HAPS Alliance

HIGH ALTITUDE PLATFORM STATION

HAPS in Defense Series

Technology Readiness Framework for Stratospheric Industry and Defense

November 2025

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Executive Summary

While high altitude platform station (HAPS) technology represents an incredible opportunity for many defense applications, significant challenges lie in testing and developing these technologies so that they can be integrated into existing defense and government programs. This document represents a significant step forward in providing the confidence leaders need to start testing HAPS technologies by providing guidelines and a framework for evaluating the technology readiness level (TRL) of stratospheric technologies for defensive research and development (R&D), acquisition, and employment. It also highlights the critical technology elements (CTE) unique to HAPS technologies to inform decision making.

Principally, this document presents the HAPS TRL Scale, designed to ensure accurate mapping and translation of HAPS technologies for defense applications. The HAPS TRL Scale provides a structured framework for accurately assessing and translating HAPS technologies for defense applications.

Building on established defense TRL methodologies, the scale identifies critical factors and development milestones that mark essential points in technical progression — such as when flight testing becomes a defining step toward maturity, or when system evaluations must align with defense operational requirements. By defining these thresholds, the TRL Scale supports informed decision-making and ensures technologies mature in alignment with mission needs and acquisition priorities. A detailed breakdown of the scale helps leaders understand and communicate why the scale is set the way it is.

We'll cover these key topics:

- How HAPS can be used in multiple defense applications.
- A look at TRL and how it is used in defense.
- A look at established frameworks, already in use, relevant to HAPS.
- TRL metrics that should be used when assessing HAPS.
- The unique critical technology elements (CTEs) that influence HAPS TRL.

Intended for aerospace and defense audiences in R&D, management, and leadership, this paper includes recommendations on how teams can start to apply the scale and provides links to other relevant HAPS Alliance papers.

Introduction

As the high altitude frontier becomes crucial for defense and military operations, modern stratospheric technologies are harnessing the power of aerospace, aviation, low Earth orbit (LEO) satellites, AI, and machine learning. This mobilization is pushing the limits of defense technology innovation while presenting new, complex challenges that have never been solved before.

As these technologies are developed, adapted, and tested for stratospheric applications with high altitude platform stations (HAPS), they present a unique challenge to evaluate. Characterizing their development progress using traditional defense technology readiness methods compounds this endeavor. Nonetheless, the proper identification of technology readiness level (TRL) is paramount in defense to evaluate maturity, investment, and risk.

The purpose of this document is to provide guidelines and a framework for evaluating TRL of stratospheric technologies for defensive research and development, acquisition, and employment while highlighting and the critical technology elements (CTE) unique to HAPS technologies to inform decision making.

HAPS TRL Scale

Formed in 2020, the HAPS Alliance is the leading voice in the industry — a consortium of over 80 member companies from the telecommunications, technology, aviation, aerospace, and defense sectors. Together, we are working to unlock the potential of technologies involving the stratosphere to enhance connectivity and sensing services for civilian and government applications globally. HAPS Alliance members include service providers, platform builders, and component manufacturers, each playing a pivotal role in advancing HAPS technology.

Each of these members has joined the Alliance because they see a strong fit between their business and what is needed for HAPS to grow and succeed. In order to support the continued growth and success of HAPS and the adaptation of HAPS technologies for defense applications, it is critical to establish a common framework for evaluating the technologies driving this innovation. The goal of this report, and others to follow, is to provide that common framework for assessing and establishing the maturity of technologies intended for HAPS for commercial, defense, and military purposes. This paper aims to establish the baseline framework using both qualitative and quantitative metrics to align technology maturity assessments for future reports, active government programs, and the HAPS industry. To do so we will answer several key questions:

- **How can HAPS be used in defense?**
  Our response will provide an overview and framework of defense applications suitable for HAPS and the capabilities they can provide.

- **What is TRL and why is it used in defense?**
  We'll define the current use of TRL in defense and establish why it is essential for supporting defense technology maturity evaluation.
- **Are there already established TRLs in use relevant to HAPS?**
  We'll identify common TRL frameworks with overlapping relevance to HAPS and show how organizational employment of TRL decision-making will influence how HAPS TRL should align to support common practices.
- **What TRL metrics should be used when assessing HAPS?**
  We'll demonstrate how understanding specific TRL metrics for HAPS will clarify the pathway for advancing technology to meet defense science and technology (S&T) needs.
- **What unique CTEs influence HAPS TRL?**
  Several CTE factors, outside typical defense TRL practices, influence the evaluation of HAPS. Discussing these will provide valuable context and resources for evaluators tasked with assessing HAPS TRL.

Future reports will build upon this baseline framework, focusing on specific technology areas critical to HAPS in greater depth and in terms of their relevance for defense applications. These will include hardware, software, and modeling and simulation (M&S).

