



INTEGRATING HAPS: A STRATEGIC ROADMAP FOR STRATEGIC OPERATIONS

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Abstract

High-Altitude Platform Stations (HAPS) are aerial systems without pilots that stay in the earth's atmosphere, around 20 kilometers above the earth's surface. Such systems, for instance, are used for remote communication, observation, and scientific research.

Technology such as solar power, lightweight materials, and autonomous control systems has recently made it possible for them to be flown for several months. As a result, these platforms have greatly extended their operating potential.

However, the regulatory structure is quite different from technological progress. Current regulations for civil aviation are suited for manned aircraft below FL600 and, thus, the needs of unmanned, long-endurance stratospheric operations are not catered to. Uncertainties in certification, management of airspace, as well as coordination between civil and military forces are the effects of the absence of specific rules for these activities.

This work is an examination of the HAPS technology evolution, a legal and operational environment assessment, and recognition of the technical and regulatory challenges as the main issues. It looks at the European Union Aviation Safety Agency (EASA) and the International Civil Aviation Organization (ICAO) in defining Higher Airspace Operations and at the governance models that would make the global integration feasible.

A strategic roadmap is suggested as an instrument to coordinate the move from fragmented, experimental missions to safe, reliable, and commercially viable HAPS operations.

Keywords

High-Altitude Platform Stations (HAPS); Higher Airspace Operations (HAO); Airspace Regulation; Unmanned Traffic Management (UTM); Stratospheric Integration

Resumo alargado

As Plataformas de Alta Altitude (HAPS) são veículos aéreos não tripulados pensados para voar continuamente na estratosfera, cerca de 20 quilómetros acima da superfície da Terra. O interesse por este tipo de plataformas disparou ao longo dos últimos anos, sempre que os avanços em materiais ultraleves, energias renováveis e sistemas de controlo automático tornaram possível libertar-se dos constrangimentos do passado. Hoje em dia, os HAPS são capazes de permanecer no ar durante semanas ou até meses, abrindo caminho a uma verdadeira revolução em várias aplicações.

De entre as mais importantes contam-se as comunicações em zonas isoladas, a monitorização do meio ambiente, a observação da Terra, a vigilância costeira e a assistência em situações de emergência. Graças a uma presença constante e versátil, estas plataformas podem funcionar como uma opção mais barata ou complemento a satélites de órbitas baixas (LEO), mas com vantagens como a recuperabilidade, a configurabilidade e o tempo de resposta. Para comunidades remotas, desafortunadas por catástrofes naturais ou sem infraestrutura de telecomunicações, os HAPS constituem uma solução realista para diminuir a exclusão digital e, de forma mais ampla, contribuir para uma maior resiliência global, tanto a nível de conectividade como de segurança.

No entanto, a legislação ficou para trás em relação à evolução tecnológica. As regras de aviação civil foram sobretudo elaboradas para aviões tripuladas a voar abaixo de FL600, o que significa que quase não existem regras para o espaço aéreo da estratosfera. A falta de uma legislação específica deixa dúvidas em termos de certificação, requisitos de segurança e partilha do espaço aéreo. A incorporação dos HAPS também levanta desafios de coordenação entre os setores civil e militar, principalmente em casos de dupla utilização, onde as questões de soberania e segurança nacional são uma preocupação.

Neste artigo, explora-se o desenvolvimento das tecnologias associadas às HAPS e o contexto legal e operacional que condiciona a sua utilização. São identificados os principais desafios técnicos, incluindo a ausência de certificação aeronáutica, a necessidade de gerir o espaço aéreo a grandes altitudes e a necessidade de criar sistemas de controlo e comunicações adaptados às características da estratosfera. Ao mesmo tempo, aborda-se a função da European Union Aviation Safety Agency (EASA) e da International Civil Aviation Organization (ICAO) na definição conceito de Higher Airspace Operations (HAO) e na construção de modelos de governação internacional que promovam um uso harmonizado e seguro desta nova fronteira.

