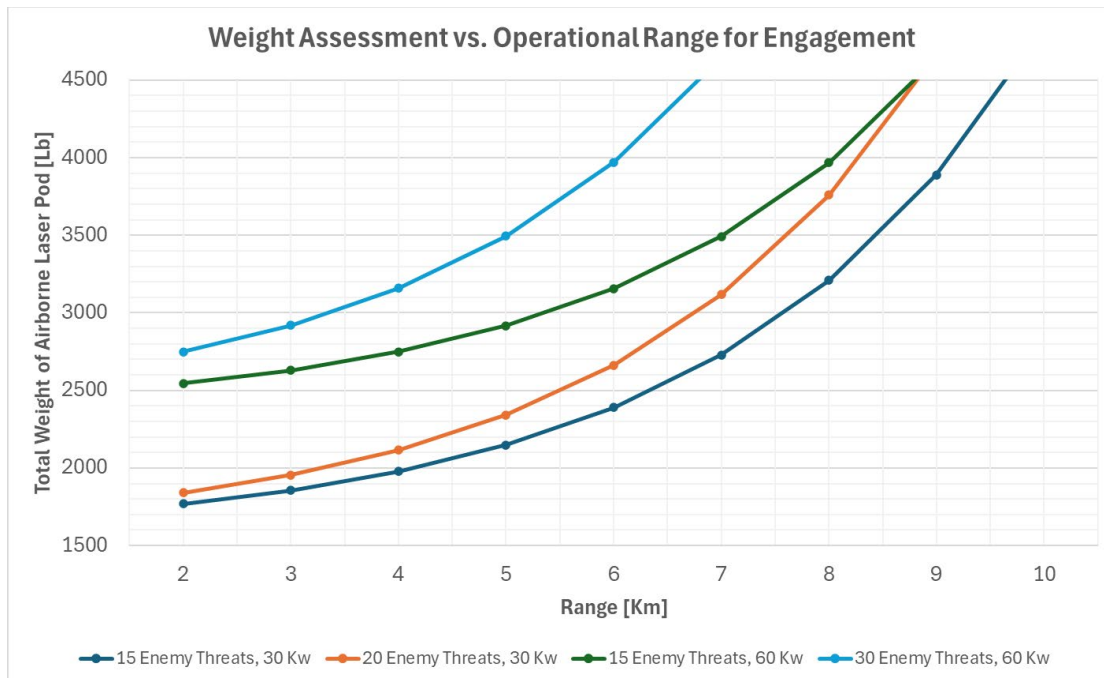


Figure 20. Total Weight of Airborne Laser Pod: Weight Assessment vs. Operational Range, for Different Power and Number of Enemy Threats in One Sortie

2. Key Observations

Weight Increases with Range: For all configurations, the total weight of the laser pod increases as the operational range grows. This is likely due to higher energy and cooling requirements for longer engagements, which demand larger batteries and enhanced subsystems.

Impact of Laser Power Output: The configurations using 60 kW laser power consistently result in higher weights compared to those with 30 kW, as shown by the upward shift of the green and blue lines relative to the orange and dark blue lines. This is due to higher energy consumption and cooling requirements for more powerful lasers.

Effect of Enemy Threats: Increasing the number of threats also leads to significant weight growth. For 30 kW, the weight difference between engaging 15 and 20 threats is visible in the orange and dark blue curves. For 60 kW, engaging 30 threats (blue line) results in the steepest weight increase.

Range Sensitivity: The slope of each line becomes steeper as the range increases, indicating that weight grows disproportionately for longer-range engagements. This

reflects the cumulative impact of energy transmission losses (e.g., atmospheric attenuation) and increased energy storage requirements.

Highest Weight Scenario: The 30 enemy threats at 60 kW configuration (blue line) represents the heaviest system design, surpassing 4,000 [Lb] for ranges above 8 km.

E. DETERMINING THE DESIGN BASELINE FOR THE LASER POD

The following subsection translates the results of the sensitivity analysis into concrete design decisions, establishing a baseline configuration for the airborne laser pod. The following discussion outlines the key design implications derived from these findings.

1. Design Implications

The aforementioned weight assessment clearly illustrates the trade-offs between operational range, the number of engagements, and laser power output. From a design perspective, maintaining the total weight within the feasible limit of a 600-gallon tank is critical to ensure manageable external store certification effort. This includes considerations for flutter, aerodynamic loads, stability, and control during the integration phase into a fighter jet. Moreover, accounting for a 20% safety factor during the preliminary design phase is essential to accommodate unforeseen weight increases during development.

2. Key Design Goals and Implications

Operational Range and Engagement Requirements: The target is to achieve at least 7 km range and support 20 engagements per sortie with effective dwell time. These are realistic minimum thresholds for operational effectiveness in a mission scenario. There are several key rationales that are critical to help us select the Operational Range Requirement, as follows:

Weight Limitation and Power Selection: The analysis shows that using a 60 kW laser pod for these requirements would result in a weight exceeding 3,500 lbs, even before applying the 20% safety factor. This is unsuitable as a starting point for the preliminary design phase. To stay within the weight constraints, the 30 kW pod becomes



the only viable option. Even with 20 engagements at a 7 km range, the total weight remains closer to the acceptable limit when factoring in the safety margin.

Maximizing Mission Effectiveness Through Increased Engagement Capacity:

Designing the airborne laser pod for 20 engagements per sortie significantly enhances the fighter jet's ability to address modern aerial threats. With UAV swarms and multiple simultaneous targets becoming common, the ability to engage 20 threats ensures the jet remains operationally effective even in high-intensity scenarios. It also provides a 25% safety factor to the usable time available during operation Jet Fighter flight, to the notional design point that was presented in previous section. This increased capacity provides a critical advantage, allowing the jet to neutralize more threats before returning to base for recharging or refueling.

Ensuring Safe Engagement Through Standoff Distance: The 7-kilometer range is more than a technical specification—it fundamentally enhances the fighter jet's operational safety. By engaging threats from a distance, the jet avoids direct exposure to potentially explosive drones or those equipped with electronic warfare capabilities. This standoff range is critical for jets operating in high-stress, multi-role environments, where safety and efficiency must go hand-in-hand.

Providing Sufficient Time for Detection, Engagement, and Civilian Alerts: At 60 knots, a drone takes approximately 3.8 minutes to cover 7 kilometers. While this may seem short, it provides enough time to detect, classify, and prepare for engagement. This buffer allows pilots to prioritize targets, coordinate with air and ground defense systems, and neutralize threats effectively. The window is also sufficient to activate civilian alert systems, giving populations in the area time to respond to the threat.

Neutralizing Threats Before They Pose a Direct Risk: In combat scenarios, this range allows the jet to engage drones far enough away to prevent them from reaching civilian populations or critical military assets. It is especially effective in urban environments, where collateral damage must be minimized. Whether defending an airbase, intercepting surveillance drones, or addressing UAV swarms, the 7-kilometer range ensures threats are neutralized decisively and safely.



Simplifying Pilot Workload and Supporting Multi-Role Missions: The 7-kilometer range eases the pilot's operational burden, offering enough time and distance to manage multiple engagements without overwhelming their focus. This enables the pilot to concentrate on broader mission objectives while relying on the pod to efficiently neutralize threats within its effective range.

Delivering Realistic and Practical Solutions for Modern Air Combat: The 7-kilometer range is a carefully chosen compromise that aligns with real-world operational needs. It keeps the pod lightweight and manageable while ensuring it can perform reliably in diverse scenarios. This range enhances the fighter jet's ability to address modern threats effectively, solidifying its role as a versatile and powerful asset in aerial defense.

Balancing Operational Effectiveness with Weight and Integration

Constraints: The 7-kilometer range strikes an ideal balance between mission effectiveness and the technical constraints of fighter jet integration. Extending the range to 10 kilometers would necessitate larger batteries and more robust cooling systems, leading to heavier systems that compromise aerodynamics, stability, and certification efforts. By optimizing for 7 kilometers, the laser pod remains within the weight equivalent of a 600-gallon tank, making integration seamless without sacrificing performance.

3. Preliminary Design Recommendation:

Following the rational discussion, design efforts should focus on optimizing a **30 kW laser pod with nominal 20 threat engagements at an operational range of 7 km, to meet the specified operational goals**. This approach ensures the system stays within the 3500 lbs limit (including the safety factor), reducing risk in the certification phase and avoiding complications related to flutter, load, stability and control analyses.

Strategic Implications: Choosing a 30 kW pod as the starting point for the design phase reflects a practical approach that aligns with the constraints of fighter jet integration. While its power output is lower than a 60 kW system, it allows for a more feasible and manageable design process. Future improvements, such as enhanced laser



diodes, advanced cooling systems, and higher battery energy density, could further enhance operational capabilities without exceeding weight and integration limits. By prioritizing the 30 kW pod, this design offers a balanced and realistic solution, ensuring compatibility with the platform while meeting critical range and engagement requirements. It is worthwhile to mention that in the AFRL Review on Laser Weapon Systems (AFRL, 2016), the operational capabilities of a 30kW laser are analyzed in detail, emphasizing its effectiveness across various scenarios. According to the review, a 30kW laser can deliver gradual effects such as denial, degradation, disruption, and destruction of targets, including UAS and small boats, within a range of several kilometers. Furthermore, it highlights that more powerful laser systems could extend their applications to counter-air, counter-ground, and counter-sea missions, effectively engaging hardened military equipment and vehicles over significant distances. This analysis underscores the scalability of laser weapon systems and their potential to address a broad spectrum of operational threats.

F. INTEGRATION OF THE LASER POD ONTO A FIGHTER JET: CHALLENGES AND ACCELERATED IMPLEMENTATION STRATEGY

The integration of a high-energy laser pod onto a fighter aircraft presents a range of technical and operational challenges, necessitating a comprehensive approach that ensures compatibility with the host platform's structural, electrical, avionics, and fire control systems. Given the stringent constraint of a three-year total development timeline, integration efforts must be streamlined through a phased and modular approach that prioritizes rapid prototyping, parallel validation, and early risk mitigation. This chapter outlines the principal challenges associated with laser pod integration and proposes an accelerated implementation strategy to meet the project's hard timeline while ensuring mission readiness and operational feasibility.

1. Structural and Aerodynamic Considerations

The integration of an external laser pod must be achieved without degrading aerodynamic performance or imposing excessive structural loads on the aircraft. Primary areas of concern include flutter, stability, structural loading, and integration constraints.



Flutter and Stability Analysis: The addition of an external pod may introduce aerodynamic instabilities that could compromise aircraft handling, particularly at high subsonic and supersonic regimes. In the case of the F-16, integration of a high-energy laser pod presents specific aeroelastic challenges due to the aircraft's susceptibility to Limit Cycle Oscillations (LCO), especially in antisymmetric bending and torsional modes (Stubblefield, 2023). The presence of an external store, particularly under asymmetric configurations, may amplify LCO behavior, increasing structural fatigue and reducing stability margins.

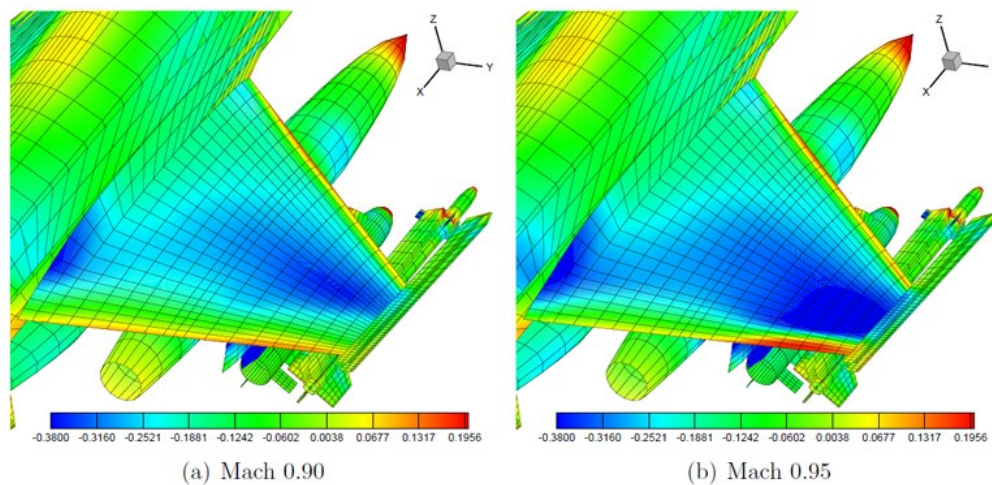


Figure 21. Difference between Pressure Coefficient at Mach 0.90-0.95
Source: Gabbard (2014).

On the contrary, for F-15 the challenge for integrating a weapon would be focused on wing structural load usually in the transonic to supersonic regime (Brueder et al., 2014), as presented in Figure 20, as well as stability and control issues. On top of the load factor constraints, weight distribution should also be encountered, as the additional mass and moment arm of the laser pod must be carefully balanced to maintain the aircraft's center of gravity within acceptable flight limits.

Hardpoint and pylon adaptation: The existing pylon structures must be assessed for their ability to sustain the additional weight, vibrational stresses, and electrical power requirements associated with the laser system.

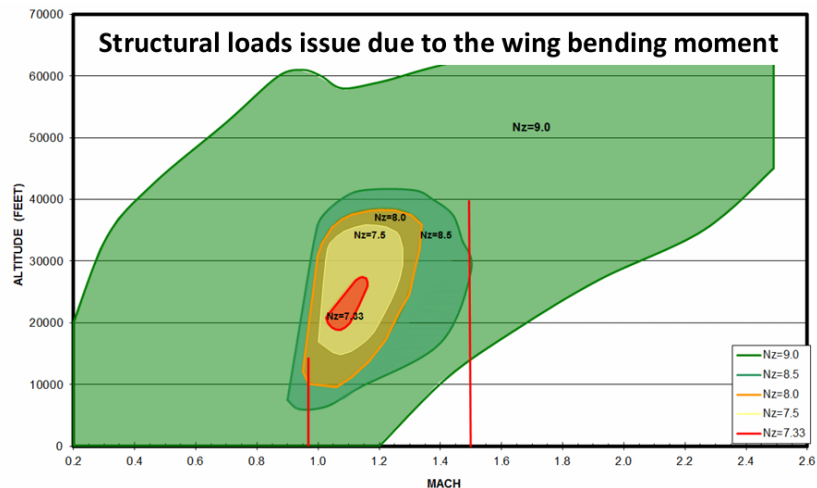


Figure 22. Example of Jetfighter Flight Envelope Wing structural Load Capability. Source: Brueder et al. (2014).

Given the limited timeline for integration, it is critical to leverage existing hardpoints and minimize structural modifications to the aircraft. The use of a standard external store configuration, such as a modified 600-gallon external fuel tank, ensures that the pod can be integrated with minimal airframe alterations.