In these future reports, we will provide recommendations on how these technologies can become operationally relevant — meaning they can be effectively employed in real world defense environments and integrated with existing military infrastructures. The employment of HAPS in defense has the opportunity to improve real time surveillance capabilities, enhance connectivity in remote regions, and reduce budgets and manpower to meet requirements — all crucial for modern defense operations.

Though initially in this paper we will leverage several United States Department of Defense (DoD) and Department of War (DoW) policies and practices to establish TRL common practices, the recommendations and guidelines provided therein are intended for general use across all defense programs. The use of U.S. DoW defense policies as a research baseline is beneficial because many international and national policies align with or mirror U.S. policy, providing a common starting point. The goal is to establish a common communication baseline between the HAPS and defense industries, which will enable the rapid, safe, and effective deployment of HAPS technologies for defense applications.

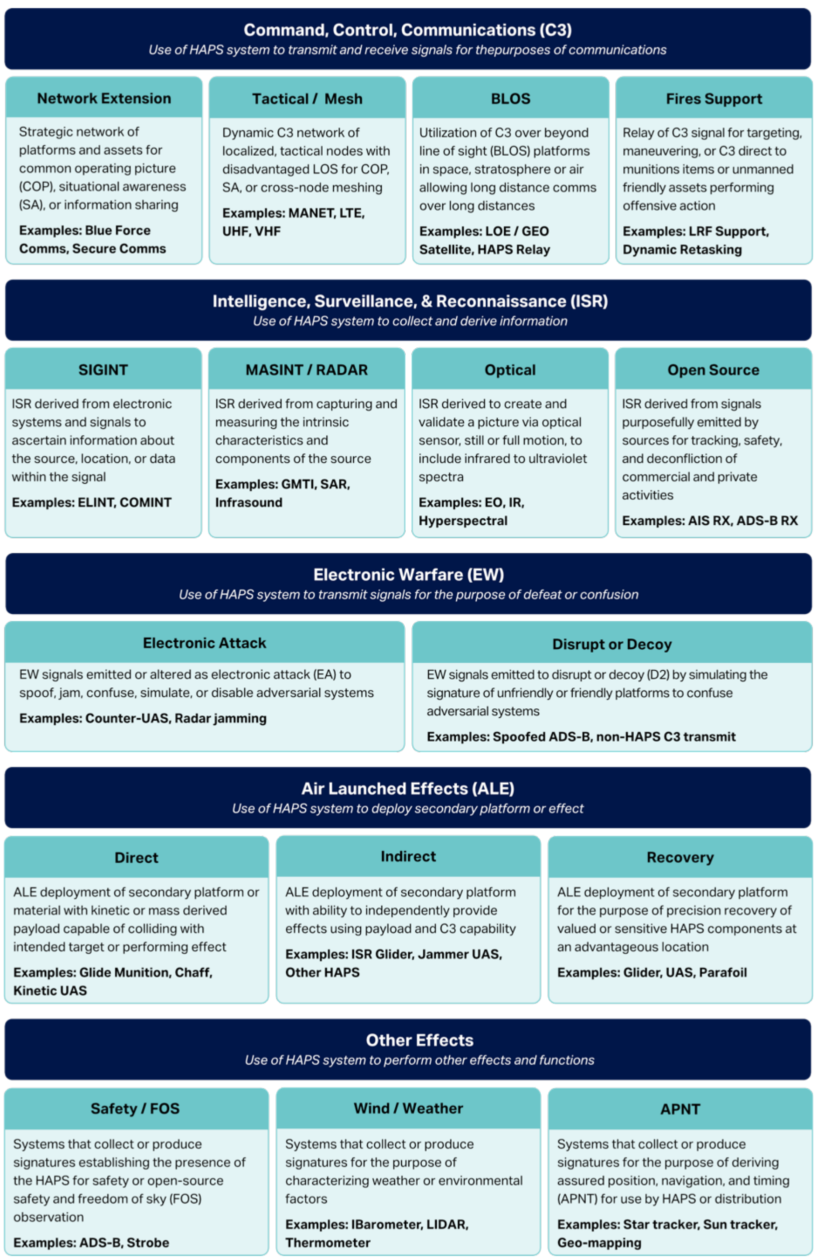
HAPS In Defense Applications

HAPS are unoccupied flight systems capable of sustained operations in the stratosphere for days, weeks, months, and potentially years, harnessing renewable energy to maximize endurance and efficiency. They include lighter-than-air platforms with a range of performance characteristics and heavier-than-air (fixed-wing) systems. HAPS are flexible, scalable, and cost-effective platforms with transformative applications across telecommunications, disaster response, earth observation, and defense.