Com base nesta discussão, é proposto um roteiro para orientar a evolução das experiências alusivas a estas tecnologias para operações estratosféricas seguras, fiáveis e sustentáveis. Este roadmap identifica as prioridades reguladoras e técnicas, sugere formas de colaboração entre as partes civis, militares e comerciais, e enfatiza a necessidade de soluções incrementais, que possam evoluir em paralelo com os avanços tecnológicos. O objetivo é promover uma inserção global que permita às HAPS contribuir para a conectividade global, monitorização ambiental e resposta a emergências, ao mesmo tempo que fortalece a segurança e a sustentabilidade do espaço aéreo.

Assim, o estudo realizado realça não apenas o impacto revolucionário das HAPS, mas também a necessidade premente de uma colaboração entre a indústria, os reguladores e a comunidade internacional. O estabelecimento de um conjunto de regras claro e a implementação de um modelo de governação apropriado serão cruciais para que estas plataformas deixem de ser uma ideia interessante e se tornem numa opção fiável e lucrativa no cenário global.

Palavras-chave

Plataformas de Alta Altitude (HAPS); Operações em Espaço Aéreo Superior (HAO);
Regulamentação do Espaço Aéreo; Gestão de Tráfego Não Tripulado (UTM);
Integração Estratosférica

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Abbreviations

ATC – Air Traffic Control

ATFM – Air Traffic Flow Management

ATS – Air Traffic Services

C2 links – Command and Control links

EASA - European Union Aviation Safety Agency

HALE – High-Altitude Long-Endurance

HAO – Higher Airspace Operations

HAPS – High-Altitude Platform Stations/Systems or High-Altitude Pseudo-Satellites

ICAO - International Civil Aviation Organization

JARUS – Joint Authorities for Rulemaking on Unmanned Systems

LEO – Low Earth Orbit

SERA – Standardised European Rules of the Air

SORA – Specific Operations Risk Assessment

SSR – Secondary Surveillance Radar

UAS – Unmanned Aircraft System

UTM – Unmanned Traffic Management

1. Introduction

The stratosphere, situated approximately 12–50 km above sea level, is now a new area for technologically advanced aerial platforms. Its temperature gradients are small, and atmospheric pressure is stable at these elevations, resulting in little turbulence, continuous sun exposure, and thus making it an ideal place for long-duration flights in communication, reconnaissance, observation of scientific phenomena, and carrying out rescue work. HAPS (High-Altitude Platform Stations) are machines that work in this layer, which lies below the edge of outer space.