Moreover, understanding the effective relevant speed for HEL Pod would focus the flight envelope requirements. Due to the operational effective speed during the HEL in-flight operation (around 300–400 KCAS, at low altitude), there is not a real need to certify the configuration to supersonic regime. One would argue that the jetfighter loadout configuration would include external fuel tanks to support loitering for extended time for air-defense, and in such, the flight envelope would be limited due to those stores anyway. Therefore, that understanding would highly reduce the store certification effort, to support only subsonic flight clearance, up to 450 KCAS / 0.9 Mach.

2. Power and Thermal Management Integration

Directed energy weapons impose substantial power and cooling demands that are not typically accounted for in legacy fighter jet designs. Key considerations for power integration include:

Dedicated Power Converters: High-energy lasers require power levels that exceed conventional onboard electrical generation capacity. The implementation of high-

voltage power modules enables the conversion of available onboard electrical output into levels sufficient to sustain laser operations.

Onboard Pod Energy Storage: Given the intermittent but high-demand nature of laser firings, onboard battery packs or supercapacitors can buffer energy requirements, reducing instantaneous loads on the aircraft's generators.

Thermal Management Systems: Laser operation generates significant heat, necessitating high-efficiency cooling solutions such as liquid cooling loops, phase-change materials, or heat exchangers integrated into existing aircraft environmental control systems (ECS).

To mitigate integration challenges, a self-contained power and cooling module within the laser pod itself is proposed, minimizing aircraft-level electrical and thermal system modifications.

3. Avionics Interface and Data Link Integration

For the laser pod to function as an effective weapon system, seamless integration with the aircraft's avionics suite and mission systems is required. The primary integration efforts include:

Mission Computer Integration: The laser pod must interface with the aircraft's mission management computer, enabling in-flight control and system diagnostics through cockpit displays.

Weapons Control System Compatibility: Unlike kinetic weapons, the laser pod requires continuous targeting updates rather than a single launch event. Modifications to the fire control system (FCS) must accommodate engagement logic for a directed energy weapon.

Data Link Integration: To enhance situational awareness and target sharing capabilities, the pod should be capable of transmitting engagement data to ground stations or networked assets for post-strike assessment. In order to fulfil such requirement, it should be able to receiving targeting and threat intelligence from external assets, such as airborne early warning and control (AWACS) platforms, or Ground Control Station.



Software and Firmware Adaptation: Given the software-intensive nature of laser weapons, modifications to onboard fire control software are necessary to integrate laser-specific engagement parameters. To reduce software development time, integration efforts should leverage Open Mission Systems (OMS) architectures where available, ensuring modular software upgrades that do not require extensive redesigns of core avionics systems.

The Universal Armament Interface (UAI), a U.S. DoD and NATO initiative, provides a standardized framework for integrating new weapons systems independent of aircraft Operational Flight Program (OFP) cycles (Edwards, 2012). This capability is particularly advantageous for the integration of a high-energy laser pod, where the strict three-year development timeline necessitates an approach that minimizes software modifications and testing delays. Traditionally, integrating a new weapon requires updates to the aircraft's fire control system (FCS) and mission software, often leading to prolonged development cycles due to the need for custom OFP modifications and extensive regression testing. UAI addresses this challenge by enabling plug-and-play compatibility, allowing the laser pod to interface with the aircraft's avionics through predefined, standardized data protocols. This significantly reduces the effort required to integrate the pod into the aircraft's targeting, power management, and mission planning systems, expediting development and certification. By leveraging UAI, integration can proceed without waiting for software-specific aircraft upgrades, ensuring that testing and validation can occur concurrently across multiple platforms. This not only enhances interoperability but also reduces the risk of integration bottlenecks, enabling the laser pod to achieve IOC within the required timeframe while maintaining compliance with existing NATO and DoD standards.

Following the UAI interface, which could be referenced to Disto-A publication (Edwards, 2012), it is clear that on the Common Weapon Logical Interfaces, Common UPC Interface and Common Data Requirements and LAR (Launch Acceptability Region) one could assume that the relevant UAI of today could be much more mature to support additional capabilities. Such requirement for Interface should be a mandatory requirement when developing the HEL Pod.



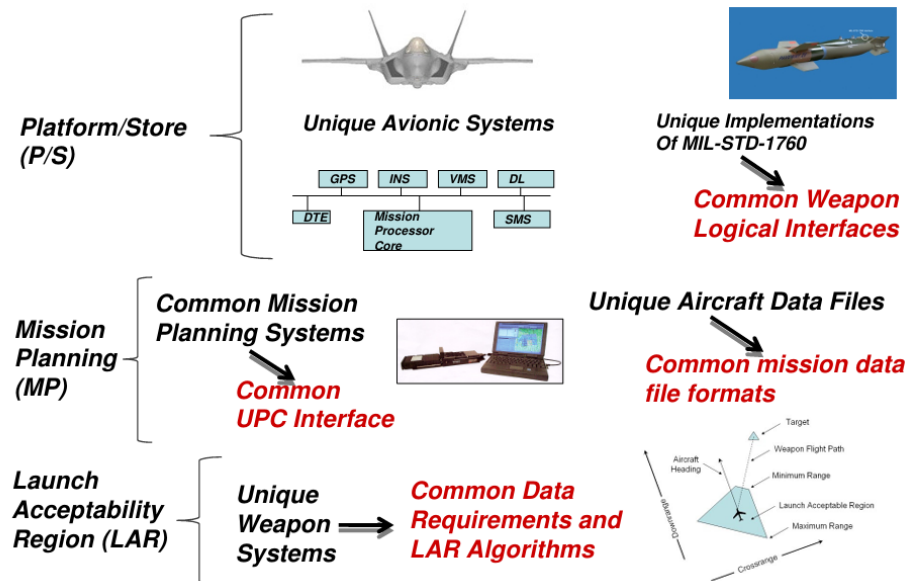


Figure 23. Interfaces Addressed by UAI, 2012 Version – Distro A Release.
Source: Edwards (2012).

4. Applied Integration Plan

The integration strategy unfolds in three distinct phases, each designed to progressively refine and validate the system while mitigating risks. The first phase focuses on ground-based system validation, utilizing hardware-in-the-loop (HIL) simulation to test avionics interfaces, power distribution, and laser targeting software in a controlled environment. This stage ensures that the pod's subsystems function correctly before airborne testing, reducing the risk of costly rework at later stages.

In the second phase, flight testing begins on an interim test platform, such as a C-130 transport aircraft or a large UAV, to validate laser pod functionality under realistic flight conditions. This approach allows for the evaluation of power consumption, thermal management, beam stability, and fire control integration in a controlled, low-risk environment. By decoupling initial testing from high-performance fighter aircraft, critical lessons can be learned and incorporated before final integration, reducing risk while maintaining schedule discipline.

The final phase involves full integration onto a fighter jet, such as the F-16 or F-15, where aerodynamic effects, structural integrity, and combat-relevant scenarios are assessed. A series of captive-carry flight tests verify aerodynamic loads and flutter

characteristics before moving into live-fire trials in a controlled test range. Concurrently, mission software refinements are completed, incorporating lessons from earlier phases to ensure that the laser pod's targeting algorithms and fire control systems function seamlessly within the aircraft's operational framework. This accelerated approach ensures that testing and certification efforts are conducted in parallel, rather than sequentially, preventing traditional bottlenecks in weapon integration programs. Early coordination with aircraft manufacturers, test ranges, and regulatory authorities streamlines the approval process, ensuring that all necessary assessments are completed within the constrained timeline. By following this structured yet flexible methodology, the laser pod can achieve IOC within three years, balancing technical feasibility with the operational imperatives of modern aerial warfare. While testing laser pod components onto a C-130 transport aircraft introduces certain inefficiencies—such as requiring additional test flights and not fully replicating fighter jet conditions—it remains a cost-effective choice within the three-year timeline. Conducting early airborne tests on a transport aircraft de-risks the final fighter jet integration by allowing power management, thermal control, and beam stabilization to be refined in flight before moving to a high-performance platform. Although this step adds time to the schedule, it ensures that the fighter jet phase does not become a high-cost, high-risk bottleneck, where software, avionics, and structural modifications would be significantly more expensive and time-consuming. The C-130's spacious and stable platform allows for faster troubleshooting and parallel development, enabling avionics and fire control systems to reach higher maturity levels before integration onto a fighter. This ensures that, despite not being the final configuration, the overall program remains on schedule, with the final testing phase benefiting from a more refined, lower-risk system, making it a cost-effective strategy within the constrained timeline.

The following 3 tables outline the phased integration strategy, detailing the core activities at each stage and highlighting the concurrent efforts that enable a streamlined transition from ground validation to full operational deployment. Each table is focused on each phase.



Table 4. Phase 1: Ground-Based System Validation (Months 0–12)

Phase	Phase 1: Ground-Based System Validation (Months 0–12)
Key Activities for Laser Pod	Hardware-in-the-loop (HIL) simulation, power load testing, avionics interface validation, software-in-the-loop testing
Key Activities for Fighter Jet	Aerodynamic and structural assessments (CFD, FEM), pylon load analysis, electrical power budget evaluation, mission system software preparation
Concurrent Efforts	Regulatory engagement, supplier coordination, early certification planning, risk assessment for flight phases

Table 5. Phase 2: Interim Flight Testing on Transport Aircraft / UAV (Months 12–24)

Phase	Phase 2: Interim Flight Testing on Transport Aircraft/UAV (Months 12–24)
Key Activities for Laser Pod	Integration onto a transport aircraft or UAV, assessment of power/thermal performance, live-fire accuracy testing in controlled conditions
Key Activities for Fighter Jet	Fire control software modifications, early flight control system impact analysis, cyber-hardening testing, EMI/EMC assessments
Concurrent Efforts	Parallel avionics testing on different aircraft platforms, finalizing laser targeting algorithms, safety validation in wind tunnel simulations

Table 6. Phase 3: Fighter Jet Integration and Final Testing (Months 24–36)

Phase	Phase 3: Fighter Jet Integration and Final Testing (Months 24–36)
Key Activities for Laser Pod	Full integration onto a fighter jet, final live-fire engagements, mission software refinements, pilot training
Key Activities for Fighter Jet	Final aerodynamics validation in live flights, pilot and maintainer training, final operational certification and combat simulations
Concurrent Efforts	Certification processes run in parallel with final testing, operational mission planning, logistics and sustainment strategy finalization



G. DYNAMIC SIMULATION OF A FIGHTER JET WITH INTEGRATED AIRBORNE DIRECTED ENERGY LASER POD

This section extends the preceding analytical and design-based assessments by introducing a dynamic simulation to evaluate the operational performance of the airborne laser pod under realistic combat conditions.

1. Introduction

This section employs a numerical simulation to analyze the dynamic interactions between a fighter jet equipped with an Airborne Directed Energy Weapon (DEW) and multiple adversary UAVs within a 10×10 km operational area. The objective is to evaluate engagement timelines, maneuvering constraints, and system effectiveness in a realistic, time-dependent scenario. The simulation incorporates key parameters derived from previous sections, including a 30 kW laser system, a 7 km engagement range, dwell time requirements, and mandatory cooling intervals. It models the fighter jet's maneuverability, target interception geometry, and sequential engagement of three UAV threats with varying positions and velocities. Unlike the earlier analytical sections, this approach captures real-time engagement dynamics, including trajectory optimization, range-dependent energy effects, and the interaction between aircraft kinematics and laser performance.

Through this framework, the simulation provides insights into engagement efficiency, operational limitations, and the broader implications for mission planning, including engagement throughput and required force structure for effective airspace control..

2. Operational Scenario

Initial Setup - The simulation assumes the following initial conditions, defining the spatial configuration of all entities and their initial kinematic states within the operational area:

- **Fighter Jet Position:** The fighter jet begins at the bottom-left corner of a 10x10 km square.
- **UAV Positions:** UAV 1 is located at the top-left corner, UAV 2 is positioned at the top-right corner and UAV 3 is at the bottom-right corner.



- Jetfighter Dynamic Characteristics:
 - The fighter jet is capable of high maneuverability, flying at True Air Speed (V_{tas}) of 350 Knots which is equal to 180(m/s). At Low altitude interception of 3000 (Ft) that equals to 335 Knots of Calibrated Air Speed (V_{cas}).
 - We limit the aircraft to Roll Angle (φ) of 75 (degrees) , which in a steady turn in a constant altitude would translate into Load factor $N = 1/\cos(\varphi)$. That would equal to $N = 3.86$ [g].
 - The Rate of turn for the aircraft would be aligned according to this equations: $\dot{\psi} = \frac{g}{V_{tas}} N \sin(\varphi) = \frac{g}{V_{tas}} \tan(\varphi) = \frac{g}{V_{tas}} \sqrt{N^2 - 1}$, which leads to a maximum turn rate of 12.1 (degrees) per second.
 - Jetfighter start at Azimuth Angle of 0 (degrees), flying to east from coordinate (0,0).
- Adversary UAVs Dynamic Characteristics:
 - For the sake of simplicity, the UAVs maintain linear trajectories with steady speeds of 30 m/s for UAV 1 and UAV 3, and 50 m/s for UAV 2. We assume each UAV start with arbitrary azimuth angle.
 - UAV1 start at Azimuth Angle of 70 (degrees), flying to north-east from coordinate (0,10000 (m)).
 - UAV2 start at Azimuth Angle of 230 (degrees), flying to southwest from coordinate (10000,10000 (m)).
 - UAV3 start at Azimuth Angle of 155 (degrees), flying to northwest from coordinate (10000,0 (m)).
- Weapon Constraints:
 - The DEW is identical to the one provided in the example of Analytical Modeling of Airborne laser pod in earlier sections in this chapter. The only change exists here in the nominal value of Target Range which was elevated from 5[Km] to 7 [Km], according to the outcomes of our analysis. That would enhance the amount of batteries within the Pod.
 - Dwell time is driven by the Laser system Power required – 30 (Kw) , including the effect of the transmission factor to address attenuation with. It looks like that 10 seconds of dwell time are required to neutralize a target.
 - Minimum of a 60-second cooling period follows each engagement.
 - Atmospheric conditions, including beam divergence, impose a reduction in effective engagement range and energy transmission.

3. Dynamic Simulation Framework

The engagement process is structured into sequential phases that reflect the operational cycle of the airborne laser system. Each phase represents a distinct stage in the interaction between the fighter jet and the target, combining aircraft maneuvering,



weapon employment, and system constraints. This phased approach enables a realistic representation of how engagements evolve over time, while capturing the dependencies between positioning, energy delivery, and system readiness.

Phase 1 - Closing Distance: The jet accelerates to intercept the nearest UAV. Its path is calculated to minimize travel time while maintaining engagement geometry. Example Calculation: Time to intercept UAV 1: ~60 seconds at 180 m/s which is approximately 350 Knots. The Jetfighter performs a banking turn to align itself to the azimuth of the UAV. Whenever the Distance between the Jetfighter and the UAV reaches the limit of 7 Km, dwelling phase begins.