For defense, HAPS represent a paradigm shift. They can deliver persistent, wide-area effects at low cost, transit thousands of miles without refueling, and maneuver forward to provide tactical or theater level impact. Their stability and energy consistency enable continuous support for critical subsystems and payloads, empowering multiple mission roles essential to modern defense doctrine and concepts of operation (CONOPS). These include the five mission critical functions as defined in the HAPS Defense applications framework: [1,2,3,4,5,6,7,8]

- Command, control, and communications (C3)
- Intelligence, surveillance, and reconnaissance (ISR)
- Electronic warfare (EW)
- Air launched effects (ALE)
- Other effects

By providing unmatched endurance, maneuverability, and global reach, HAPS serve as a force multiplier — extending operational reach, reducing logistical burden, and delivering decisive capabilities in competition and conflict.



TRL Purpose and Function in Defense

Across defense and aerospace industries, several primary TRL frameworks exist to standardize the evaluation of technologies. Since its development by NASA in the 1970s and subsequent integration into the U.S. Department of Defense in 1999, the TRL scale has become a critical tool for evaluating the maturity of a wide range of technologies, from handheld radios to space shuttles. Today, the primary purpose of TRL and technology readiness analysis (TRA) in defense is to provide government programs with a framework for assessing technology maturity and risk of potential technologies.

Common US DoW defense policies that include TRL: [9,10,11]

10 U.S. Code 4252 Major Defense Acquisition Programs January 01, 2024	“MDAPs may not receive Milestone B approval until the milestone decision authority… certifies that the technology in the program has been demonstrated in a relevant environment, as determined by the milestone decision authority on the basis of an independent review and technical risk assessment conducted under section 4272 of this title.”
DODI 5000.88 Engineering of Defense Systems November 18, 2020	“For programs for which an ITRA (Independent Technical Risk Assessment) is conducted, a TRA report is not required. Programs will continue to assess and document the technology maturity of all critical technologies consistent with the technology readiness assessment guidance. ITRA teams may leverage technology maturation activities and receive access to results in order to perform independent technical reviews and assessments.” “Assess and document the technology maturity of all potential critical technologies and provide the results for independent review and assessment by the ITRA team.”
DODI 5000.86 Acquisition Intelligence September 11, 2020	“Test and Evaluation Master Plan … A concept of operations will document: (1) How the system will be employed and the environment in which it is expected to perform each mission...” OUSD Coordinates and provides acquisition intelligence considerations for use in DoD Component and USD(R&E) independent technology readiness assessments”

TRL in Organizational Decision Making

Though most defense and aerospace TRL approaches use a similar structure and scale, they often apply TRL differently to inform organizational decision making in various ways. This speaks to the versatility and importance of organizational TRL strategies in that they can be used to evaluate investment opportunities, provide gatekeeping for access to resources, mitigate risk, rapidly share information, and justify budgets. All modern defense TRL programs are effective because they establish a common framework of criteria, metrics, and measures to align various technologies.

The effectiveness of these programs lies not only in the framework but also in the unique policies and strategies that guide how organizations should interpret and apply TRL within their defined mission.

Through assessment of various examples of established TRL in defense we have identified that a stratospheric TRL will require additional guidance to address stratospheric-specific CTEs and to provide recommendations on the types of decisions the framework is designed to support and influence.

- NATO (North Atlantic Treaty Organization)
- US AFRL (United States Air Force Research Lab)
- US Army / US DoW (United States Department of War)
- NASA (United States National Aeronautics and Space Administration)
- ESA (European Space Agency)
- ASEAN (Association of Southeast Asian Nations)

Examples of Defense and Government Organizations Employing TRL Methods [12,13,14,15,16,17]