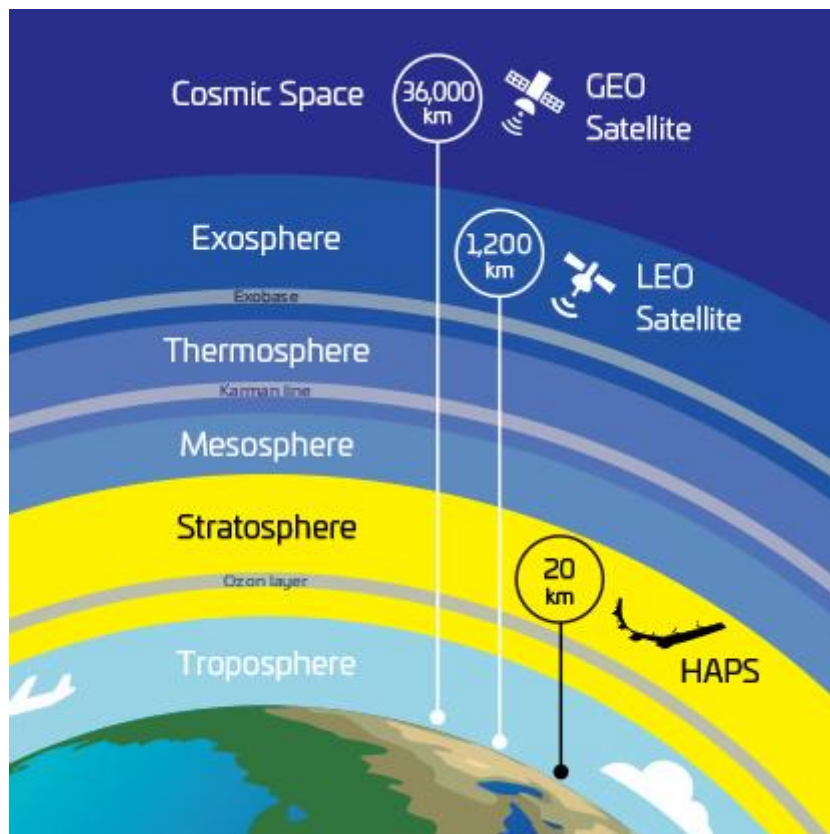


Figure 1.1 Atmospheric layers and the typical operating altitude of High-Altitude Platform Stations (HAPS). Source: adapted from SoftBank Corp. (2019).

The standard working height of HAPS is in the stratosphere about 20 km over the Earth's surface, which is the area between the flight of traditional aircraft and satellites, as shown in Figure 1.1.

Since the end of the last century, the creation of HAPS has gained momentum as it relies on the tremendous progress in materials, physics, photovoltaics, and unmanned aerial vehicles (UAVs). The NASA Helios prototype, HAPSMobile Sun glider, and Project Loon are some of the projects that have proven the technical ability to maintain flight at 20 km altitude.

Recently, several stratospheric UAV missions performed by the platforms, such as Zephyr, PHASA-35, and Aerostar's Thunderhead Balloon System, have demonstrated how the endurance of the stratosphere has been pushed to the extreme, going beyond weeks to months, without any doubt showing continuous stratospheric operations as viable.

HAPS are free of regulation in the domain, which means that they can easily become a reality, despite the fact that there are still formidable obstacles and fears surrounding them. Most civil aviation regulations have been designed mainly with man considerations in flight under FL600 (approximately 18km) in mind. Their coverage of all aspects of the solar unmanned robots operating in the stratosphere is far from enough, thus leaving a regulatory vacuum for the unmanned airspace integration, certification, airworthiness, and operational safety. Lack of a dedicated international framework generates a lot of uncertainties and delays in the implementation, which, in turn, limits scalability.

This study dwells on the evolution of HAPS technology and the historical, legal, and operational scenarios regarding the same. Moreover, it examines the main issues that, when solved, make the worldwide transfer of the new technologies smooth. The work also looks into the Higher Airspace Operations plan of the European Union Aviation Safety and the potential models of governance in the future.

The purpose of the examination is to find out the prerequisites for the HAPS operations to be safe, dependable, and financially acceptable on the one hand, and to point out the role of the collaborative global work in determining the way stratospheric flights will progress.

1.1 Research Questions

The rapid evolution of HAPS and the increasing international attention towards Higher Airspace Operations (HAO) reveal a dual reality: on the one hand, the technological maturity of solar-powered, long-endurance platforms has reached unprecedented levels; on the other hand, the regulatory, operational and governance structures necessary for safe and scalable deployments remain incomplete.

This gap raises several fundamental uncertainties that currently prevent the transition from experimental flight campaigns to routine stratospheric operations. To guide the analytical and strategic work developed throughout this dissertation, the following research questions were defined:

1. **What are the key technical, operational and system-level limitations that currently constrain the sustainable, safe and continuous operation of HAPS within the stratosphere?**
This includes constraints related to aerodynamics, energy balance, meteorological sensitivity, endurance, C2 reliability and integration with conventional air traffic.
2. **How do existing international regulatory frameworks (ICAO, EASA, FAA) address stratospheric flight, and what gaps persist for the certification, operation and governance of HAPS?**
This question underpins the regulatory analysis presented in Chapters 3 and 4.
3. **Which governance model — civil, military, hybrid or distributed — is better suited for coordinating transboundary HAPS operations, given the shared nature of the stratosphere and the need for common rules of access and accountability?**
4. **How can a coherent, realistic and dependency-based strategic roadmap be developed for the period 2025–2035, aligning technological readiness, regulatory cycles, safety requirements and multi-stakeholder responsibilities?**

These research questions establish the conceptual foundation of the dissertation, ensuring that the subsequent technical, regulatory and strategic analyses remain problem-driven and anchored to a coherent overarching purpose.