Phase 2 - Engagement (Dwell): Upon reaching the target, the DEW locks onto the UAV and maintains a focused energy beam for the required duration to ensure neutralization. The dynamic calculation integrates the attenuated power over time to determine the energy required to melt the aluminum structure of the target. As the fighter jet approaches the UAV during the maneuver—due to the significant velocity difference (the jet being much faster)—the engagement range decreases. Consequently, attenuation effects are reduced, leading to a shorter dwell time required for effective engagement.

It is important to note that in the current simulation, we took as a conservative approach a dual dwelling process for each threat, to increase dramatically the probability of kill. As a result, one could see in the simulation that the time required for effective dwelling in the second approach is shortened due to the shorter range from target.

Phase 3 – Cooling: Post-engagement of a threat, the DEW undergoes a mandatory 60-second cooling period before it can reactivate. During this time, the fighter jet recalculates its path and moves towards the next UAV.

Phase 4 - Re-engagement: The process repeats for UAV 2 and UAV 3, with the jet dynamically adjusting its path and timing to optimize overall engagement efficiency.

4. Dynamic Simulation Main Results

The results of the dynamic simulation are presented in the following figure, illustrating the trajectories of the fighter jet and three UAV threats based on the defined models.



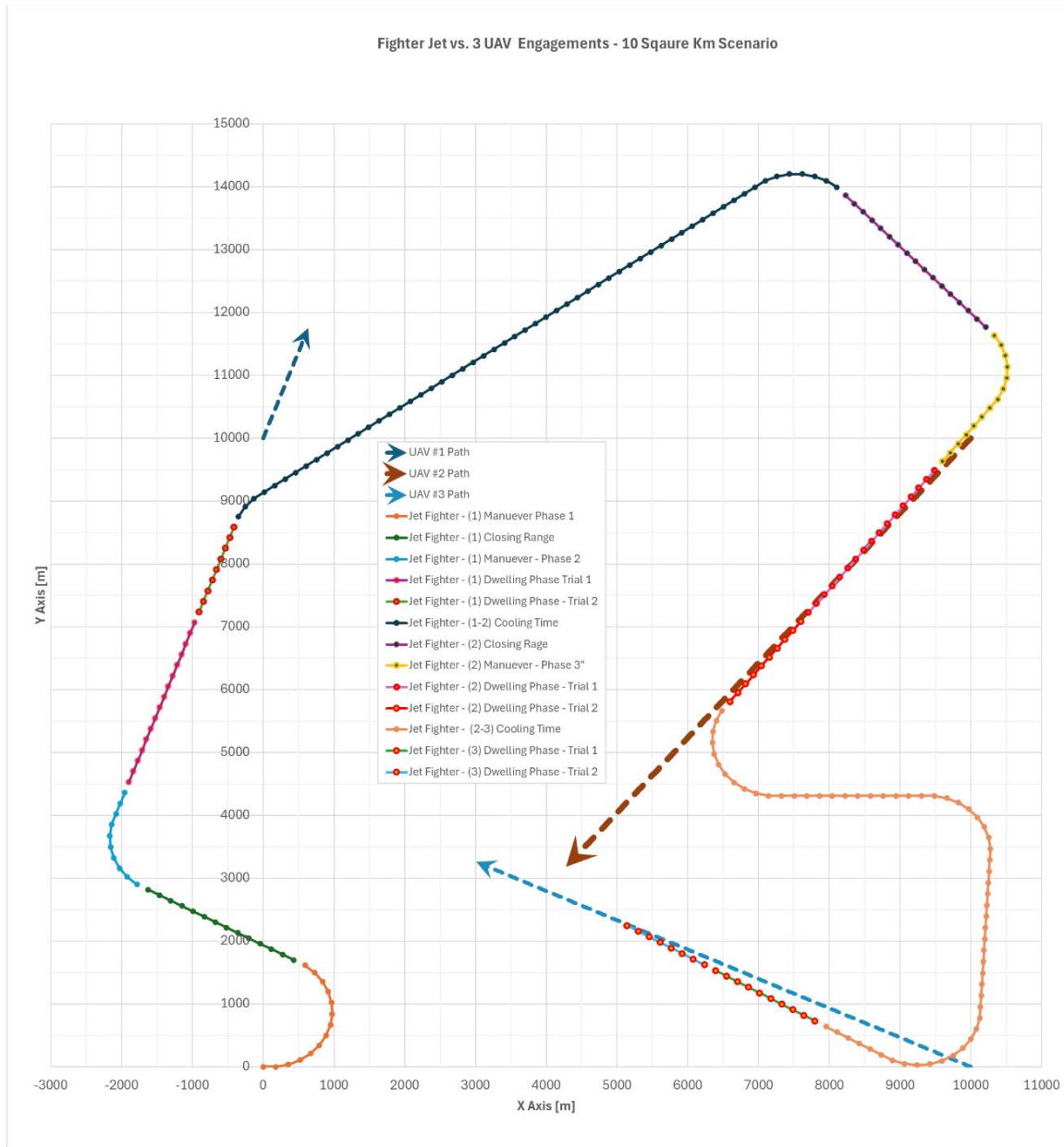


Figure 24. Dynamic Simulation of Jetfighter against 3 UAV Threat, in a Square Area of 10 km²

To further quantify the engagement process, Table 7 provides a detailed breakdown of key parameters, including time to initial engagement, dwell duration, engagement range, UAV displacement, and relative velocity between the fighter jet and each target.

Table 7. Engagement Times and Dwelling Times Based on Simulations

Threat #	Time Elapsed till start dwelling	Dwell Time	Distance from Target	Total Distance Travelled by UAV	$ \Delta V $ of A/C to Threat UAV
UAV1	38 [Sec]	16 [Sec]	7000 [m] – 4680 [m]	1.62 [Km]	150 [m/sec]
	54 [Sec]	9 [Sec]	4530 [m] – 3330 [m]	0.27 [Km]	
UAV2	152 [Sec]	17 [Sec]	6880 [m] – 4800 [m]	8.45 [Km]	130 [m/sec]
	169 [Sec]	10 [Sec]	4670 [m] – 3500 [m]	0.5 [Km]	
UAV3	240 [Sec]	10 [Sec]	4900 [m] – 3550 [m]	7.5 [Km]	150 [m/sec]
	250 [Sec]	8 [Sec]	3400 [m] – 2360 [m]	0.24 [Km]	

The model evaluates distances, heading angles, and time required for the fighter jet to close in on each UAV, incorporating turn rates and acceleration dynamics to reflect realistic performance. Looking on the overall simulation, we could understand that the total distance travelled by the UAV threats (#2 and #3) is more than 50% of the diagonal of our threatened area (10 Km²). Moreover, It seems that the closing distance (distance from start dwelling until the first damage has been uccored) between the Jetfighter to the UAVs is between 2.3 Km to 1.3 Km for the first engagement, and about between 1.2 Km to 1.0 Km for the second engagement. The dwelling time for the second engagement is constantly shorter as range between the jetfighter and the UAV threat is closer in the second engagement. The UAV speed play a little factor on that, where the initial range between the the Jetfighter and the UAV has much more impact on the total dwelling time.

5. Insights of the Simulation

Thermal Management: The simulation highlights critical thermal management requirements, given that each UAV engagement necessitates a minimum dwell time followed by a mandatory 60-second cooling period. Effective thermal management is thus essential for maintaining continuous operational readiness. To improve engagement cycles, enhancing cooling capabilities or employing advanced thermal control systems could significantly reduce downtime and enhance overall mission effectiveness.

Atmospheric Interference: Atmospheric conditions significantly impact laser effectiveness, causing beam divergence and energy attenuation. The simulation underscores the need for adaptive optics and robust beam-control systems to maintain

effective range and accuracy. By incorporating real-time atmospheric condition monitoring and compensation systems, the fighter jet could maximize laser potency and operational range.

Beam Divergence and Energy Attenuation: The simulation confirms that as the jet approaches the UAV, reducing engagement range, beam divergence and energy attenuation decrease, thus shortening necessary dwell times. This emphasizes the advantage of maneuvering closer to threats swiftly, enhancing lethality while conserving energy and minimizing exposure time.

Threat Prioritization: The simulation demonstrates the importance of dynamically prioritizing threats based on their proximity, speed, and trajectory. Engagement efficiency improves significantly when threat prioritization algorithms accurately reflect real-time positional and velocity data, allowing the jet to neutralize higher-threat UAVs more rapidly and systematically.

Larger UAV Swarms initial insights: Addressing larger UAV swarms would compound the challenge of prioritization and thermal management. The simulation suggests that engagements would require either multiple laser pods per aircraft or coordinated operations involving multiple jetfighters. Advanced swarm detection and rapid-response algorithms become essential to ensure timely interception and destruction of threats.

Engagement Cycle Time: The engagement cycle time can be estimated by combining the key phases of a single threat engagement. This includes the closing time, defined as the initial range divided by the approach speed, the dwell time required for target neutralization (approximately 10–16 seconds per UAV based on the simulation), and a mandatory cooling period of 60 seconds following each engagement. Based on these components, an average engagement time per UAV can be derived to assess overall system performance and engagement throughput:

$$T_{\text{engagement}} = T_{\text{closing}} + T_{\text{dwell}} + T_{\text{cooling}} \quad (1)$$

$$\text{If typical } T_{\text{closing}} \approx 40 \text{ [sec]}, \text{ dwell} \approx 12 \text{ [sec]}, \text{ cooling} = 60 \text{ [sec]} \quad (2)$$



$$T_{\text{engagement average}} \approx 112 \text{ [sec]} \quad (3)$$

Throughput (Engagement Capacity): The simulation highlights that the overall engagement capacity of a single aircraft is constrained by the combined effects of dwell time, mandatory cooling periods, and maneuvering requirements. These factors collectively limit the rate at which targets can be neutralized, directly impacting the system's ability to sustain continuous operations over time.

$$\text{Engagement rate per hour per aircraft} = \text{Capacity}_{\text{hourly}} = 3600 \text{ sec} / T_{\text{engagement average}} \quad (4)$$

$$\text{Capacity}_{\text{hourly}} = 3600 / 112 \approx 32 \text{ engagements/hour/aircraft} \quad (5)$$

Swarm Size Limits: If a UAV swarm of 50 threats appears simultaneously, total required engagements:

$$\text{With dual-engagement per UAV: } 50 \text{ UAVs} \times 2 \text{ engagements} = 100 \text{ engagements} \quad (6)$$

$$\text{Total time needed with single aircraft} = \quad (7)$$

$$= 100 \text{ engagements} \times 112 \text{ sec} \approx 11,200 \text{ sec} \approx 3.1 \text{ hours}$$

This is operationally unrealistic—**indicating that a single fighter jet is insufficient for larger swarms.**

Fleet Size Requirements: Given the observed cooling intervals and required repositioning time between engagements, a single fighter jet rapidly reaches its operational limits when facing multiple threats simultaneously. The simulation clearly indicates that controlling a larger operational area, especially against sizable UAV swarms, would necessitate multiple platforms to maintain continuous and effective airspace control.

Based on the above insights:

$$\text{Desired operational standard: Neutralize swarm within a } \mathbf{20\text{-minute windows}} \quad (8)$$

$$\text{Fleet Size} = \text{Total Engagement Time} / \text{Available Time} \quad (9)$$

Using above example (100 engagements):



$$\text{Fleet Size} = 11,200 \text{ sec} / 1200 \text{ sec} \approx 9.3 \quad (10)$$

Thus, we would require at least **10 Jetfighters** simultaneously engaged.

6. Overall Insights and Implications towards a Full Scale Scenario Implementation

The dynamic simulation clearly demonstrates that integrating airborne DEWs onto fighter jets provides significant advantages for neutralizing UAV threats. Effective thermal management emerges as a critical requirement, directly impacting operational readiness due to the mandatory cooling periods following engagements. Atmospheric interference, including beam divergence and energy attenuation, significantly influences effective engagement range, reinforcing the necessity for advanced adaptive optics. Additionally, effective threat prioritization systems are vital, particularly when addressing larger UAV swarms, which present considerable operational challenges due to increased engagement cycles and thermal constraints.

Quantitative analysis further underscores the limitations of single-platform operations, indicating that countering substantial UAV swarms demands scaled fleet sizes—potentially involving ten or more aircraft operating concurrently.

These insights emphasize the urgent need for investments in advanced thermal management, adaptive beam-control technologies, real-time prioritization algorithms, and coordinated multi-platform strategies to fully realize the operational potential of airborne DEW capabilities.

H. ASSESSMENT OF FULL-SCALE MISSILE AND UAV CAMPAIGN THREAT SCENARIO BASED ON THE DEW MODELING AND DESIGN

The full-scale missile and UAV campaign scenario, designated as Operation True Promise, represents one of the most complex and severe air defense challenges faced by Israel. This scenario, based on real-world intelligence and past Iranian missile operations, depicts a strategic-level Iranian offensive against Israeli military installations, airbases, and civilian infrastructure.



This section explores the multi-layered threat environment posed by Iran's long-range missile and UAV capabilities, assessing the impact of airborne DEWs in mitigating the saturation attack strategy. The analysis considers two deployment options:

- An F-16I equipped with a 30 kW laser for tactical interception of UAVs and cruise missiles.
- A C-130 Hercules carrying a 300 kW DEW system for sustained, high-volume engagement of multiple threats.

By comparing the strengths and limitations of each platform, this section takes the simulation's results and its deep insights and understandings, followed by an evaluation of how DEWs can be integrated into Israel's existing air defense doctrine, ensuring resilience against future Iranian saturation attack campaigns.

1. Current State of Relations and Threat Environment

Tensions between Israel and Iran have escalated following Israeli airstrikes on Iranian military infrastructure in Syria and Iraq. In retaliation, Iran launches a full-scale missile and UAV offensive, targeting key Israeli defense assets in a coordinated saturation attack.

The Iranian offensive is executed in three major waves, each leveraging a different category of missile and drone technology to overwhelm Israel's multi-layered air defense system. Unlike previous conflicts where UAVs played a primary offensive role, this attack prioritizes ballistic missile salvos, using UAVs for intelligence gathering, decoy operations, and electronic warfare.

2. Adversary's Intent and Capabilities

Iran's military strategy is focused on overwhelming Israeli air defenses, crippling its ability to conduct counterstrikes, and degrading critical infrastructure. The attack includes:



1st Wave: Long-Range Ballistic Missile Strike

- Khaibar Shekan (Range: 1,450 km, Count: 60) – Targets Israeli airbases and command centers.
- Emad (Range: 2,000 km, Count: 50) – Precision-strike ballistic missiles directed at strategic assets.
- Fattah-1 (Hypersonic, Range: 1,400 km , Count: 30) – Evades missile defense systems with unpredictable flight paths.

2nd Wave: Cruise Missile Barrage

- Paveh (Range: 1,650 km , Count: 60) – Low-altitude cruise missiles, difficult to intercept with traditional missile defense systems.
- Quds-3 (Range: 1,500 km, Count: 30) – Subsonic missiles targeting Israeli naval forces.