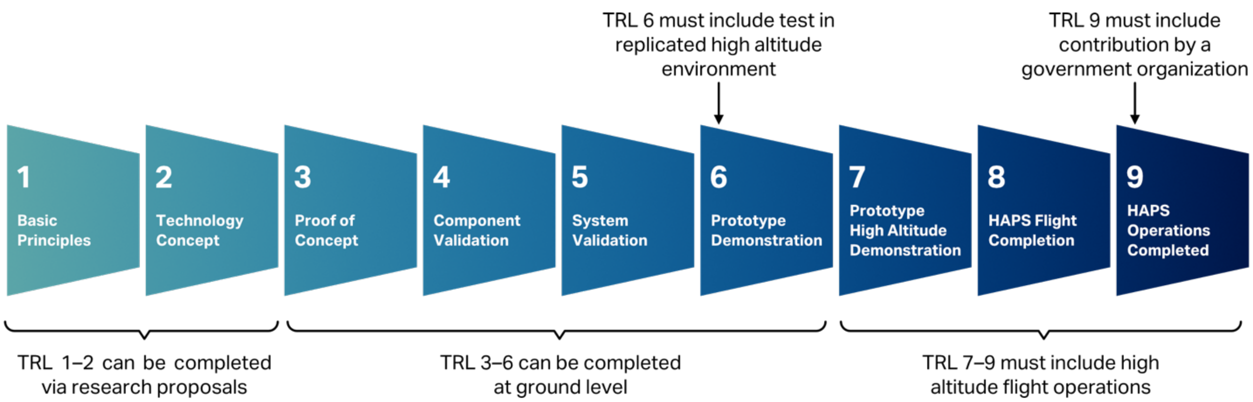
NATO A Holistic Approach to NATO Research and Technology (R&T), AUGUST 2008	*"6.1 Keeping in mind that most NATO capabilities are brought by nations, R&T activities in NATO primarily aim at disseminating knowledge in order to harmonize views, improving mutual understanding, avoiding duplications and enhancing future interoperability. They consist of three main categories:* *a) Providing and disseminating common assessment of technology present or future state of the art, issues and needs to non R&T decision makers as well as R&T managers and specialists, both from NATO and nations;* *b) Achieving common research investigations or demonstrations and providing facilities in a few areas in which all NATO nations agree to cooperate, sharing both the financial burden and relevant background and foreground knowledge;* *c) Fostering a collaborative environment to enable R&T managers and specialists from NATO and nations to exchange information and views and better know one another, and consequently facilitating more focused bottom up cooperation."* Based on published policy, NATO uses TRL to establish consistency across partner nations, enabling rapid information sharing between researchers and decision makers. This facilitates collaboration in a dynamic, multi-lingual organization by unifying technology maturity standards.
AFRL (Air Force Research Laboratory) AFRLI61-113, 3 JUNE 2022	*3.7.3. "While similar to Existing Program Protection Plans (PPP)s S&T Protection Plans are focused on protecting research and emerging technologies of all Technical Readiness Levels (TRL) before they transition to acquisition programs. AFRL protection information and strategies transition to customers' protection plans as technologies transition from AFRL research to customer programs.* *A5.1 "Critical Technology Element (CTE) Risk Assessment… 12. What is the Technology Readiness Level?... The Results of the CTE Risk Assessment will be incorporated into the formal CTC-level S&T Protection or effort-specific annex."* U.S. AFRL utilizes TRL to efficiently support both development and acquisition planning, particularly when transitioning technologies to the USAF, and documentation and risk evaluation for programs. In this manner TRL directly influences transition and investment by the USAF in mature technologies.

US Army / DoW Defense Acquisition Guidebook, 16 SEPTEMBER 2013	*The Test and Evaluation (T&E) Strategy section 3.2 states, "Evaluation Framework. Describe the overall concept of the T&E program with an emphasis on decisions in the Technology Development phase and information required to draft the CDD. Specific areas of evaluation should include Technology Readiness Level (TRL) and prototype testing. Include a Top-Level Evaluation Framework matrix that shows the correlation between decisions, the primary capabilities, critical technologies, critical technical parameters, and other key test measures."* *3.3.3.: "Test Limitations. Discuss any test limitations that may significantly affect the evaluator's ability to draw conclusions about the TRL and capabilities..."* *3.4.1.: "Mission-Oriented Approach. Describe the approach to evaluate the system performance at the appropriate TRLs."* US DoW defense and Army TRL evaluation plays a key role in the test and evaluation strategy for prototype systems, driving decision making frameworks and defining test objectives to promote technology maturity.
NASA SP-20205003605 Technology Readiness Assessment Practices Guide	*"This best practices guide is suitable for reliably determining a meaningful technology readiness level (TRL) to both technology development and flight development projects.1 This guide defines TRLs and shares best practices for TRAs, including process and implementation. This guide also suggests a process for assessing risk associated with technology maturing to a higher level."* *"Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress."* NASA employs TRL to evaluate technology and program progression, using organizational standards and guidelines for TRL, TRA, and risk evaluation based on future maturity expectations.
European Space Agency (ESA) ECSS-E-HB-11A, 1 MARCH 2017	*"For project activities, a technology readiness assessment informs the project manager (until the end of B phase) of the risk when adopting a new technology for a critical function of an element of the system. In the C and D phases TRL is no longer used by the project and the maturity of technology is managed in the critical item list"* *"Adoption Notice of ISO 16290 Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment" adopts ISO 16290 with a minimum set of modifications, to allow for reference and for a consistent integration in ECSS system of standards"* ESA uses TRL both to evaluate technology maturity and to assess strategies for integrating adopted technologies from partner nations into the existing structure. TRL directly informs the transition to higher phases of development and implementation.

Association of South Eastern Nations (ASEAN) 8303.483, OCTOBER 2017	*"Strategic Thrusts and Actions. Strategy 1: Supporting regional S&T programs that are economically and socially beneficial to ASEAN… Select and prioritize program areas and projects that offer the greatest impact and the most benefits to ASEAN as a whole; Establish a set of criteria for prioritizing program areas and projects based on technical and economic factors"* *"Strategic Thrusts and Actions. Thrust 1: Intensifying R&D collaboration and promoting technology commercialization… Develop a policy framework for strategic partnership in R&D and technology development with the private sector."* Although not explicitly referred to as TRL, ASEAN's key science and technology directives emphasize the importance of establishing criteria and frameworks that prioritize S&T programs based on both technical and economic factors. These frameworks also support the partnership between member nation governments and the private sector. Unlike NATO, ASEAN is a non-military alliance, and its criteria and frameworks, while similar to TRL, focus on fostering technological and economic collaboration. This approach promotes partnerships both between ASEAN member nations and with the private and commercial sectors, benefiting all parties involved.