1.2 Objectives of the Study

The objectives of this work derive directly from the research questions and reflect the need to address HAPS not only as an emerging aeronautical technology but as a potential new class of operational actor within a higher airspace ecosystem.

General Objective

To develop an integrated, multi-dimensional and regulation-aware strategic roadmap that supports the safe, internationally coordinated and scalable integration of High-Altitude Platform Stations (HAPS) into the global aviation system between 2025 and 2035.

Specific Objectives

1. **To characterise the historical evolution and technological state-of-the-art of HAPS**, identifying critical drivers of performance, endurance and operational feasibility. This objective informs the technical foundations of Chapter 2.
2. **To analyse current international regulatory and policy frameworks**, with particular attention to ICAO's emerging higher airspace discussions, the EASA HAO Roadmap (2023) and FAA rules applicable to high-altitude UAS. This supports the comparative regulatory analysis in Chapter 3.
3. **To identify, classify and prioritise the main technical and operational challenges associated with long-endurance stratospheric operations**, including energy constraints, meteorological sensitivity, C2 vulnerabilities and integration with conventional airspace users. This motivates the systematic analysis in Chapter 5.
4. **To explore and compare different governance models** (centralised, decentralised, hybrid), assessing their applicability to HAPS considering safety oversight, state responsibility, liability, and cross-border operations.
5. **To construct a hierarchised SWOT analysis** that synthesises the technical, operational, regulatory and strategic factors influencing HAPS adoption, enabling an evidence-based transition into the roadmap.
6. **To design a strategic roadmap for the integration of HAPS between 2025 and 2035**, including regulatory milestones, technological dependencies, TRL-informed projections, institutional responsibilities, risks, and mitigation pathways.

Together, these objectives ensure a coherent methodological flow from technical characterisation to regulatory assessment, from systemic challenges to strategic planning.

1.3 Methodology

The dissertation adopts a **qualitative, exploratory and integrative methodology** that combines four complementary analytical approaches:

1. **Structured Literature Review:**

A systematic review of scientific, technical and institutional sources (Scopus, Web of Science, IEEE, ICAO, EASA, FAA) was conducted to establish the technological and regulatory baseline for HAPS and Higher Airspace Operations. Sources were selected according to relevance, scientific quality, recency and applicability to stratospheric operations.

2. **Regulatory and Policy Analysis:**

A comparative assessment of ICAO, EASA and FAA frameworks was carried out, focusing on airspace classification, certification pathways, operational requirements and gaps above FL600. This analysis supports the understanding of current regulatory limitations and future trajectories.

3. **Technical and Operational Assessment:**

Technical constraints were identified through published test results, platform specifications, meteorological data and endurance studies. This assessment enabled the classification of challenges related to aerodynamics, energy balance, meteorological sensitivity and C2 reliability.

4. **Strategic Tools — SWOT and Roadmap Construction:**

A hierarchised SWOT analysis was built by extracting and prioritising factors from the technical and regulatory assessments. The strategic roadmap (2025–2035) was developed using dependency mapping, TRL alignment, regulatory cycle forecasting and scenario-based reasoning.

Together, these steps provide a coherent analytical framework linking the state of the art, regulatory context and strategic planning required for HAPS integration.

1.4 Methodology Limitations

Several limitations affect the scope and precision of the study:

1. **Emerging Regulatory Environment:**

ICAO and EASA frameworks for HAO are still under development, meaning some conclusions depend on preliminary or evolving documents.

2. **Restricted Access to Technical Data:**

Certain HAPS platforms — especially military or proprietary ones — provide limited technical and operational data, constraining the depth of analysis.

3. **Limited Operational History:**

Long-endurance stratospheric missions remain relatively rare, reducing the availability of reliability, failure mode and long-term performance data.

4. **Qualitative Nature of Strategic Forecasting:**

The roadmap relies partly on scenario reasoning and expert-informed judgement, as future regulatory and technological developments cannot be predicted with full certainty.

Despite these limitations, the use of diverse sources and a multi-method approach increases the robustness and credibility of the results.