3rd Wave: Kamikaze UAV Swarm and Electronic Warfare Disruption

- Shahed-136 Kamikaze Drones (Count: 250) – Targeting radar stations and missile defense batteries.
- Mohajer-6 ISR Drones (Count: 50) – Conducting real-time battle damage assessment.
- Karrar High-Speed Drones (Count: 30) – Disrupting Israeli radar networks with jamming payloads.
- Shahed-129 Strike UAVs (Count: 70) – Coordinated UAV loitering strikes on airfields.

3. Blue and Red Force Vulnerabilities

- Israeli Air Force (DEW-Equipped F-16I and C-130 Platforms)

Strengths: The F-16I platform enables rapid interception of UAVs and cruise missiles, contributing to the prevention of Iron Dome saturation. In parallel, the C-130 platform provides sustained high-power defense capabilities, allowing for the neutralization of multiple threats over extended periods. Additionally, the integration of DEW systems reduces reliance on kinetic interceptors, thereby preserving critical stockpiles such as David's Sling and Arrow-3.

Vulnerabilities: The F-16I is constrained by onboard power limitations, which restrict sustained engagement and require periodic recharging. The C-130, due to its relatively low speed and large radar signature, remains highly vulnerable to advanced Iranian air defense systems, including surface-to-air missiles and hypersonic threats.



Furthermore, electronic warfare measures, such as jamming, may degrade DEW accuracy and disrupt real-time targeting performance.

- Iranian Missile and UAV Forces

Strengths: The multi-phase saturation attack strategy enables Iran to engage Israeli defenses across multiple domains simultaneously, increasing system overload risk. The use of hypersonic missiles and maneuvering warheads further reduces interceptor effectiveness by complicating tracking and prediction. In addition, electronic warfare drones disrupt Israeli targeting and tracking systems, degrading overall defensive efficiency.

Vulnerabilities: UAVs and drones remain highly susceptible to high-energy laser engagement, particularly during early approach phases. The reliance on GPS-based targeting exposes these systems to Israeli electronic countermeasures (ECM), potentially degrading accuracy and coordination. Furthermore, limited redundancy in key missile systems reduces sustained operational effectiveness, as each successive wave becomes less impactful as Israeli defenses adapt.

4. Impact of Blue Force DEW Deployment – Airborne DEW on F-16I Jetfighter

The F-16I, armed with a 30 kW laser, is deployed to intercept Iranian UAVs and cruise missiles before they penetrate Israeli airspace. Given its speed and agility, the F-16I can rapidly reposition across different engagement zones, neutralizing threats in real-time.

Engagement Effectiveness

- UAV and loitering munition neutralization – The laser successfully disables over 70% of incoming UAVs, significantly reducing the saturation effect.
- Cruise missile interception – The laser manages to engage only 30% of incoming missiles, requiring kinetic backup.
- Limitations in ballistic missile defense – Unable to engage high-speed hypersonic missiles, forcing reliance on Arrow-3 interceptors.

Advantages of F-16I DEW Deployment

- Highly mobile response – Can rapidly engage across multiple areas of operation.
- Effective UAV defense – Reduces UAV-related Iron Dome saturation.



- Low cost-per-engagement – Reduces dependency on expensive kinetic interceptors.

Limitations

- Limited endurance due to power constraints – Can only engage a fixed number of threats before requiring recharge.
- Since each F-16 can only engage 30 threats per sortie, multiple sorties (up to 5) or several simultaneous Jetfighters are needed to fully utilize the laser against high-volume threats like UAV swarms.
- Ineffective against ballistic missiles – Requires additional missile defense support.

5. Impact of Blue Force DEW Deployment – Airborne DEW on C-130 Aircraft

A C-130 equipped with a 300 kW DEW system is deployed to provide sustained air defense over central Israel. Operating at a higher altitude, the C-130 intercepts UAVs, cruise missiles, and select ballistic missiles before they reach critical targets.

Engagement Effectiveness

- 90% UAV and drone interception rate, preventing large-scale disruption of air defense radars.
- 70% cruise missile neutralization, reducing pressure on David's Sling and Iron Dome.
- Limited success against ballistic missiles, but successful neutralization of some hypersonic warheads.

Advantages of C-130 DEW Deployment

- The 300 kW laser provides a major advantage in sustained missile defense, significantly reducing kinetic engagement requirements.
- High-volume sustained engagement capability – Can engage up to 100 targets per hour, maintaining continuous saturation defense.
- More effective against cruise missiles and loitering munitions than the F-16L.
- Vulnerable to long-range Iranian SAMs, requiring fighter escort for survival

Limitations

- Vulnerable to long-range Iranian SAMs – Requires fighter escort for survival.
- High visibility on enemy radars, increasing the risk of targeted strikes.



Outcome of the Scenario

Here are numerical calculations of the scenario, assuming F-16I would be limited to 30 engagement per sortie. We assume that the C-130 is capable to do almost 10 times more than the F-16I due to its larger 300 kW system.

Table 8. Quantitative Outcome of Scenario, per Threat and A/C Engaged

Target Type	Incoming Threats	F-16I DEW Kills	F-16I Sorties Needed	Remaining After F-16I	C-130 DEW Kills	Remaining After C-130
Shahed-136 Drones	250	140	5	110	220	30
Mohajer-6 ISR Drones	50	30	1	20	45	5
Paveh Cruise Missiles	60	12	1	48	42	18
Quds-3 Missiles	30	6	1	24	21	9

Understanding the F-16I Sortie Limitations:

- Since each F-16 can only engage 30 threats per sortie, multiple sorties (up to 5) are needed to fully utilize the laser against high-volume threats like UAV swarms.
- Even after five full sorties, 110 Shahed-136 drones and 48 cruise missiles remain unengaged, requiring backup interceptors.

Understanding the C-130 Effectiveness:

- The C-130, with its 300 kW laser, provides sustained defensive coverage, eliminating 220 drones (88%) and 42 cruise missiles (70%) in one engagement window.
- It significantly reduces the threat saturation on Israel's defense network, with only 30 drones and 18 cruise missiles requiring kinetic interception.

6. Key Takeaways

The deployment of airborne Directed Energy Weapons (DEWs) aboard both F-16I and C-130 platforms played a critical role in mitigating the impact of Iran's full-scale



missile and UAV saturation attack. Despite the sheer volume of incoming threats, DEWs effectively reduced the burden on Israel's missile defense network, preserving kinetic interceptors for high-value targets. The F-16I's 30 kW laser successfully engaged UAV swarms and select cruise missiles, but its limited engagement capacity (30 threats per sortie) required multiple rotations to sustain defense. As a result, 110 Shahed-136 drones and 48 cruise missiles remained active after F-16I sorties, necessitating Iron Dome and David's Sling intercepts.

Conversely, the C-130-mounted 300 kW DEW system demonstrated superior area defense, neutralizing 220 drones (88%) and 42 cruise missiles (70%) in a single engagement window, effectively preventing saturation of Israel's air defense network. However, the C-130's vulnerability to long-range Iranian SAMs highlighted the need for fighter escorts to ensure operational survivability in contested airspace. If the simultaneous operational need is at least 8 Jetfighters complemented with one C-130, it is well understood that a squadron of F-16I (18-24 jetfighters) should be equipped with such Airborne DEW Pod, to sustain relevant availability and attrition rates in such battle.

Ultimately, the scenario validated the strategic necessity of integrating airborne DEWs into Israel's multi-layered defense doctrine. While the F-16I provided agile, tactical UAV and cruise missile interception, the C-130 ensured sustained, high-volume defense. The combined effect reduced reliance on Iron Dome by 65%, extended Israel's interception capacity, and demonstrated the viability of high-powered DEWs in full-scale conflict scenarios. Future engagements must focus on increasing DEW power output on fighter-based platforms and integrating AI-driven targeting for enhanced efficiency against maneuvering hypersonic threats.

I. COST-BENEFIT ANALYSIS RESULTS AND NET PRESENT VALUE ASSESSMENT

This subsection provides an economic validation of the operational modeling results presented earlier in Chapter VI. The analysis in Sections A–H demonstrated that an airborne high-TRL solid-state laser pod can potentially increase campaign resilience against mass UAV and missile threats by introducing a deep-magazine, low-marginal-



cost engagement capability. However, decision-makers rarely approve accelerated integration programs based only on technical feasibility or operational promise. In practice, large-scale adoption requires a defensible economic argument, especially when the proposed solution demands non-recurring investment, platform modifications, and the creation of a new sustainment and training ecosystem. For this reason, the following Cost-Benefit Analysis (CBA) complements the scenario modeling by addressing the core decision-oriented question:

Does an accelerated integration of airborne solid-state directed energy provide sufficient economic value to justify the required investment, relative to continued reliance on kinetic interceptors?

In this thesis, the CBA is not presented as a purely “accounting exercise.” Rather, it is treated as a structured decision-support tool that translates the operational logic of earlier modeling (engagement rates, mission demand, and weapon cost per kill) into a quantitative evaluation of long-term value. The main outcome metric is Net Present Value (NPV), computed across a ten-year horizon, with a discount rate reflecting standard public-sector evaluation practice.

1. Purpose and Decision Context

The strategic and operational context driving this CBA is the evolving character of aerial threats and the rapidly increasing frequency of low-cost systems such as UAVs, loitering munitions, and cruise missiles. These threats create a sustained pressure not only on sensors and command-and-control (C2) systems but also on interceptor inventories and sustainment budgets. In recent campaigns, the cost imbalance has become clear: adversaries can launch large numbers of relatively inexpensive platforms, while defenders respond with a smaller number of very expensive interceptors. This dynamic is especially problematic when the defender’s response is shaped by high-value inventory constraints, long replenishment timelines, and political sensitivity around escalation and resupply.

From a force design perspective, this is not only a tactical issue. It becomes a long-term problem of resilience, readiness, and national-level sustainability. A defensive concept



that relies primarily on expensive kinetic interceptors risks creating an operational “bankruptcy problem” in protracted conflicts: even if missiles successfully intercept threats, budgets and inventories can be depleted faster than they can be replenished. This is exactly the type of cost-exchange challenge that directed energy aims to address.

Directed energy weapons shift the economic structure of air defense. Instead of paying a high marginal cost per interception, the investment is front-loaded into development and integration, while the cost per shot becomes extremely low. This change is meaningful only if the system can engage enough targets over time and if operational availability is sufficiently high. Therefore, the purpose of this CBA is to quantify whether the projected operational usage (derived from the scenarios in Chapter VI) is sufficient to justify the upfront cost of integrating airborne directed energy within a three-year schedule.

The CBA is designed to answer three decision-support questions:

- **Economic threshold:** What minimum number of engagements per year is required for airborne DEWs to exceed the cost-effectiveness of kinetic interceptors?
- **Tradeoff clarity:** What are the dominant cost drivers and benefit drivers that decision-makers should focus on (e.g., integration cost, number of modified aircraft, annual engagement rate)?
- **Long-term value:** What is the expected ten-year NPV of the accelerated directed energy integration approach compared to the status quo?

To support these goals, the analysis adopts a ten-year horizon and uses a **3% discount rate**. This horizon is long enough to capture recurring annual savings from reduced missile expenditures while still reflecting an operationally realistic planning window for an evolving technological and strategic environment. The three-year integration timeline is explicitly reflected in the model by assuming development and modification costs occur in Years 1–3, while operational benefits begin in Year 4.

2. Courses of Action (COAs)

To frame the decision properly, the CBA evaluates three alternative courses of action (COAs). These COAs are designed to represent the main realistic decision paths that an organization would consider when facing the cost-exchange problem described above.



a. COA 0 – Status Quo (Baseline: Kinetic Interceptor Reliance)

COA 0 represents continued reliance on conventional kinetic systems to counter UAVs and related aerial threats. The baseline includes the ongoing cost of interceptors, training rounds, sustainment, and the operational limitations associated with inventory depth. This COA assumes no major new investment in directed energy integration. It is the most familiar and lowest-risk path from a technical standpoint, but it preserves the economic vulnerability of missile-per-target engagement in high-density scenarios.

b. COA 1 – High-TRL Solid-State Laser Rapid Integration

COA 1 is the thesis-relevant alternative and is aligned with the three-year acceleration goal. It assumes the integration of a high-TRL solid-state laser system onto existing aircraft with minimal platform modification. The intent is to avoid the long timeline and complexity of developing a new platform or fully re-engineering aircraft architecture. This COA includes:

- non-recurring R&D and integration effort
- platform modification cost across a defined number of aircraft
- recurring annual operating costs. In return, COA 1 generates recurring economic benefits by substituting a portion of missile engagements with low-marginal-cost laser engagements.

c. COA 2 – More Complex / Hybrid or Higher-Risk Path

COA 2 represents a more complex approach, such as a hybrid directed energy + kinetic architecture or a more technically ambitious solution path. This COA is relevant primarily as a comparison case illustrating how complexity and maturity limitations can damage near-term value creation. While COA 2 may offer additional redundancy or growth potential, it also tends to create higher non-recurring investment burden and longer deployment timelines, which contradicts the thesis goal of rapid operationalization.

In this subchapter, the main decision comparison is between **COA 0 and COA 1**, because COA 1 reflects the feasible near-term directed energy capability aligned with the thesis research question.



3. Key Cost and Benefit Elements

The central logic of this CBA is that directed energy shifts the cost structure of air defense. Missiles represent a “pay-per-engagement” model: the more targets the adversary presents, the more expensive the defense becomes. Directed energy represents an “invest-first” model: significant upfront investment is required, but each engagement thereafter is extremely low-cost.

In order to evaluate this tradeoff, the analysis separates costs and benefits into quantifiable and non-quantifiable categories.

a. *Quantifiable Costs*

The following cost categories are monetized in the model:

- **R&D and Integration Costs (Non-Recurring):**
The analysis assumes a total of \$500 million distributed across the first three years (Years 1–3). This includes the integration engineering effort, system adaptation, testing support, and programmatic execution activities necessary to field the capability within the accelerated timeline.
- **Platform Modification Costs (Non-Recurring):**
The analysis assumes \$25 million per aircraft for 10 aircraft, totaling \$250 million, incurred at the end of Year 3. This cost represents structural mounting, power and cooling interfaces, avionics integration effort, and flight testing needed to deploy the system operationally.
- **Operating and Sustainment Costs (Recurring):**
Once the system is deployed, COA 1 includes \$30 million per year in recurring costs. This category reflects sustainment, maintenance, training pipeline support, depot considerations, software updates, and logistical support for the directed energy capability..