HAPS TRL Scale

By aligning common TRL defense policies and frameworks with established HAPS technology and industry standards, we present a simplified TRL scale designed to ensure accurate mapping and translation of HAPS technologies for defense applications. The HAPS TRL scale incorporates well-established defense TRL principles to facilitate the streamlined integration of HAPS technologies into existing defense and government programs. The scale highlights key factors and milestones to emphasize critical development thresholds in the development of HAPS technologies – such as when actual flight testing becomes critical to technical maturity or when evaluation of HAPS technologies should meet defense requirements for intended operations. Additionally, it is important to understand the TRL of HAPS in the context of iterative development: A given maturity is relevant to a given capability, while the same system could be iterated upon with a new set of more demanding capabilities. Examples include greater payload capabilities or increased station-keeping capabilities for a given mission set.



HAPS TRL Technology Considerations

Stratospheric technologies for HAPS should be evaluated via the presented TRL scale in three technology areas: hardware, software, and stratospheric modeling and simulation (SMS).

- Hardware encompasses the equipment, materials, and physical systems involved in or supporting stratospheric capabilities, including HAPS and the ground-based infrastructure required for their launch, operation, and landing.
- Stratospheric software refers to the operating systems and software programs used by flight electronics and control systems that enable the operation of HAPS technologies, including those software programs onboard HAPS and the ground-based infrastructure providing command, control, and safety.
- Stratospheric modeling and simulation (SMS) involves analytical processes used to analyze, predict, and simulate stratospheric conditions, critical for tasks such as navigation and system regulation.

HAPS TRL Technologies

Although both software and SMS are crucial for the development and testing of HAPS, they are typically evaluated and developed by separate groups within government and defense S&T organizations. Therefore, to align with these organizational practices, we propose separating these two technology areas into distinct TRL scales. As the goal of this paper is to provide an effective method for translating HAPS technologies into defense applications, the separation of these two technologies ensures clarity and alignment with existing defense practices.

Evaluation of HAPS Technologies for TRL Applications

	HAPS Hardware	HAPS Software	HAPS SMS
TRL 1 **Basic Principles**	General principles of capability based on hardware technology concepts and applications.	General principles of capability based on software technology concepts and knowledge.	General principles of capability based on software technology concepts and knowledge.
TRL 2 **Technology Concept Established**	Initial investigation of practical application of concepts coherently without detailed analysis.	Initial exploration of basic principle code and algorithm concepts. Experimentation with synthetic data.	Initial exploration of basic principle code and model strategy. Experimentation with synthetic M&S inputs.
TRL 3 **Proof-of-Concept**	Analytical investigation of technologies with initial proof-of-concept testing for all key technology groups.	Development and proof-of-concept of critical properties via isolated limited functionality testing.	Development and proof-of-concept of critical M&S properties for data, computation elements, and mapping variables.
TRL 4 **System Validation in Lab Environment**	Limited build of hardware components with basic functionality testing to meet performance expectations of system layout.	Key functionality components integrated to test interoperability. Initial architecture development for critical system layout.	Key functionality of computation elements integrated for interoperability. Initial simulation engine layout.
TRL 5 **System Validation in Representative Environment**	System build of ready components operated to demonstrate basic functionality in lab conditions of desired end state performance. Development of strategy to support system software.	End-to-end software components integrated and tested via interoperability validation in lab conditions. Development of strategy to install to system hardware.	End-to-end model testing via simulation engine based on representative input datasets for observing model behavior and simulation accuracy. Development of strategy to support HAPS testing.
TRL 6 **Prototype Demonstration in Representative Environment (Minimum 1)**	Prototype build of full system representing all features of final system. Testing of build and functionality of key systems in representative thermal vacuum chamber (TVAC) environment simulating high altitude conditions.	Implementation of built prototype software with existing hardware/software systems. Evaluate full functionality on full scale problem sets and inputs.	Fully test model as prototype on representative datasets and dynamic problem criteria. Evaluate with simulated environmental conditions for realistic behavior.
TRL 7 **Prototype Demonstration at High Altitude (Minimum 3)**	Prototype build of full system tested and operated at high altitude. Performance evaluated during exposure to high altitude environment.	Full integration of software with prototype hardware and systems. Performance evaluated on systems operating at high altitude with live inputs.	Full implementation and test of modeling and simulation outputs on systems operating at high altitude with limited data loopback to system control.
TRL 8 **HAPS Flight Completion at High Altitude (Minimum 6)**	HAPS capability in final configuration form demonstrated at high altitude operating in isolation as intended. System meets requirements.	HAPS software is thoroughly debugged after full integration and demonstration at high altitude with HAPS capabilities. System validated in isolation and meets requirements.	HAPS SMS capability fully tested at high altitude with full loopback control based on model outputs. Testing includes abnormal dataset rejection validation in actual environments.
TRL 9 **HAPS Flight Operations at High Altitude in Defense Application (Minimum 6)**	HAPS capability demonstrated in final configuration during high altitude demonstration and validation (DEMVAL) event(s), meeting military specification (MILSPEC) hardware requirements for defense operations.	HAPS software capability demonstrated in final implementation form during high altitude DEMVAL event(s) meeting MILSPEC software and network requirements for defense operations.	HAPS SMS capability demonstrated in final form during high altitude DEMVAL event(s) involving HAPS systems meeting predictive accuracy requirements for defense operations.