2. Historical Context and Technological Evolution

As early as the 1990s, projects were carried out to fly communication, observation and surveillance equipment in the stratosphere. It was precisely in that decade that new materials, solar power, and UAV design developments significantly helped the high-altitude operations move from a theoretical ambition to a real achievement. Going from the exploration of the stratosphere, the research led to the conclusion that this altitude offered a very wide range of benefits, such as almost no atmospheric interferences, persistence in line-of-sight coverage, and minimal air traffic interference.

Different projects that showed the potential of HAPS in rapidly changing technological times were held over the years. These activities provided the necessary infrastructure for today's missions at higher altitudes using newly available solar energy, long endurance power management, new autonomous flight control, and lightweight structures. Every project utilized previous experiences as its basis, thus providing essential information about the difficulties and the future of the HAPS systems operating in the stratosphere.

Today's commercial and military HAPS systems are the results of those early projects. These projects not only confirmed the ability to operate efficiently at high altitudes but also unveiled the enormous potential of such platforms for a variety of applications, including communication, research, and observation. Thus, modern HAPS are the outcome of decades of research and numerous failures before their development, in addition to the stratosphere being initially considered for aviation and space applications.

2.1 Helios Prototype

Back in the late 1990s, a one-of-a-kind cooperation between AeroVironment and NASA gave birth to the Helios project, which also represented one of the most challenging technical enterprises in the domain of early high-altitude and long-endurance technology development. Helios was on the cusp of stratospheric flight when researchers were still largely ignorant of that part of the sky; thus, it became a landmark experiment to try out the most advanced technologies for the flight of the highest altitudes by means of solar-powered unmanned aerial systems. The project had two target points, both of which were innovative and dangerous: the first one was to ascend to an altitude of 30km (approximately 100,000ft) within one day and the second one was to sustain level flight for several days at the altitude of 15 km (approximately 50,000ft) only using solar energy, something that had never been tried before.

Helios concept proved its applicability in 2001, when the aircraft managed to fly almost up to 100,000 feet, therefore claiming a solar-powered flight world record. The key enablers for this unprecedented accomplishment were the combination of ultralight composite materials, high-performance photovoltaic systems, and a design that was tailored to pivot around slow, non-turbulent flight in the outer air of the stratosphere. The wings of the solar craft were made exceptionally long, and the total weight of the frame was kept at a minimum for the plane to have the maximum lift and the lowest energy consumption while enabling it to convert solar power into electrical energy efficiently during the daytime.

Based on the above achievement, a Helios multi-day endurance flight test was carried out back in 2003 with the aim of maintaining Helios for a continuous period at an

altitude of 15 km to check operational stability. However, the airframe disintegrated due to structural strains on the fourth day of the flight, compelling engineers to discontinue the test early. Despite the misfortune, the mission managed to provide the valuable data and the insight it was looking for about the phenomena happening at the extreme altitudes, such as gas emission, the effect of solar exposure on the material, slow speed and high altitude flight, which the aerospace sector is facing.

The Helios project, besides being a showcase of technical abilities, was the foundation of the future HAPS development. One of the major contributions of it was to provide knowledge necessary for things like energy conversion from the sun, energy storage that can be used at night, an aircraft's dynamic behavior in low-density air, or the autonomous control of the mission at very high altitudes. Their work, the concepts, and system design of Sunlider, Zephyr, and Horus A have progressively been linked to Helios's past contributions.

Starting off as one of the pioneer campaigns that investigated the feasibility of long endurance flight in the stratosphere, Helios has made the first step in establishing a vibrant field of aviation innovation that has allowed unmanned platforms for communication, surveillance, and environmental monitoring to be transported and operated safely in the stratosphere.

2.2 Sunlider

From the notable achievements accomplished by the Helios project, the first prototype of the Sunlider emerged as the successor of its technology — a next-generation high-altitude platform system that was created by AeroVironment in association with HAPSMobile, a SoftBank group company in 2019. The driving force behind the Sunlider project was to maintain solar-powered stratospheric flights with a significant increase in all parameters, including reliability and efficiency, and maintain environmental responsibility by using techniques from Helios to make the vehicle better, and still being innovative and reflecting over ten years of developments in aerospace engineering.