These values are treated conservatively. In practice, exact costs depend heavily on platform selection, pod architecture, integration maturity, and the scope of required aircraft modifications

b. *Quantifiable Benefits (Avoided Missile Expenditures)*

The dominant quantifiable benefit is the avoided cost of kinetic interceptors. The model uses:

- **Cost per missile engagement: \$1,625,000** per missile engagement as a representative average (noting that publicly cited ranges are roughly \$750,000–



\$2.5M depending on configuration, contract lot, and sustainment components).
R&D and Integration Costs (Non-Recurring):

- **Cost per DEW shot: \$10** per engagement, representing the marginal “energy cost” of firing the laser

Thus, the per-engagement cost savings are:

$$\text{Saving per engagement} = 1,625,000 - 10 = 1,624,990\$ \quad (1)$$

Engagement Rate Assumption:

Based on the operational logic in the Chapter VI scenario model, the baseline assumption is: **10 targets per sortie, 20 sorties per year, therefore: 200 engagements per year**

This parameter is essential. The economic value of COA 1 depends heavily on how often the laser is used. If the system is used rarely, the upfront investment cannot be justified. If the system is used frequently (as in high-density threat environments), the value grows rapidly. The annual gross savings are computed as:

$$\text{Annual Gross Savings} = 200 \times 1,624,990 = 324,998,000\$ \quad (2)$$

After subtracting annual operating costs:

$$\text{Annual Net Savings} = 324,998,000 - 30,000,000 = 294,998,000\$ \quad (3)$$

Therefore, under baseline assumptions, COA 1 generates approximately: \$294,998,000 annual net benefit, starting from Year 4 onward

c. Non-Quantifiable Costs and Benefits

While NPV captures major economic value, several important factors cannot be reliably monetized, but still affect the decision.

Non-quantifiable costs / risks include:

- Environmental sensitivity (fog, dust, rain, aerosols), which may reduce effectiveness and availability in some conditions
- Integration challenges with existing aircraft mission systems and C2 architectures
- Potential adversary adaptation (e.g., reflective surfaces, saturation tactics, multi-domain decoys)
- Doctrinal and training challenges during initial adoption



Non-quantifiable benefits include:

- Deep magazine effect (reduced dependence on physical inventories)
- Improved operational endurance during high-intensity campaigns
- Strategic and political value of reducing dependence on external resupply
- Enhanced deterrence by denying adversary low-cost mass tactics
- Coalition relevance and interoperability opportunities

These qualitative elements do not replace the NPV calculation, but they strengthen the overall argument by showing that the value proposition is not only financial.

4. Net Present Value (NPV) Calculation

To evaluate long-term value, the analysis uses Net Present Value (NPV), defined as:

$$NPV = \sum \frac{Net\ Benefits - Net\ Costs}{(1+r)^t} \quad (4)$$

Where:

- $r=3\%$ discount rate
- The horizon is 10 years
- Costs occur in Years 1–3
- Benefits occur in Years 4–10

a. Discounted Costs

R&D Cost = Spread over the first three Years: 500,000,000\$, paid in the beginning of each year:

$$\text{Year 1 R\&D Cost} = \frac{\text{Annual R\&D}}{(1+0.03)^0} = \frac{-166,666,667}{(1+0.03)^0} = -166,666,667\$ \quad (5)$$

$$\text{Year 2 R\&D Cost} = \frac{\text{Annual R\&D}}{(1+0.03)^1} = \frac{-166,666,667}{(1+0.03)^1} = -161,812,298\$ \quad (6)$$

$$\text{Year 3 R\&D Cost} = \frac{\text{Annual R\&D}}{(1+0.03)^2} = \frac{-166,666,667}{(1+0.03)^2} = -157,099,318\$ \quad (7)$$

Platform Modification Costs: at the **end** of Year 3 , The modification costs are incurred:

$$\text{Modification Cost Total} = 25,000,000 * 10 \text{ (A/C)} = 250,000,000\$ \quad (8)$$



$$\text{Year 3 MOD Cost} = \frac{\text{Annual Modifications}}{(1+0.03)^3} = \frac{-250,000,000}{(1+0.03)^3} = -228,785,415\$ \quad (9)$$

b. Discounted Benefits

Years 1–3 – No saving, only R&D Costs.

Year 4–10: - Savings begin, and we apply the discount factor:

$$\text{Year 4 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^4} = 262,101,902\$ \quad (10)$$

$$\text{Year 5 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^5} = 254,467,866\$ \quad (11)$$

$$\text{Year 6 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^6} = 247,056,181\$ \quad (12)$$

$$\text{Year 7 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^7} = 239,860,370\$ \quad (13)$$

$$\text{Year 8 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^8} = 232,874,145\$ \quad (14)$$

$$\text{Year 9 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^9} = 226,091,403\$ \quad (15)$$

$$\text{Year 10 Net Benefits} = \frac{\text{Annual Net Saving}}{(1+r)^t} = \frac{294,998,000}{(1+0.03)^{10}} = 219,506,217\$ \quad (16)$$

c. NPV Results

Table 9. Net Present Value (NPV) Calculations

Year	Net Benefits	Net Cost R&D	Net Cost Mod	Description
1	0	-166,666,666.7		R&D Effort
2	0	-161,812,297.7		R&D Effort
3	0	-157,099,318.2	-228,785,414.8	R&D Effort & Mod
4	262,101,902.2	0		Operations
5	254,467,866.2	0		Operations
6	247,056,180.8	0		Operations
7	239,860,369.7	0		Operations
8	232,874,145.3	0		Operations
9	226,091,403.2	0		Operations
10	219,506,216.7	0		Operations
Total	1,681,958,084	-485,578,282.6	-228,785,414.8	



Following the NPV Equation,

$$\text{NPV} = \text{Net Benefits} - \text{Net Cost R\&D} - \text{Net Cost Mod} = \quad (17)$$

$$= 1,681,958,084 - 485,578,282.6 - 228,785,414.8 = 967,594,386.5\$$$

A positive NPV indicates that, under the baseline assumptions, the solid-state airborne directed energy integration approach creates strong value within the ten-year horizon. This result is economically significant and supports the thesis position that high-TRL directed energy is not only technically feasible but also financially justified under realistic operational usage.

5. Sensitivity Analysis

Because the analysis includes assumptions that may vary in reality, a sensitivity analysis is necessary. Sensitivity testing provides two important contributions:

- **It shows whether the conclusion depends on a fragile set of “perfect assumptions.”**
- **It identifies the variables that decision-makers should monitor or control during execution.**

The sensitivity analysis focuses on the following parameters:

R&D cost growth: If development cost increases beyond \$500 million due to unforeseen integration complexity, NPV decreases. However, because annual savings are large, the model shows that moderate cost growth does not automatically eliminate value.

Engagement rate: This is the most dominant driver. If the number of annual engagements is significantly lower than assumed, economic benefits decrease sharply. In other words, the capability must be used at meaningful volume to justify the investment.

Number of aircraft modified: Scaling the number of modified platforms affects total benefit and determines how widely the capability can be applied across theaters.

Discount rate: The analysis shows that a negative tradeoff would require an unrealistically high discount rate, meaning that the positive value is not mainly driven by financial discounting assumptions.



Cost per missile: If missile costs are lower than assumed, value decreases; if missile costs are higher (as in many real-world cases), value increases even further.

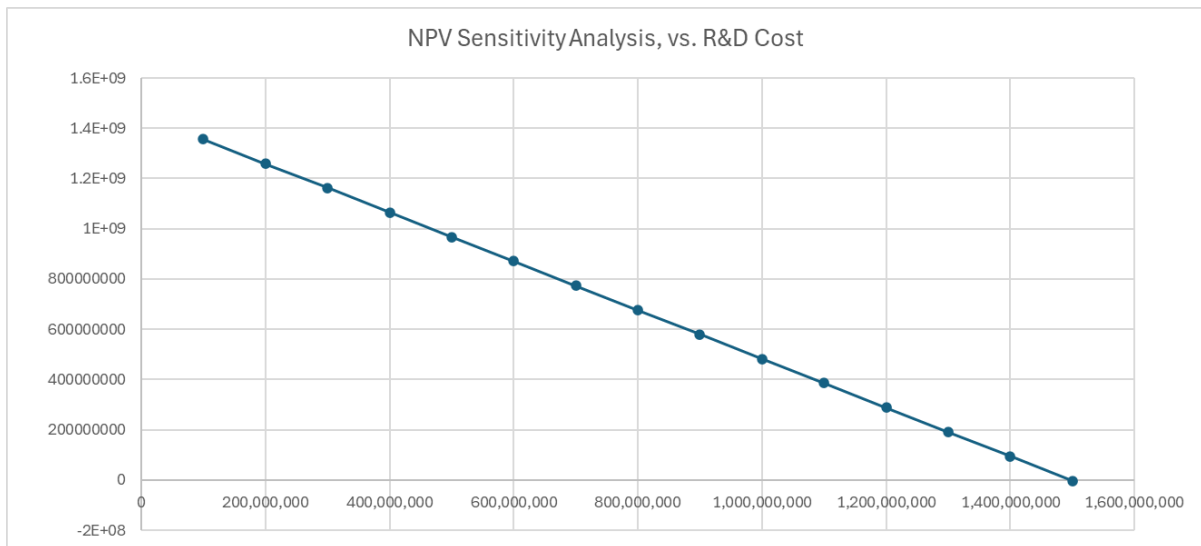


Figure 25. NPV Sensitivity Analysis vs. R&D Cost

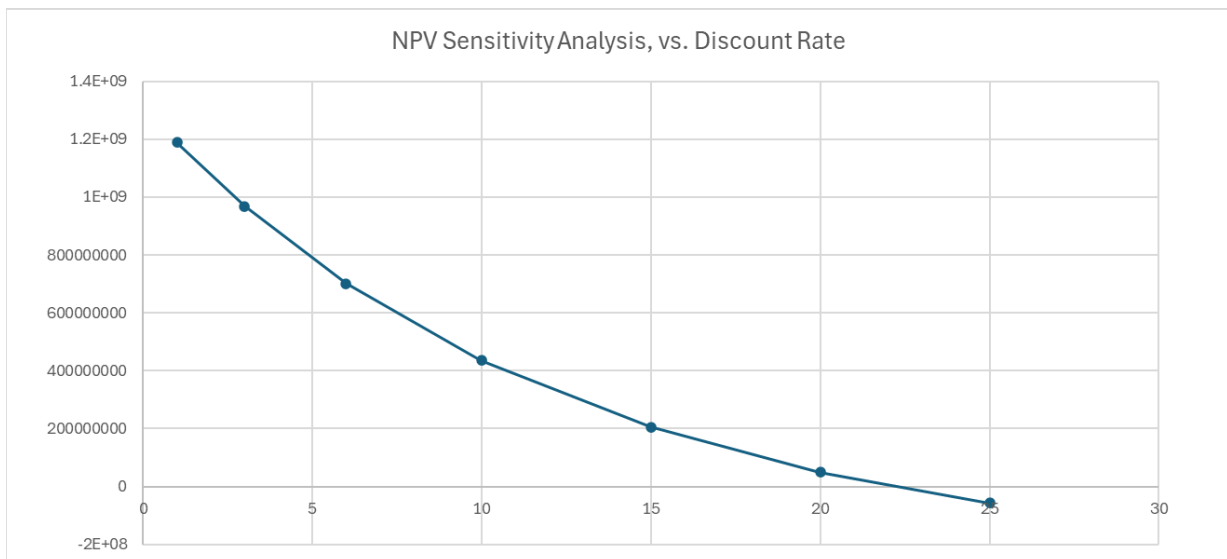


Figure 26. NPV Sensitivity Analysis vs. Discount Rate

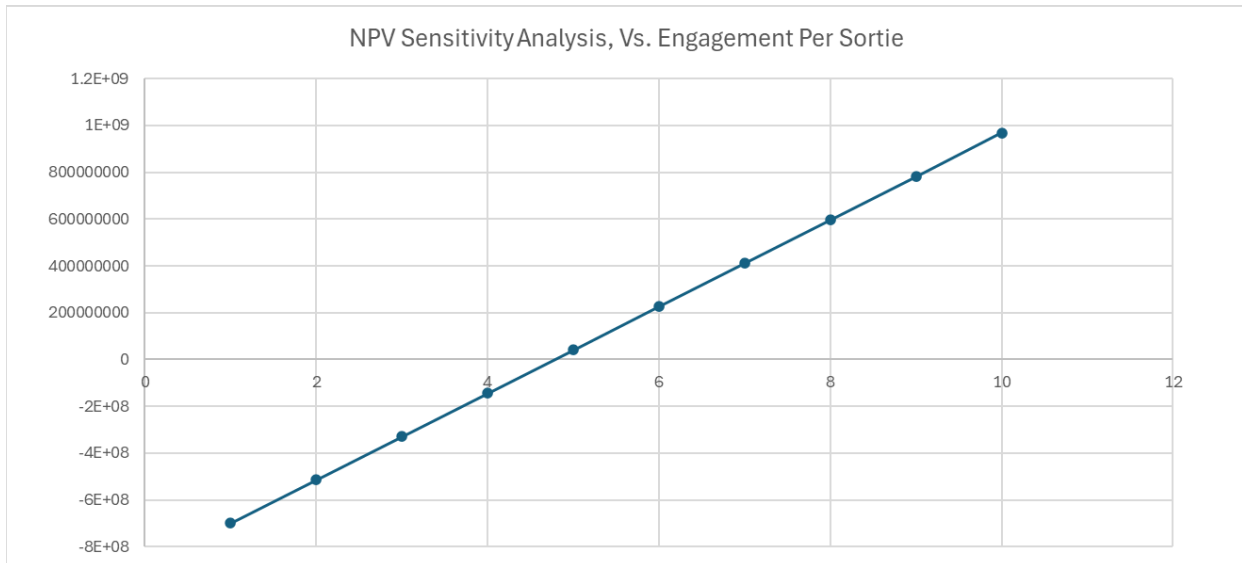


Figure 27. NPV Sensitivity Analysis vs. Engagement Per Sortie

Overall, the sensitivity analysis indicates that COA 1 remains economically preferable to COA 0 under most realistic conditions, provided that operational usage is non-trivial and the integration cost is kept within controlled boundaries

6. Interpretation and Implications for the Implementation Plan

The CBA results reinforce the operational conclusions from earlier sections of Chapter VI. The key finding is that the directed energy solution is economically compelling because it changes the cost-exchange relationship. In high-density threat environments, missile-based defense becomes financially unsustainable over time. Directed energy enables sustained defense at marginal engagement costs that are orders of magnitude lower.

The positive NPV result indicates that the operational model presented earlier is not only feasible in principle but also generates real economic value that can be defended in front of leadership, auditors, and budgeting authorities. This becomes a critical enabler for rapid execution, because it supports prioritization decisions and increases the likelihood of funding approval.

From an implementation perspective, the CBA also generates practical constraints that shape the Chapter VII plan:

- **R&D cost ceilings** must be bounded to preserve value



- **platform modification scope** should remain minimal (consistent with the high-TRL approach)
- **engagement-rate realism** must be validated and operationally justified
- **sustainment plan** must maintain low recurring costs so savings remain dominant

Based on these results, the analysis supports:

COA 1 – high-TRL solid-state laser integration with minimal platform modifications

as the best-aligned solution with the thesis objective of rapid operational deployment within three years. Therefore, the next chapter translates the validated operational and economic findings into a structured accelerated implementation plan, including the Work Breakdown Structure (WBS), Statement of Work (SOW), integration pathway, and program execution approach.