HAPS Critical Technology Elements

Critical technology elements (CTEs) refer to new or novel technologies, or unique factors that significantly influence the performance and development of a system. For HAPS, CTEs represent factors unique to operating in the stratosphere, at high altitudes, over extended timeframes, or under unusual system conditions resulting from stratospheric operations.

For example, while solar energy collection via solar panels is common in aerospace and energy sectors, many HAPS rely on the energy collected solar panels not just to maintain system functionality, but also to sustain flight. This creates additional safety and design considerations, particularly during integration and functionality testing, which must be factored into TRL evaluations. The HAPS Alliance has published a document providing an outline for HAPS CTEs relevant to defense and commercial applications in "HAPS Reference Architecture Series Cell Towers in the Sky" (October 2024):

- **Aviation systems**
  - **Flight vehicle systems** — HAPS systems that sustain lift, flight, or propulsion.
  - **Energy system** — HAPS systems that collect, store, or distribute energy.
  - **Flight / fleet control systems** — HAPS systems that support flight safety, navigation, or coordination with other platforms and aircraft.
- **Service systems**
  - **Payload systems** – HAPS systems that support effects or provide services.
  - **Communication systems** – HAPS systems that support communication of effects and services between HAPS and other nodes.

The outlined CTEs identified here apply to all HAPS, additionally there are guiding principles that apply to most, if not all, HAPS technologies applicable to defense and defense related TRL. While specific systems may present additional unique circumstances based on their unique capabilities and functionality, these apply to most HAPS in defense.

Representative Environments

Creating and utilizing representative conditions for stratospheric environments remains one of the most significant challenges in stratospheric operations. HAPS must adequately evaluate multiple dynamic environmental factors that include low atmospheric pressure, high solar energy loading, poor heat convection, and stratospheric winds currents. For a full baseline of key environmental factors influencing HAPS, the HAPS Alliance's "Guidelines for Payload Operation in the Stratosphere" (13 December 2022)" can serve as a primary reference.

Thermal vacuum chamber (TVAC) systems are standard in the HAPS industry for simulating many stratospheric conditions. Primarily used to test and evaluate systems in a reduced atmosphere, TVAC capabilities replicate several atmospheric and thermal factors experienced by HAPS. However, TVAC systems fail to replicate the full spectrum of stratospheric conditions, such as the thermal loading from solar radiation, the dynamic jostling of platforms in flight, and the intermittent or lost signals for critical functions like command and control (C2), GPS, and other systems at high altitudes.

Moreover, most commercial TVAC facilities are designed to support volumes of 8 to 15 cubic feet, which makes it difficult to test larger HAPS platforms fully assembled. For this reason, HAPS TRL 6 and below are designed to allow component and subsystem testing in representative environments like TVAC.

However, as outlined, these testing methods do not fully replicate high altitude conditions, and thus, a HAPS system must be tested in the stratosphere to account for difficult-to-replicate factors to achieve HAPS TRL 7. Achieving HAPS TRL 7 represents a significant milestone on the TRL scale, as the gap between TRL 6 and TRL 7 involves a substantial increase in time, resources, and commitment.

Integrating Technologies of Various TRL

HAPS often represent a diverse, multisystem capability that leverages various technologies to support platforms, payloads, systems, software, and flight operations. When combining technologies with different TRLs, the overall system maturity and risk posture can be difficult to quantify. For instance, a system or payload that has undergone rigorous testing might be combined with other systems or platforms of lower TRLs, which have undergone minimal testing and lack flight qualification.

In general, the TRL of the platform and systems that control and enable flight is the most critical factor for assessing flight safety and overall risk. Therefore, it may be prudent to evaluate the TRL of HAPS platforms, payloads, and subsystems independently, while using the HAPS platform TRL as a general indicator of overall system maturity for flight safety considerations during HAPS testing and evaluation.