A big step for the Sunlider was the improvement of the propulsion system of the vehicle. The Sunlider, with the help of updated structural dynamics and motor efficiency, as well as a more aerodynamic airframe, managed to achieve superior performance powered by only 10 electric motors compared to Helios, which at that time needed 15 motors, making it more energy-efficient. The plane, as a result of the reduction was not only less complex, but it was much lighter. This change consequently affected the aircraft's range and the duration it could operate without a decrease in reliability, performance, and safety during flights.

A further significant change was the combination of the aircraft's structure and materials. The use of advanced composite materials and the high aspect ratio of the extremely efficient wings enabled the Sunlider not just to be stable enough to get a lift and continue its flight in the very thin air of the stratosphere but also to transport the delicate payload that could be used for communication, the observation of the earth or data collection.

In September 2020, the Sunlider underwent a significant 20-hour test mission that was highly successful, marking an important development in the entire process. During this mission, it flew for over 5 hours at a consistent altitude of 19 km (roughly 62,500 ft) without stopping, which was still far from the heights typical of HAPS platforms. This operation not only confirmed its flight capabilities but also demonstrated the efficiency

of solar energy, validated the ability for autonomous flight, and evaluated performance in extreme atmospheric conditions.

The performance of Sunlider confirmed it as a mature and practical potential for long-enduring, high-altitude missions. Its capabilities made it a more accessible and scalable platform for persistent stratospheric operations if compared to previous prototypes. Having the ability to provide broad-area coverage for telecommunications, environmental monitoring, and disaster response, Sunlider was a huge step forward in the HAPS becoming the operational solution for global connectivity and aerial infrastructure reality.

2.3 Project Loon

Back in 2011, Project Loon started as a Google X project and later in 2018, it became a company by Loon LLC. The project was just beginning to cross the digital gap by delivering the internet to off-the grid and rural areas worldwide. Fundamentally, the initiative was a groundbreaking effort to address the planet's most persistent infrastructure problem, namely how to provide the least expensive yet reliable telecommunications services to those parts of the earth where businesses find it unprofitable to serve, the areas where both cell towers and internet cables have not spread. Loon was a new type of high-altitude communications system being developed to provide mobile connectivity in disaster zones, remote areas, and places without adequate infrastructure.

While fixed-wing HAPS such as Helios or Sunlider use aerodynamic lift and propulsion for station-keeping, Loon was based on a fleet of superpressure balloons, passively floating in the stratosphere at altitudes ranging from 18 to 25 km. These balloons couldn't propel themselves, but they were able to control their altitude, to intercept wind streams blowing in the direction they needed to go, thanks to complex algorithms for modelling the wind and up-to-the-minute meteorological information. It was with this novel approach that Loon balloons were able to self-position and hover over target areas relative to one another via the atmospheric wind layering.

The Loon system could supply wireless internet to an area around 200 times larger than that served by terrestrial base stations, as both are able to cover a broad area and also arrive on the scene quickly. One of the most impactful proofs of concept happened after Hurricane Maria devastated Puerto Rico (2017) — when cellular towers were either knocked out or disabled, Loon balloons were used to restore limited emergency communications in the region. These missions served as a showcase for the platforms' capabilities for humanitarian aid, emergency response, and reinforcement of infrastructure.

Loon had significant technical accomplishments. In May 2019, a balloon released from Puerto Rico achieved what was then a stratospheric endurance record, circling the Earth in the upper atmosphere until March 2020, when it returned to Earth in Mexico. Over 312 consecutive days, it flew almost 217,000 km (approximately 135,000 miles), proving that HAPS can sustain long-duration, autonomous flights without additional infrastructure. This achievement highlighted the incredible advancements in balloon sustainability, on-board power generation, and communication system reliability that have all increased over the life of the project.

However, despite these technological triumphs, Project Loon was officially phased out in 2021. The move was blamed mainly on the lack of commercial viability — namely, the

high cost of operating such a venture, the challenge of making the business profitable, and the complicated task of coordinating with national air space regulators and telecoms carriers. But Loon's legacy remains extremely influential. It reignited a revival in interest and investment in balloon-based stratospheric platforms, confirmed key concepts of atmospheric navigation, and was fundamental to the development of follow-on platforms, including Aerostar's Thunderhead Balloon.