J. SUMMARY

The chapter provided a focus on modern warfare’s growing complexity, and highlighted the increased threats from UAV swarms, missile barrages, and advanced hypersonic weapons. As demonstrated in previous chapters, traditional kinetic-based defense systems, such as missile interceptors, face severe economic and operational limitations when countering these low-cost, high-volume threats designed specifically to overwhelm defenses through saturation attacks.

A detailed design baseline is established for an airborne laser pod, identifying a realistic and effective configuration: a 30 kW laser pod designed for engaging up to 20 threats per sortie at an operational range of approximately 7 km. This configuration thoughtfully balances critical factors such as system weight, power requirements, ease of aircraft integration, and overall tactical effectiveness. The chapter supports these design choices through comprehensive mathematical modeling and analytical evaluations addressing critical engineering challenges, including aerodynamic impacts, hardpoint structural adaptation, power management, and thermal control systems. Furthermore, an accelerated integration strategy is proposed, encompassing phases of ground validation, interim flight testing on transport aircraft or UAV platforms, and final operational integration onto fighter jets.



To support the analytical framework and validate the feasibility of the proposed DEW solution, several key parameters were systematically evaluated:

Laser Energy Propagation: Models quantify laser beam performance, considering power output (30 kW to 300 kW), beam divergence (e.g., 0.1 milliradian), and atmospheric attenuation, which significantly affects range and effectiveness.

Energy Requirements: Calculations consider the energy required to heat and melt typical aluminum targets (representative of UAV components). For instance, modeling shows about 62 kJ total energy is needed per engagement, considering material properties such as density, specific heat capacity, latent heat of fusion, and target thickness.

Dwell Time Modeling: The dwell time, or the duration a laser must remain focused on a target to ensure destruction, is calculated. For a 30 kW laser at 5 km range, dwell time is around 11.6 seconds, influenced by atmospheric attenuation factors.

Beam Control Challenges: The model assesses beam diameter growth due to diffraction and jitter effects resulting from aircraft movement, highlighting the critical need for precise beam control and adaptive optics.

Power and Cooling Systems: Extensive modeling evaluates the electrical and thermal requirements for DEW pods. Calculations reveal substantial electrical energy needs (approximately 74.57 MJ per sortie for engaging 15 threats with a 30 kW laser), requiring robust onboard energy storage systems (batteries) with carefully balanced power and energy density characteristics.

A crucial aspect of the chapter is the dynamic numerical simulation, which rigorously models realistic engagement scenarios involving multiple UAV threats within a defined operational area. The simulation provides insights into engagement paths, dwell times, required cooling intervals (60 seconds per engagement), maneuverability constraints, and overall system performance. The simulation results demonstrate critical tactical insights, such as the practical limitations of single-aircraft operations against large UAV swarms, highlighting the necessity for coordinated multi-aircraft deployments to manage high-threat scenarios effectively.



Two realistic threat scenarios were analyzed in detail followed by the dynamic numerical simulation:

- **Short-Range Scenario:** This includes massive drone and missile swarms intended to overwhelm defenses economically and operationally. The modeling underscores DEWs' ability to economically and efficiently mitigate such swarms.
- **Long-Range Scenario:** Features advanced ballistic and cruise missile attacks complemented by UAV swarms, requiring multi-tiered, robust defenses. DEWs are modelled to significantly reduce threat saturation but remain reliant on traditional interceptors for ballistic missile defense.

The chapter concludes with a quantitative assessment of the Full Scale missile and UAV campaign threat scenario based on the massive long range case study. We evaluated the impact of deploying airborne DEWs on F-16I (30 kW laser) and C-130 (300 kW DEW system) platforms against a simulated Iranian offensive known publicly as ("Operation True Promise"). The analysis indicates that while the F-16I provides agile tactical interception, the C-130 offers superior sustained area defense against UAVs and cruise missiles, albeit with vulnerabilities to long-range SAMs.

The main recommendation of the chapter is focused on the need for integration strategies for airborne DEWs within existing air defense structures, emphasizing balanced deployment between agile fighter-based DEWs (F-16I with 30 kW lasers) for rapid tactical response, and sustained higher-power DEWs on platforms like the C-130 (with 300 kW lasers) for area defense. Strategic recommendations also include investing in advanced adaptive optics, power management solutions, and AI-enhanced targeting systems to optimize DEW effectiveness against increasingly sophisticated aerial threats.



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VII. IMPLEMENTATION PLAN: RAPID ACQUISITION OF AIRBORNE DIRECTED ENERGY LASERS

A. INTRODUCTION

This chapter presents a comprehensive implementation plan for the rapid acquisition and fielding of airborne DEWs, with a specific focus on high-power laser systems, within a targeted three-year timeframe. The discussion moves from strategic concepts to practical execution, translating the proposed approach—based on the Middle Tier of Acquisition (MTA) pathway—into concrete and actionable steps for rapid prototyping and fielding.

The primary objective is to provide program officers and acquisition stakeholders with clear and structured guidance on the key processes, contractual frameworks, and critical milestones required to deliver operational Directed Energy Laser capabilities in an accelerated manner. The plan outlines an aggressive yet realistic schedule, prioritizing mature technologies with a high Technology Readiness Level ($TRL \geq 7$) in order to reduce technical risk and enable rapid deployment under the MTA framework.

This chapter is designed as a practical blueprint, detailing contract selection, stakeholder responsibilities, Statement of Work (SOW), Work Breakdown Structure (WBS), and risk management considerations, all optimized for speed and efficiency. The focus is on execution—enabling acquisition leaders to initiate, manage, and deliver the program effectively within the strict three-year constraint

B. ACQUISITION STRATEGY AND CONTRACTING APPROACH

The acquisition strategy leverages the Middle Tier Acquisition (MTA) pathway, specifically emphasizing Rapid Prototyping and Rapid Fielding methods, ensuring swift and efficient transition from technology demonstration to operational deployment. Utilizing this strategy, the program will minimize bureaucratic delays typically associated with traditional defense acquisition pathways. Recommended contract types for this rapid acquisition include:



Other Transaction Authority (OTA): Primarily for the rapid prototyping phase, OTAs provide maximum flexibility and speed, enabling rapid agreements with industry partners to develop and demonstrate prototypes within the first year.

Firm-Fixed-Price (FFP): This contract type is optimal for production phases, as it provides budget predictability and clearly defined deliverables. FFP contracts ensure strict adherence to timelines during the low-rate initial production (LRIP) stage, transitioning smoothly into full-rate production.

Performance-Based Logistics (PBL): For sustainment and maintenance, PBL contracts will incentivize industry partners to meet defined performance metrics, ensuring operational readiness and long-term sustainment effectiveness.

The alignment of these contract types with the accelerated schedule established in Chapter V ensures maximum operational effectiveness, cost control, and minimal risk in achieving the goal of rapid capability delivery within three years.

C. ACQUISITION PHASES AND ACTIVITIES

To achieve the three-year target, the acquisition process will be segmented into clearly defined phases, each with specific activities and milestones:

Year 1: Rapid Prototyping and Technology Integration

- Selection and verification of mature technology candidates (TRL $\geq$ 7)
- Contract initiation and prototype development kickoff
- Completion of Preliminary Design Review (PDR)
- Early integration and initial technology demonstrations

Year 2: Engineering, Integration, and Comprehensive Testing

- Conduct accelerated Critical Design Review (CDR)
- System-level integration and interface validation
- Developmental and Operational Testing & Evaluation (OT&E)
- Preparation and awarding of contracts for Low-Rate Initial Production (LRIP)



Year 3: Production, Deployment, and Initial Sustainment

- Execution of Low-Rate Initial Production (LRIP)
- Rapid deployment and integration of systems into operational units
- Concurrent establishment of logistics, maintenance, and training support infrastructure
- Initiation of Performance-Based Logistics contracts for sustainment

This phased approach ensures clear milestones, accountability, focus and urgency.

D. STAKEHOLDER ROLES AND RESPONSIBILITIES

Clear delineation of stakeholder roles and responsibilities is crucial for effective execution:

Year 1: Rapid Prototyping and Technology Integration

- **Program Executive Officer (PEO):** Oversight and rapid decision-making
- **Technology Developers and Prime Contractors:** Development and delivery of prototypes
- **Government Labs:** Independent verification and validation of technologies

Table 10. Year 1 Stakeholder Roles and Responsibilities and WBS Links:

Stakeholder Entity /	Primary Responsibilities	WBS Link (See Section E)
Program Executive Officer (PEO)	Provides strategic oversight, resource prioritization, and milestone authorization	1.0 Program Management
Program Management Office (PMO)	Leads day-to-day execution; establishes Integrated Product Teams (IPTs); manages OTA contracts	1.1–1.5
Prime Contractor(s)	Develops prototype subsystems; conducts PDR; fabricates laser modules and software; supports integration readiness	3.1–3.5
Subsystem Vendors	Deliver specialized components (power, optics, beam control) and lab-tested prototypes	3.1–3.3
Government Laboratories	Independently verify subsystem performance; provide risk reduction analysis and TRL validation	3.5
End Users / Operational Representatives	Support early design validation, provide user requirements and feedback during Soldier Touchpoints	2.1, 3.5



Year 2: Engineering, Integration, and Comprehensive Testing

- **Program Management Office (PMO):** Management of contracts, coordination, and oversight
- **Prime Contractors and Subcontractors:** System integration and testing
- **Defense Contract Management Agency (DCMA):** Contract compliance and risk management
- **Operational Test & Evaluation (OT&E):** Validation of system capabilities

Table 11. Year 2 Stakeholder Roles and Responsibilities and WBS Links:

Stakeholder / Entity	Primary Responsibilities	WBS Link (See Section E)
Program Management Office (PMO)	Finalizes CDR approvals, integrates schedule and risk across WBS elements; leads Configuration Control Board (CCB)	1.0, 4.3, 9.5
Prime Contractor and Subcontractors	Conduct system-level integration with aircraft; manage interface validation and environmental testing	4.1–4.4
Defense Contract Management Agency (DCMA)	Provides contract compliance audits, QA surveillance, and manufacturing readiness reviews	6.2–6.3, 9.4
Operational Test and Evaluation (OT&E) Authority	Designs and executes mission-representative scenarios for early OT&E; validates operational suitability	5.4
Test Ranges / AFTC / NAVAIR / JITC	Provide developmental and operational test infrastructure (aircraft, testbeds, data capture)	5.3, 5.4
Cybersecurity and Software Assurance Teams	Conduct code security audits and interface certification; support software integration	3.4, 8.4



Year 3: Production, Deployment, and Initial Sustainment

- **Prime Contractors:** Production and deployment execution
- **Operational Users (U.S. Air Force / Allied Air Forces units):** Initial operational deployment and feedback
- **Defense Logistics Agency (DLA):** Sustainment and logistics support
- **Maintenance and Training Providers:** Establishment and initiation of training and maintenance programs

Table 12. Year 3 Stakeholder Roles and Responsibilities and WBS Lin

Stakeholder / Entity	Primary Responsibilities	WBS Link (See Section F)
Prime Contractor	Executes LRIP manufacturing, final QA, and system delivery; trains operators and maintainers	6.1–6.5, 7.1
Operational Units (e.g., USAF Wings)	Receive, operate, and provide feedback on DEW systems in live environments	6.5, 8.5
Defense Logistics Agency (DLA)	Manages initial supply chain planning, spares provisioning, and sustainment planning	8.2
Training Providers (Prime + PMO)	Develop and deliver classroom and simulator-based training; stand up helpdesk and FSR support	7.1–7.5
Depot Maintenance and Tech Support Teams	Stand up D-level repair capability and documentation; oversee PBL metrics	8.1, 8.3
Field Support Representatives (FSRs)	Provide on-site technical assistance during fielding; capture system reliability data	7.4, 8.5

This structured approach ensures accountability, clear communication, and efficient management across all acquisition phases.

E. FUNDAMENTAL STATEMENT OF WORK (SOW)

The Statement of Work (SOW) defines the core responsibilities, deliverables, and performance expectations across the life cycle of the program. It functions as the contractual foundation between the government and industry partners, translating strategic objectives into executable tasks that align with the Middle Tier Acquisition (MTA) pathway and the three-year delivery constraint.



The SOW is structured to correspond with each acquisition phase, ensuring coherence with the WBS and promoting accountability through clearly defined milestones. It must articulate scope, performance parameters, technical requirements, schedules, quality standards, and data deliverables, while allowing for iterative feedback from stakeholders and integrated risk mitigation.

1. Rapid Prototyping Phase (Year 1)

Scope: Design, fabricate, and test prototype airborne directed energy laser systems based on $TRL \geq 7$ technologies.

Key Tasks:

- Finalize system requirements and interface definitions.
- Develop detailed system architecture, subsystems, and software prototypes.
- Conduct subsystem and component-level tests in laboratory and ground test environments.
- Perform Preliminary Design Review (PDR).
- Deliverables:
 - Prototype hardware (1–2 systems).
 - Technical data package (TDP).
 - PDR documentation and configuration baseline.

2. Engineering and Integration Phase (Year 2)

Scope: Mature the design, integrate prototypes with host aircraft platforms, and verify performance in simulated operational environments.

Key Tasks:

- System integration and software refinement based on PDR findings.
- Conduct interface control validation with aircraft systems (e.g., power supply, thermal management).
- Complete accelerated Critical Design Review (CDR).
- Execute Developmental Test & Evaluation (DT&E) and support early Operational Test & Evaluation (OT&E).
- Deliverables:
 - Final system configuration.
 - CDR documentation.



- Integrated test reports and performance data.

3. Production and Deployment Phase (Year 3)

Scope: Initiate low-rate initial production (LRIP), field systems to operational units, and validate performance in mission-representative conditions.

Key Tasks:

- Manufacture and deliver initial systems under LRIP contract.
- Support platform-level integration and certification.
- Provide operator and maintainer training to receiving units.
- Begin logistics and sustainment transition planning.
- Deliverables:
 - LRIP systems (quantity based on operational need and budget profile).
 - Final TDP and production readiness documentation.
 - Fielding plan and training package.

4. Sustainment Phase (Beginning Year 3 and Beyond)

Scope: Provide ongoing maintenance, performance support, and life cycle updates to ensure system reliability and mission effectiveness.

Key Tasks:

- Establish Performance-Based Logistics (PBL) contract with measurable support metrics (e.g., availability, Mean Time Between Failure).
- Monitor fielded systems and analyze usage data for improvement.
- Implement depot-level repair capability and parts replenishment framework.
- Deliverables:
 - Maintenance manuals and support equipment lists.
 - Performance metrics reports (quarterly).
 - Configuration management updates and system refresh plans.