However, HAPS capabilities are often designed with highly integrated components. Even a payload or subsystem not directly involved in flight safety can influence platform performance, such as through weight, power consumption, electromagnetic interference (EMI), etc. For example, a well-tested, high-TRL payload or communication system might be used to improve overall system reliability during testing when combined with a new platform of lower TRL.

In traditional aviation, platform and payload TRLs are typically tracked separately, and they do not achieve TRL 8 or 9 until they have been flown and operated in the exact configuration intended for real world operations. The HAPS TRL scale follows a similar approach, recognizing the need for operational qualification and demonstration of the final configuration to achieve TRL 8-9.

Managing Risk in Test Conditions

HAPS introduce unique risk management challenges not typically encountered in traditional aerospace industries and defense S&T programs. Having no person onboard and flying above the vast majority of aircraft in very low congestion airspace, HAPS have a uniquely low risk profile. Due to their operating profile and unmanned nature, HAPS primarily present risks to third-party populations on the ground and to manned aircraft operating below them during ascent and descent, particularly concerning the potential for mid-air collisions.

Low TRL technologies in defense S&T programs typically mitigate these risks by operating exclusively in controlled environments, such as national laboratories, test ranges, or proving grounds – minimizing or eliminating risk to third parties. However, due to the altitude, duration, and distances that HAPS utilize, this may not always be conducive or fiscally feasible. Moreover, to achieve high TRL and demonstrate HAPS capabilities in their final operational profile, testing under real-world conditions is necessary.

HAPS present a unique opportunity to maintain third-party risk at acceptable levels, even outside of controlled or sterile test environments through existing regulations for HAPS or certificates of authorization. They can achieve this by operationally managing risk in real time. By adapting their flight path to control the duration of risk exposure and the density of populations and aircraft below, HAPS can adjust their operations proportionally to their maturity level. This technique can provide HAPS with the real-world flight experience they need to achieve high TRL and demonstrate HAPS capabilities. However, this approach requires more sophisticated safety modeling and acceptable levels of risk which can account for the overflown population/aircraft densities and the duration of exposure in and effort to enable less restrictive or confined areas to effectively test and develop HAPS. It is essential for HAPS operators and evaluators to assess the TRL of systems under test to ensure the safety of the HAPS, the general public, and manned aircraft.

The HAPS Alliance published a comprehensive guidance document, "Acceptable Levels of Risk for HAPS" (31 January 2024), which provides detailed guidance on HAPS flight risk evaluation and mitigation. This publication also draws out several examples where traditional aviation risk evaluation procedures and metrics are ineffective in characterizing HAPS and should not be used.

Specialized Modeling and Simulation for HAPS

HAPS continue to push the boundaries of flight duration, distance, and altitude. Capable of operating on a global scale like no other defense platform can, they can navigate across oceans, circle continents, or maintain persistent coverage over locations for months through active station-seeking maneuvers. These capabilities make HAPS a game-changing technology for defense, enabling sustained operations over long distances and extended periods. However, while the ability to operate in the stratosphere provides these benefits, it also presents unique challenges that cannot be addressed by traditional tools and models designed for conventional defense planning.

HAPS are sensitive to the stratospheric weather and environmental conditions in which they operate including stratospheric wind-currents, solar-power management, surface conditions at launch, and low atmospheric density. Even HAPS with active propulsion systems are affected by stratospheric wind currents, which can influence maneuverability.

The operating altitude further complicates matters, as the drastic variability between 15,000 m (50,000 ft) and 30,000 m (100,000 ft) can drastically alter critical HAPS components such as signal propagation, field of regard (FOR) range, or necessitate design changes to maintain flight in lower atmospheric density. Additionally, HAPS software technologies operating at higher altitudes may encounter hard-coded limitations intended to control aspects of functionality, such as export restrictions.

For these reasons, many traditional defense and aerospace modeling and simulation (M&S) approaches, designed for aircraft, satellites, or UAS, are ineffective for HAPS. Defense models that do not incorporate stratospheric factors will not only fail to assess the risk and functionality of HAPS accurately but will also hinder the development of an accurate understanding of SMS TRL.

Many HAPS industry companies and programs have invested years in developing specialized SMS software to account for the unique stratospheric influences on HAPS, such as navigation, signal propagation, and other key operating factors. The topic of SMS for defense is likely to be further explored in a future publication by the HAPS Alliance. This upcoming publication will provide additional insights and recommendations on how to utilize and improve the accuracy of SMS technologies for defense applications.

Global Navigation and Prediction

When evaluating HAPS SMS technologies, it is critical to test and analyze systems across different global regions to ensure accuracy and performance in specific local environments. Unlike traditional aerospace modeling which is generally region and season agnostic, HAPS navigation modeling is often both region and season specific. Some regions experience dramatic seasonal changes in stratospheric winds, while others do not. For example, a HAPS may be able to navigate from one location to another during the summer, but in the reverse direction, the platform may need to operate at a different altitude, take a different flight path, or wait for seasonal changes to enable the desired maneuver.