More generally, Project Loon was intended to prove the concept of utilizing the stratosphere as a reliable operational layer for communication infrastructure. It showed that a network of distributed, autonomous, high-altitude platforms could offer substantial connectivity to underserved or underconnected regions, supporting the overarching goal of global internet accessibility and shaping the future of next-generation HAPS systems.

2.4 Thunderhead Balloon

Aerostar, a veteran heavyweight in the high-altitude balloon field, whose involvement in the market ranged over a number of years, has introduced the Thunderhead Balloon System that represents a notable development for the whole range of stratospheric platforms. The system resembles Project Loon in many respects, keeping its central idea but going further with a better self-sufficiency, energy saving, payload, and lifetime. The Thunderhead balloon become a HAPS that is very flexible, indicating a mixing of aviation, data science, and communication technology.

One thing that made the Thunderhead very special was its ability to fly alone on a solar power system. Highly efficient solar panels look up all day and charge both the plane's system and the lithium battery that keeps the aircraft operational at night. Besides that, the steady energy flow also ensures that the aircraft's capabilities in communication, data transfer, and environmental monitoring of the very remote places are not weakened or interrupted. Moreover, the other element that makes this type of balloon stand out is its state-of-the-art navigation and flight control system called Thunderstorm. This system allows the balloon to pinpoint and adjust the position of the balloon depending on the altitude and the wind direction. It is through the smart use of the air currents that the Thunderhead is able to be almost fixed on particular spots without the necessity of traditional engines.

On March 24, 2025, Thunderhead was very proud to announce a milestone on its journey. When one of the balloons managed to complete an extremely difficult mission, remaining in the stratosphere for a total of 336 days uninterrupted, it was a spectacular feat, and not just a personal one. Breaking the world record of 312 days set by Project Loon was the main feature of this triumph. The Thunderhead balloon went away on this assignment, travelling tens of thousands of miles letting the bad weather not be an obstruction to it flying at high altitudes during this long exceeding mission. With this, it showed what it could do, revealing the very nature of the sky it was able to go through and also how it could save energy.

This is a major breakthrough with far-reaching implications. According to Thunderhead, high-altitude platforms, or HAPS, can now be left in the sky for as long as or even longer than the small satellites orbiting close to the Earth (LEO satellites), while also being a more economical option. Satellites are quite expensive because they require rockets to carry them into space, and once they are deployed, they cannot be easily retrieved or modified. However, these Thunderhead balloons present a different opportunity. Doing

so will not be difficult. Simultaneously, you can address issues and even recall them after launch if necessary. This flexibility is crucial for rapidly changing tasks, such as providing emergency communication, monitoring border areas, or collecting scientific data from regions that are difficult to access or politically sensitive.

The Thunderhead platform is highly adaptable, meaning it can be quickly adjusted for different missions. Whether it's needed to boost LTE/5G networks, run radar, or gather weather and location data, it's up to the task. Thanks to its impressive staying power and agility, the Thunderhead is a top candidate for making persistent stratospheric infrastructure a reality.

Fundamentally, the Thunderhead Balloon System shows just how far HAPS technology has come. It doesn't just demonstrate what's technically achievable in the stratosphere, but also what's practical and affordable in today's world. This system proves that solar-powered, self-flying balloons are not just a dream – they're becoming a key part of the future of aerial and near-space systems.

2.5 Zephyr 78

AALTO's Zephyr platform exemplifies the best HAPS currently under development. This vehicle indicates the growing quality of solar-powered high-altitude long-endurance (HALE) drones, evidenced not only by its advanced technology but also by its actual representation. This aircraft serves as a prime example of the progress made in solar-powered HALE drones. It is designed for continuous operation, much like soldiers did while patrolling the frontier, responding to disasters, observing the natural environment, and relaying telecommunications. The Zephyr project can be seen as advancing high-altitude pseudo-satellites from experimental phases to the realization of commercial and operational applications.