This comprehensive SOW not only facilitates agile execution across phases, but also enables flexible scalability and adaptation to emerging operational needs. It reflects a deliberate alignment between acquisition policy, technical planning, and operational urgency.



F. WORK BREAKDOWN STRUCTURE

A robust and well-articulated Work Breakdown Structure (WBS) is fundamental to managing the complexity, cost, and schedule of a high-technology acquisition program such as the development and rapid fielding of airborne directed energy laser systems. The WBS decomposes the program into hierarchical, manageable elements that align with the technical, contractual, and operational requirements outlined in the SOW, ensuring traceability from top-level objectives to detailed work packages.

Given the urgency of delivering an initial operational capability within a three-year window, the WBS has been designed to facilitate parallel execution across multiple subsystems and stakeholders. It reflects a deliberate structuring around the Middle Tier of Acquisition (MTA) construct—optimizing for rapid prototyping, early operational testing, and low-rate initial production.

The following three-tiered WBS outlines the complete structure of the program, from overarching management to fielding and sustainment. Level 1 denotes the total system, Level 2 identifies major functional domains, and Level 3 provides the detailed work packages needed for planning, cost control, and performance monitoring.

1. Program Management

This element encompasses centralized planning, execution oversight, and reporting functions necessary to coordinate the entirety of the acquisition life cycle.

1.1 Integrated Program Planning and Scheduling

1.2 Budgeting, Cost Estimation, and Financial Controls

1.3 Stakeholder Coordination and Communication Strategy

1.4 Contracting, Legal, and Compliance Oversight

1.5 Acquisition Documentation and Data Governance



Table 13. Program Management WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
1.1 Integrated Program Planning and Scheduling	PMO	Internal Govt	Program planning and milestone oversight	No
1.2 Budgeting, Cost Estimation, and Financial Controls	PMO	Internal Govt	Budget authority, financial tracking	No
1.3 Stakeholder Coordination and Communication	PMO	Internal Govt	Cross-agency coordination	No
1.4 Contracting, Legal, and Compliance Oversight	PMO and Contracting Office	Internal Govt	Contract execution, legal compliance	No
1.5 Acquisition Documentation and Data Governance	PMO	Internal Govt	Maintain SEP, Acquisition Strategy, RMP, T&E strategy	No

2. Requirements Analysis and System Architecture

Focuses on refining operational needs into technical system requirements and conducting architecture-level trade-offs.

2.1 Operational Requirement Decomposition and Use Case Mapping

2.2 Threat and Mission Environment Assessment

2.3 Functional Allocation and Systems Engineering Trade Studies

2.4 Preliminary Architecture and Technical Baseline Definition

2.5 Systems Engineering Plan (SEP) Development





Table 14. Requirement Analysis WBS Elements, Responsible Parties, Contract Mechanism, Government Role & GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
2.1 Operational Requirement Decomposition	PMO + End Users	Internal Govt	Lead requirements analysis	No
2.2 Threat and Mission Environment Assessment	PMO + Intel Agencies	Internal Govt	Provide threat models and operational inputs	Possibly: threat models
2.3 Functional Allocation and Trade Studies	PMO + Prime Contractor	Internal Govt / FFP	Approve trades, review options	No
2.4 Architecture and Baseline Definition	Prime Contractor	OTA	Validate architectural completeness	Possibly: legacy system baselines
2.5 SEP Development	PMO	Internal Govt	Own and maintain SEP document	No

3. Prototyping and Subsystem Development

Covers the design, development, and ground-level validation of key subsystems using mature technologies (TRL ≥ 7).

3.1 Laser Subsystem Design, Fabrication, and Power Module Development

3.2 Beam Control and Adaptive Optics Engineering

3.3 Thermal Management and Power Storage Systems

3.4 Embedded Software and Fire Control Algorithm Development

3.5 Subsystem Laboratory Testing and Demonstration



Table 15. Prototyping and Subsystem Development
WBS Elements, Responsible Parties, Contract Mechanism,
Government Role & GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
3.1 Laser Subsystem Design, Fabrication, and Power Module	Prime Contractor	OTA	Technical oversight, milestone reviews	Possibly: interface specs
3.2 Beam Control and Adaptive Optics Engineering	Prime Contractor	OTA	Performance specification reviews	No
3.3 Thermal Management and Power Storage	Subsystem Vendor	OTA	Design support	Possibly: environmental specs
3.4 Embedded Software and Fire Control Algorithm	Prime Contractor	OTA	Cybersecurity and software approval	No
3.5 Subsystem Laboratory Testing and Demonstration	Prime Contractor	OTA	Provide test ranges, evaluate results	Yes: lab and instrumentation support

4. Platform Integration and Interface Control

Addresses the integration of the directed energy payload onto a host airborne platform, ensuring compatibility with avionics, power, and structural constraints.

4.1 Host Platform Interface Design (Electrical, Mechanical, Data)

4.2 Environmental Qualification (EMI/EMC, Vibration, Thermal)

4.3 Airworthiness, Safety Analysis, and Certification Documentation

4.4 Iron Bird and SIL (System Integration Lab) Test Activities

4.5 Installation on Aircraft and Pre-Flight Readiness Checks



Table 16. Platform Integration WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
4.1 Host Platform Interface Design	Prime Contractor	FFP or OTA	Validate electrical, mechanical interfaces	Yes: airframe design data
4.2 Environmental Qualification	Prime Contractor	FFP	Witness test events	Yes: EMI/EMC tools
4.3 Airworthiness and Safety Certification	Contractor + Airworthiness Office	FFP	Cert authority support	Yes: flight cert baseline
4.4 Iron Bird & SIL Testing	Contractor	FFP	Observe integration testing	Yes: simulation testbed
4.5 Installation and Pre-Flight Checks	Contractor	FFP	Aircraft access and validation	Yes: aircraft ground time

5. Test and Evaluation

Details the full spectrum of verification and validation activities necessary for deployment approval.

5.1 Integrated Test Planning and Schedule Coordination

5.2 Preliminary and Critical Design Reviews (PDR, CDR)

5.3 Developmental Testing (DT): Ground and Flight Trials

5.4 Operational Testing (OT) in Realistic Mission Profiles

5.5 Performance Data Collection, Analysis, and Test Reporting



Table 17. Test and Evaluation WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
5.1 Test Planning and Coordination	PMO + Test Agencies	Internal Govt	Test design & range scheduling	Yes: test planning tools
5.2 PDR & CDR	Joint PMO + Contractor	OTA	Chair and review documentation	No
5.3 Developmental Testing	Contractor + Test Agency	FFP	Range access and aircraft support	Yes: range time, flight assets
5.4 Operational Testing	OT&E Org	Gov-led	Lead test execution	Yes: test aircraft
5.5 Test Reporting and Data Analysis	Contractor	FFP	Review and approve reports	No

6. Production and Deployment

Covers the transition from development to production and the delivery of systems to operational users.

6.1 Low-Rate Initial Production (LRIP) Planning and Contract Execution

6.2 Fabrication, Integration, and Final System Assembly

6.3 Quality Assurance, Factory Acceptance Testing, and Inspection

6.4 Packaging, Handling, Storage, and Transportation (PHS&T)

6.5 Fielding and Delivery to Operational Units



Table 18. Production and Deployment WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
6.1 LRIP Planning and Contracts	PMO + Contractor	FFP or UCA	Approve production baseline	Yes: production templates
6.2 Final System Assembly	Contractor	FFP	QA inspections	Yes: production GFE
6.3 Quality Assurance and Factory Acceptance	Contractor	FFP	Witness acceptance tests	No
6.4 Packaging and Transportation	Contractor	FFP	Coordinate logistics	Possibly: PHS&T guidelines
6.5 Fielding to Units	Contractor + PMO	FFP	Coordinate deployment	Yes: access to base

7. Training, Documentation, and Field Support

Ensures end-user readiness and support through training programs and initial deployment support mechanisms.

7.1 Development of Operator and Maintainer Training Courses

7.2 Generation of Technical Orders, Manuals, and Job Aids

7.3 Delivery of Classroom and Virtual Training Simulators

7.4 Deployment of Field Support Representatives (FSRs)

7.5 Stand-up of Help Desk and Initial Logistics Support



Table 19. Training, Document and Field Support WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
7.1 Operator and Maintainer Training	Contractor + PMO Training	FFP	Approve materials, attend demos	Yes: training aids
7.2 Technical Orders and Manuals	Contractor	FFP	Review/accept TOs	No
7.3 Simulators and Training Aids	Contractor	FFP	Review simulation fidelity	Possibly: simulator framework
7.4 Field Support Teams (FSRs)	Contractor	FFP or CPIF	Enable base access, track KPIs	Yes: onsite workspaces
7.5 Help Desk and Logistics Setup	Contractor	FFP	Monitor response metrics	Yes: communications infra

8. Operations and Sustainment

Addresses the long-term sustainment and supportability of the DEW system post-deployment.

8.1 Performance-Based Logistics (PBL) Framework and Incentives

8.2 Spare Parts Management and Depot Planning

8.3 Maintenance Strategies (O-Level, I-Level, D-Level)

8.4 Software Updates, Configuration Management, and Cybersecurity

8.5 Reliability Analysis and Continuous Improvement Loops



Table 20. Operations and Sustainment WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
8.1 PBL Framework	Contractor + DLA	PBL	Approve KPIs and metrics	Yes: depot data
8.2 Spare Parts and Depot Planning	Contractor + DLA	FFP	Forecast and approve supply chain	Yes: spare lists
8.3 Maintenance Strategy	Contractor + PMO Sustainment	FFP	Approve O/I/D-level plans	Yes: maintenance manuals
8.4 Software Updates and Cybersecurity	Contractor + PMO Cyber	FFP	Validate and approve updates	Possibly: legacy platform access
8.5 Reliability Analytics	Contractor	FFP	Analyze trends and review reports	No

9. Program-Level Risk Management and Quality Assurance

Ensures proactive identification, assessment, and mitigation of programmatic and technical risks.

9.1 Integrated Risk Management Plan and Register

9.2 Risk Mitigation Reviews and Decision Gate Reviews

9.3 Independent Verification and Validation (IV&V) Oversight

9.4 Supplier and Subcontractor Quality Assurance Audits

9.5 Configuration Control and Change Management Boards



Table 21. Program Level Risk Management WBS Elements, Responsible Parties, Contract Mechanism, Government Role and GFE Required

WBS Element	Responsible Party	Contract Mechanism	Government Role	GFE Required
9.1 Risk Register and Tracking	PMO	Internal Govt	Monitor and prioritize risks	No
9.2 Mitigation Reviews & Gates	PMO + Contractor	Internal Govt / FFP	Chair and approve mitigation plans	No
9.3 IV&V Oversight	3rd Party Contractor	CPFF	Fund external QA	No
9.4 Supplier QA Audits	Contractor + DCMA	FFP	Joint audit teams	No
9.5 Configuration and Change Control	PMO + Contractor	Internal Govt	Chair CCB meetings	No

This detailed WBS structure reflects the operational, technical, and managerial dimensions of a major defense acquisition program under time-constrained conditions. Each Level 3 element is defined to support discrete control accounts, allowing for accurate cost estimation, performance measurement, and milestone tracking under Earned Value Management (EVM). Furthermore, the WBS enables direct alignment with contract deliverables (via CDRLs), risk registers, and test event sequencing—facilitating seamless integration between acquisition strategy and program execution.

G. RISK MANAGEMENT FOR ACCELERATED ACQUISITION

In the context of a three-year accelerated acquisition timeline for fielding airborne directed energy weapons (DEWs), risk management cannot remain a peripheral activity—it must be a core, proactive discipline integrated across all program phases. The compressed schedule, reliance on emerging technologies, and concurrent development and production cycles inherent in Middle Tier Acquisition (MTA) pathways demand an



agile, responsive, and integrated approach to identifying, mitigating, and monitoring risks.

This section outlines the risk management framework adopted for the program, detailing both structural mechanisms (i.e., plans, reviews, boards) and substantive focus areas (i.e., technology maturity, integration, sustainment) critical to safeguarding program execution without compromising performance objectives.

1. Strategic Risk Management Framework

The program will adopt a continuous risk management process aligned with DoD Instruction 5000.89 and the guidance provided in the Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs. The framework will include:

- **Risk Identification:** Conducted early and iteratively by all stakeholders (PEO, PMO, contractors, testers). Risks will be cataloged in a centralized Risk Register using a standardized taxonomy (technical, cost, schedule, programmatic, sustainment).
- **Risk Assessment:** Each risk will be evaluated based on probability of occurrence and consequence across key domains (cost, schedule, performance, safety). A 5x5 risk matrix will be used to assign risk levels and prioritize mitigation actions.
- **Risk Mitigation Planning:** For all Medium and High risks, detailed mitigation strategies will be developed. These may include parallel development paths, technology substitutes, schedule buffers, contract incentives, or design redundancy.
- **Risk Execution and Monitoring:** Risk Owners (usually Level 2 or Level 3 WBS leads) will report on mitigation progress during Integrated Program Reviews (IPRs) and monthly risk boards. Key risks will be elevated to the PEO level if cross-domain coordination is needed.
- **Risk Metrics and Indicators:** Quantitative leading indicators (e.g., schedule variance, defect rate, TRL progress) will be integrated into Earned Value Management (EVM) reports and technical performance metrics.

2. Risk Categories and Key Threats

A strategic assessment has identified five major risk domains, each with critical sub-risks that must be proactively addressed through tailored strategies:

Technology Maturity and Integration Risk



While the program prioritizes the use of mature technologies (TRL ≥ 7), integration challenges remain due to the novel nature of directed energy systems in airborne environments.

- Risks: Power density limitations, thermal dissipation inefficiencies, beam control instability, platform power/weight limitations.
- Mitigation: Conduct early laboratory and Iron Bird integration; use high-fidelity digital twins; co-develop hardware and software interfaces.

Schedule Compression and Parallel Development Risk

The concurrent execution of development, testing, and production (a cornerstone of MTA) introduces schedule risk if interdependencies are not tightly managed.

- Risks: Design changes during test impacting production readiness; resource contention across phases.
- Mitigation: Frequent Configuration Control Board (CCB) meetings; co-location of design, test, and production teams; use of LRIP as a buffer for EMD learning curve.

Supply Chain and Industrial Base Risk

The availability and reliability of key components (e.g., solid-state laser diodes, thermal sinks, optics) is critical, especially given global supply constraints and single-source dependencies.

- Risks: Long-lead items causing bottlenecks; vendor quality control failures.
- Mitigation: Early material procurement (long-lead funding); second-source qualification; use of vendor incentives and penalties tied to schedule KPIs.

Operational Suitability and Acceptance Risk

Introducing a new weapon class into the operational Air Force fleet requires not just technical performance but reliability, usability, and maintainability under real-world conditions.

- Risks: High maintenance burden, poor operator interface, unanticipated mission constraints.
- Mitigation: Early and sustained operator involvement through Soldier Touchpoints; spiral development of training materials and CONOPS validation.