While surface and near surface weather conditions are extensively measured, modeled, and forecasted, stratospheric weather and wind patterns are often poorly measured, inadequately modeled, and rarely forecasted effectively. For instance, to remain stationary and persist over a specific region, a HAPS may need to operate at varying altitudes in different seasons, which could impact the types of signals it can transmit, the range of sensor collections, or even change the type of defense mission that can be supported. Oceans, frequently a preferred operating area for HAPS due to greater permissibility and flight safety, present significant challenges for SMS accuracy because they lack sufficient data for precise modeling and forecasting.

In defense applications, establishing certainty and predictability in platform positioning and navigation is crucial. Therefore, operating a HAPS globally requires thorough analysis and modeling across all regions where it is intended to operate. However, it is important to recognize that predictions, even in high-data regions, can often be inaccurate due to a variety of factors. HAPS should be operated in their intended environment, region, and season to fully validate and characterize their specific operational capabilities.

Recommendations

The HAPS TRL scale presented in this report serves as a guideline and recommendation from HAPS and defense industry experts, based on thorough research and analysis of available information. The HAPS TRL scale is organized to serve as a translation bridge between the HAPS industry and traditional defense S&T programs, outlining practical milestones and thresholds for TRL progression. Additionally, we have outlined the three HAPS technology areas of hardware, software, and modeling and simulation and detailed the approach to evaluate TRL for each technology. The HAPS TRL scale is designed to be used interchangeably with traditional TRL evaluation practices to:

- Evaluate technology maturity and operational readiness.
- Assess S&T program risk and mitigation strategies.
- Compare disparate technologies for integration purposes.
- Characterize CTEs and their impact on technology development.

HAPS technologies have several unique CTE across all platforms and systems, including environmental testing, airspace utilization, risk evaluation and mitigation, and combined technology TRL evaluation. These elements present unique challenges and significantly influence the TRL of HAPS technologies. The HAPS Alliance has published several guidance documents offering insight and practical recommendations for addressing these challenges and mitigating risks. S&T evaluators and HAPS technology developers should familiarize themselves with these documents and use their knowledge to better guide and navigate HAPS CTE challenges.

The HAPS Alliance Defense Applications Work Group (DAWG) will continue to publish follow-up documents providing further information, guidance, and documentation on HAPS in defense applications. These will offer additional details on the technology areas defined in this publication, explore additional CTEs that influence HAPS technologies, and explore their adoption for defense use.

Definitions

- **Critical technology element (CTE)** – An essential technology component that HAPS rely on to achieve success in flight and safe operations
- **DEMVAL** – Short for "demonstration and validation." A defense sponsored flight or test event including elements of both technology demonstration and technology validation
- **Demonstration** – A defense sponsored flight or test event intended to demonstrate or prove the baseline concept of a capability and develop requirements for future validation
- **High altitude platform station (HAPS)** – A type of un-occupied aircraft or lighter than air platform that operates at high altitudes, typically in the stratosphere, to provide effects
- **Stratospheric modeling and simulation (SMS)** – Modeling and simulation techniques specialized to analyze, predict, and simulate stratospheric conditions
- **Lab environment** – A benchtop or virtual testing environment relying heavily on personnel safety techniques and surface level environmental conditions
- **MILSPEC** – Military specifications or military standards that outline the essential requirements for military items and equipment
- **Prototype** – A preliminary model or system that performs all major functions for the purpose of system development and design improvements
- **Representative environment** – The use of technologies and procedures to simulate the effects and conditions of stratospheric flight at the surface, such as low pressure atmosphere, low oxygen content, high solar energy loading, poor convection heating and cooling, etc.
- **Requirements** – Formal documented metrics and measures of performance established by a program office to evaluate technology performance
- **Research paper** – A formal industry or academic report providing basic information on research topics, including reports written by industry to solicit interest and funding by government programs
- **Technology readiness assessment (TRA)** – An established organizational procedure for evaluating TRL in a consistent and reliable manner
- **Technology readiness level (TRL)** – Method for assess technology maturity, often used in the defense and aerospace industry to evaluate risk, investment, and readiness
- **Validation** – A defense sponsored flight or test event intended to validate requirements or established metrics of performance for a platform
- **White paper** – A formal government or industry report providing information or proposal on a given topic, including reports written by industry to solicit interest and funding by government programs

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About the HAPS Alliance DAWG

The HAPS Alliance Defense Applications Working Group (DAWG) articulates how HAPS technologies can be utilized for defense purposes, such as command, control, computers, communications, cyber intelligence, surveillance, and reconnaissance (C5ISR). Because global threats continue to evolve, HAPS are emerging as an advantage due to its unique capabilities in command, control and communications (C3); intelligence, surveillance, and reconnaissance (ISR); electronic warfare (EW); air launched effects (ALE) and other effects such as safety, wind and weather, and assured position, navigation, and timing (APNT).

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