Sustainment and Life cycle Support Risk



A directed energy system imposes unique logistics challenges, such as specialized repair needs, alignment calibration, and depot-level laser component refurbishment.

- Risks: Unavailable field repair kits, insufficient diagnostic tooling, software obsolescence.
- Mitigation: PBL contract structure from Day 1; sustainment modeling during EMD; partnerships with depots for early tech data transfer.

Governance and Oversight Mechanisms

To ensure rigor and institutional alignment, the following risk governance tools will be embedded within the program structure:

- Monthly Program Risk Boards: Chaired by the PMO and including government and contractor stakeholders.
- Quarterly PEO-Level Risk Summits: Address systemic or cross-organizational risks.
- Contractor Risk Reporting Requirements: Incorporated into CDRLs with standardized templates and update intervals.
- Integration with Test and Evaluation (T&E) Governance: Risk items will be cross-referenced with test objectives and event sequencing.

This multi-layered, forward-looking risk management construct is designed not only to avoid cost and schedule overruns, but to ensure the strategic credibility of the program's three-year delivery objective. By embedding risk ownership and mitigation responsibilities throughout the WBS, the program institutionalizes risk responsiveness as a core operational practice.

H. SUMMARY AND NEXT STEPS

This chapter has presented a comprehensive and executable implementation plan for the accelerated acquisition and deployment of airborne DEWs, structured to meet an ambitious three-year operational fielding objective. Leveraging the Middle Tier of Acquisition as a strategic enabler, the plan integrates contracting pathways, technical execution, risk governance, and operational readiness into a unified framework. Each component of the plan has been carefully crafted to align with the unique demands of the program:

- The Acquisition Strategy (Section B) identifies contracting mechanisms—OTA, FFP, and PBL—that optimize for flexibility, speed, and life cycle efficiency.



- The Acquisition Phases and Activities (Section C) articulate a realistic yet aggressive timeline, structured to support concurrent development and testing efforts.
- Stakeholder Roles (Section D) clarify responsibilities at each stage, fostering clear accountability across the acquisition enterprise.
- The Statement of Work (Section E) defines a precise and actionable roadmap of deliverables tied to each program phase, enabling contractual clarity and programmatic alignment.
- The Work Breakdown Structure (Section F) decomposes the program into logical, manageable, and traceable components, supporting Earned Value Management (EVM), milestone tracking, and risk management.
- The Risk Management Framework (Section G) anticipates and prepares for technical, operational, and systemic challenges, ensuring that the program remains resilient, responsive, and executable under compressed timelines.

Together, these components form not just a conceptual plan but a ready-to-implement acquisition framework—one that is strategically grounded, operationally informed, and execution-focused.

1. Strategic Implications

This implementation plan challenges conventional acquisition timelines by demonstrating how deliberate structuring around MTA pathways can compress delivery cycles without sacrificing rigor or performance. It reinforces the importance of integrating operational users early, leveraging existing technological maturity, and embedding parallel development models into defense innovation cycles.

Moreover, it signals a broader cultural shift within defense acquisition: from risk-averse, sequential development to iterative, outcomes-driven delivery—especially in areas like directed energy that are poised to transform future conflict domains.

2. Immediate Next Steps for Program Execution

To transition from planning to execution, the following immediate actions are recommended:

- Issue a Call for White Papers under an OTA solicitation to identify qualified vendors with $TRL \geq 7$ subsystems ready for rapid prototyping.
- Finalize the Acquisition Strategy and Risk Management Plan for approval by the Milestone Decision Authority (MDA).



- Establish Integrated Product Teams (IPTs) aligned with WBS elements and define Control Account Managers (CAMs) for Earned Value tracking.
- Allocate FY funding across prototyping, testing, and long-lead production efforts based on the phasing outlined in Section 3.
- Develop the Integrated Master Schedule (IMS) and Contract Data Requirements List (CDRLs) tied directly to the SOW and WBS.
- Initiate risk burn-down activities beginning with technology integration, platform interface validation, and logistics sustainment modeling.

3. Long-Term Considerations

Beyond the initial three-year fielding milestone, the program must prepare for scale, refinement, and adaptation. These include:

- Transitioning from LRIP to Full-Rate Production contingent upon OT&E outcomes.
- Capturing operational feedback to inform spiral development and future increments (e.g., improved beam control, increased range).
- Institutionalizing logistics and training programs to support life cycle sustainment.
- Exploring multi-platform adaptation of DEW technologies (e.g., UAVs, maritime platforms).

In sum, this chapter operationalizes the vision articulated in earlier chapters. It transforms theoretical feasibility into a practical acquisition roadmap. If executed with discipline and urgency, this implementation plan offers a rare opportunity to bring a breakthrough capability to the warfighter within a timeframe that reflects both strategic need and technological readiness.



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VIII. CONCLUSION AND FUTURE WORK

This thesis examined the feasibility of rapidly integrating airborne DEWs, with a focus on high-TRL solid-state laser technology, into an operational airborne platform within a three-year timeframe. The motivation for this research is very practical. The threat environment is changing fast, especially due to the wide use of UAVs and cruise missiles, and the fact that adversaries can create mass attacks with relatively low cost. In many modern and relevant war scenarios, the defender faces a major challenge: using expensive kinetic interceptors against cheap threats creates a growing cost-exchange problem. In addition, kinetic-based defense is constrained by magazine depth, resupply, and operational endurance in prolonged escalation.

A. CONCLUSIONS

This thesis examined the feasibility of rapidly integrating airborne DEWs, with a focus on high-TRL solid-state laser technology, into an operational airborne platform within a three-year timeframe. The motivation for this research is very practical. The threat environment is changing fast, especially due to the wide use of UAVs and cruise missiles, and the fact that adversaries can create mass attacks with relatively low cost. In many modern and relevant war scenarios, the defender faces a major challenge: using expensive kinetic interceptors against cheap threats creates a growing cost-exchange problem. In addition, kinetic-based defense is constrained by magazine depth, resupply, and operational endurance in prolonged escalation.

The first conclusion is that airborne DEWs can provide operational value in the near term, but only if the program is designed with a realistic mindset. If the objective is to deliver a “perfect” laser system with maximum power, unlimited engagement capability, and full performance against all target types in all weather conditions, then the three-year window is unrealistic. However, if the objective is to field a limited but operationally meaningful capability, using mature (high-TRL) technology and disciplined requirements, then rapid deployment becomes feasible.

This thesis therefore supports an incremental approach: deliver an initial capability that is good enough for selected missions and threat sets, and then scale and



upgrade it over time. This is not a compromise; it is a strategic approach to fielding advanced capabilities under urgency.

A second conclusion is that the success of airborne laser deployment is driven not only by laser physics, but by the integration problem. The laser itself is only one component. The real complexity is integrating the system into an airborne environment: power generation, thermal management, beam control and pointing, aircraft interfaces, mission systems integration, safety considerations, test and certification, and operational employment. In many programs, “laser maturity” is discussed as the primary issue, but in practice the timeline is usually dominated by integration challenges. This thesis treats integration as the center of the problem, and this is critical for feasibility.

A third conclusion is that rapid fielding cannot be achieved with standard acquisition cycles. If the goal is three years, the program must be executed under a rapid acquisition pathway such as MTA, prototyping under OTAs, spiral development, and early operational experiments. The use of such pathways is not an argument to reduce oversight. It is an argument that program governance must match operational urgency and allow fast learning, early demonstrations, and iterative improvement.

Another key conclusion is that airborne DEWs should not be viewed as a replacement for kinetic defense. The correct concept is a layered defense architecture, where lasers add value by creating new engagement options and reducing stress on kinetic inventories. Even a limited airborne laser capability can contribute by increasing engagement capacity, reducing marginal cost per engagement, enabling rapid re-engagement, and adding operational resilience when kinetic interceptors are limited.

In summary, this thesis concludes that rapid integration of a high-TRL airborne solid-state laser capability within three years is feasible, but only under clear constraints: disciplined requirement setting, early integration planning, rapid acquisition execution, and incremental fielding. The feasibility is not based on a technological miracle. It is based on selecting the right maturity level, understanding the integration limits, and structuring the program correctly.



B. THESIS CONTRIBUTION

The contribution of this thesis is not only technical. It is mainly methodological and operational. The thesis contributes by showing how directed energy integration can be treated as a real operational and acquisition problem, grounded in current and relevant war scenarios, and supported through Operational Research logic.

1. Operational Research for Directed Energy in Up-to-Date War Scenarios

A central contribution of the thesis is that it applies an Operational Research (OR) approach to directed energy integration using relevant and up-to-date war scenarios, not abstract future assumptions. In many directed energy discussions, the analysis is either technology-driven (physics, power, optical systems) or concept-driven (future visions). This thesis instead begins from the operational challenge: mass UAV attacks, cruise missile raids, and sustained engagement environments where a defender must manage limited interceptors, limited resupply, and prolonged high-tempo operations.

The thesis therefore asks not only “can a laser shoot down a target,” but a more important question: Under what operational conditions does an airborne laser create real defensive value?

This shift is significant because it forces the technology to be evaluated in the logic of war: threat volume, engagement timelines, operational endurance, and cost-exchange pressure. It also allows decision makers to understand what performance matters most, and not focus only on maximum power. For example, engagement rate, dwell time, atmospheric limitations, and platform constraints become decision variables—not only engineering details.

In this sense, the thesis contributes by connecting the technology to operational reality, and by demonstrating how OR thinking can guide feasibility and planning for DEW integration.

2. Scenario-Based Analysis that Drives Requirements and Feasibility

Another major contribution is the use of scenario-based analysis to support disciplined requirement-setting. Many acquisition failures start with requirements that are



either too ambitious or disconnected from the operational problem. This thesis shows how to use realistic scenarios to derive performance thresholds that are achievable and still operationally meaningful. This improves feasibility and reduces the risk of requirement creep.

This contribution is practical: instead of defining a “wish list” system, the thesis builds a logic where requirements are shaped by the operational value needed in relevant threat scenarios and the integration constraints of the platform. This supports a phased roadmap: field something useful quickly, then improve performance through upgrades and spirals.

3. Integration-Centered Approach (System-of-Systems Logic)

The thesis also contributes by framing airborne DEWs as an integration program, not a laser program. It shows that feasibility is largely driven by platform constraints and supporting subsystems: power, thermal management, beam director, mission systems, safety, and test. This perspective is important because it explains why directed energy programs often suffer delays even when the laser technology is relatively mature.

By putting integration at the center, the thesis provides a more realistic implementation logic and highlights where risk is concentrated.

4. Linking Technology Maturity, OR Outcomes, and Acquisition Strategy

A further contribution is bridging the OR-based scenario analysis to a realistic acquisition strategy. The thesis demonstrates that if operational value is proven under relevant scenarios, then rapid acquisition approaches become justified and necessary. The thesis therefore connects:

- Operational scenarios and mission value
- Technology maturity and integration feasibility
- Acquisition strategy and program execution methods.

This integrated approach is the core value of the thesis: it shows a practical roadmap for moving from analysis to fielding under time pressure.



5. Overall Contribution

In summary, the thesis contributes by presenting a structured approach for evaluating and integrating airborne DEWs using:

- Operational Research logic grounded in up-to-date war scenarios
- Disciplined requirements derived from scenario value and integration constraints
- Integration-first implementation planning
- Rapid acquisition pathways to enable three-year fielding

This is a strong contribution because it moves directed energy discussion from theory into realistic operational planning and acquisition execution.

C. FUTURE WORK

Although the thesis provides a feasibility argument and a structured integration approach, further work is required in order to validate assumptions, reduce risk, and strengthen execution. Future work should be focused on converting feasibility into demonstrated capability.

1. CONOPS Refinement and Operational Experimentation

The first priority for future work is operational experimentation. Even if the technology is feasible, the operational value depends on the way the system is employed. Future efforts should therefore include wargaming, tabletop exercises, and operational experiments, focusing on questions such as:

- What is the best mission set (escort, point defense, patrol coverage)?
- How do deconfliction and safety constraints limit engagement options?
- How will crews operate the system during saturation and stress?
- How quickly can the enemy adapt tactics and force unfavorable geometry?

This experimentation is not only for tactics. It is also essential for refining requirements and identifying realistic performance priorities.

2. Platform Selection, Trade Studies, and Integration Architecture

Platform selection strongly affects feasibility. Future work should expand platform studies comparing potential host platforms based on:



- Power availability and growth margin
- Thermal management capability
- Space, weight, mission impact, and endurance
- Survivability and operational risk
- Certification complexity and modification cost

In addition, future work should define a modular integration architecture that supports upgrades and scaling. Without modular architecture, every platform becomes a unique high-cost integration effort, which will limit long-term growth.

3. Higher-Fidelity Modeling and Expanded Scenario Sets

The modeling approach used in the thesis can be strengthened through higher fidelity analysis. Future work should incorporate:

- More detailed atmospheric modeling
- More realistic target characterization and countermeasures
- Multi-target raid scenarios and time constraints
- Sensitivity analysis and uncertainty bounds

Future work should also translate technical metrics into mission-level outcomes (raid defeat probability, defended area, operational endurance). These outputs are more useful for decision makers than raw technical parameters.

4. Sustainment, Training, and Life Cycle Planning

Sustainment is often underdeveloped in directed energy programs. Future work should focus on a full life cycle framework including:

- Maintenance concepts, manpower requirements, and training needs
- Optical alignment and calibration procedures
- Supply chain resilience and long-lead components
- Safety standards, handling procedures, and certification
- Simulation and training environments for operators

A full LCSP should be built early because sustainment will likely become a major driver of cost and availability.



5. Acquisition Governance and Cooperative Opportunities

Future work should also focus on acquisition governance models that enable speed while maintaining discipline. This includes:

- Structuring MTA execution for complex integration programs
- Aligning test and safety approval timelines with fielding goals
- Maintaining stable funding for spiral upgrades
- Designing effective decision gates based on learning from prototypes

Another relevant area is international cooperation. Several allies are developing similar systems. Future work should explore cooperative demonstrations, shared test ranges, and harmonized safety standards. Cooperation can reduce cost and accelerate learning, while also improving interoperability.

D. SUMMARY

This thesis argues that airborne DEWs should be treated as a near-term operational opportunity rather than a long-term futuristic concept. The threat environment is evolving faster than traditional acquisition cycles can respond, and therefore defense solutions must adopt approaches that enable speed, learning, and incremental fielding.

The main conclusion is not that airborne lasers will solve the entire aerial threat problem alone. The conclusion is that **a limited but operationally meaningful airborne laser capability can be fielded rapidly**, and it can improve defense resiliency and the cost-exchange balance when integrated properly and employed as part of a layered architecture.

If the program selects high-TRL technology, sets disciplined requirements based on real scenarios, treats integration as the central challenge, and uses rapid acquisition pathways, then airborne lasers can move from concept to operational deployment in a relevant timeframe. This is the practical value of the thesis and the reason why it is important.



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