The Zephyr is set to reach between 18 and 21 km (around 60,000 to 70,000 ft) altitude with its aerodynamically shaped high aspect ratio and precisely crafted lightweight airframe. These altitudes are defined as the lower stratosphere, which provides stable weather conditions, no commercial aircraft are rarely seen, and sunshine is plentiful. By flying at these heights, the Zephyr is capable of offering services in the whole wide geographical region, along with uninterrupted connectivity or sensor coverage for very long periods. With its featherlight weight, the Zephyr can take off at a slow speed of about 37 kilometers per hour, and usually it is already there in almost 10 hours.

Back in June of last year, a real feather in the cap was achieved by the Zephyr 78. This model managed to stay up in the air for a whopping 64 days straight during a test run. Even though some unexpected turbulence eventually brought it down, the mission was a huge success, proving that the Zephyr could do a lot of what it was designed for. This super-long flight was one of the best ever recorded for a solar-powered drone flying in the stratosphere. It really showed that these kinds of planes could fly high and independently for extended periods. With this, the Zephyr cemented its position as a top contender for becoming a key part of our near-space infrastructure.

In order to sustain lengthy deployments and accommodate future growth, AALTO has made investments in specialized infrastructure for launches and operations. They've revealed their intention to construct a stratospheric operations center in Laikipia County, Kenya, a spot picked for its advantageous weather patterns and constant access to the stratosphere throughout the year. AALTO anticipates initiating regular activities from this facility by 2026, with other international launch locations to be added afterward.

Their aim is to make Zephyr a globally applicable answer for airborne networks that offer low latency and high availability, serving to enhance—or sometimes substitute—satellite or ground-based alternatives.

2.6 PHASA-35

Besides the Zephyr, a breakthrough in the global HAPS area is PHASA-35 (Persistent High Altitude Solar Aircraft), a ground-breaking program by Prismatic Ltd. and BAE Systems that is. PHASA-35 is aimed at long-term solar-electric flight in the stratosphere for durations up to 180 days. This is the first time the mission to provide such services as surveillance, communication, and remote sensing has been launched.

The PHASA-35 drone is designed to fly at cruising heights of about 20 km (65,000 ft) and comes with a massive wing, a highly durable carbon fiber frame, and power systems that are well-suited for uninterrupted solar-electric propulsion. One of the features of PHASA-35 among its previous models is the modular and scalable design, which makes it possible to quickly change the payload that can be from the space tools for imaging and sensing, to broadband communication, and even to equipment for environmental monitoring that is specialized.

The first test flights have revealed that the performance of the plane is at a very high level. PHASA-35 managed to stay in the stratosphere for 24 hours, showing that the basic design and the energy systems are working well. However, the dimensions of the plane restrict it from going to the usual high altitudes where it supposedly stays for a long time. Like this aircraft, many others suffer from the same problem due to the existence of a turbulent zone in the troposphere, which causes difficulties in the ascent and descent.

The plane's design, which is very light and slow, is ideal for efficient travel at high altitudes, but it also makes it more vulnerable to weather issues and unpredictable air currents at lower levels. The engineers are still dedicated to developing a more robust aircraft and simplifying the flight controls to address and mitigate this weakness.

PHASA-35 is being tested at Spaceport America in New Mexico, however, spaceport sites are still being searched to optimize the climate conditions year-round. The objective should be to have it ready for use in 2028, and the subsequent version, although details are still secret, will be equipped with new technology that makes HAPS less vulnerable to turbulence without compromising the efficiency of the operation in the stratosphere.

Once operational, the PHASA-35 is expected to participate in a wide range of civil defense aerospace projects. The plane can potentially be used as a multi-purpose and budget-friendly replacement of satellites for tasks such as the real-time collection of data, the continuous monitoring of the situation, and the provision of communication services. The PHASA-35's capability to fly non-stop for a long time determines it as the most suitable candidate for undercover operations covering such unique and problematic areas without the common availability of regular planes which would be either too expensive or hampered by logistical issues.

2.7 Horus A

One of the latest and most outstanding occurrences in the field of HAPS is the Horus A project by AeroVironment. This company is known for its long tradition of developing unmanned solar aircraft filled with creative ideas. The technology of Horus A is based on

earlier models like the Helios Prototype and SunGlider. However, this move marks a significant step in the evolution of HAPS. While keeping the core aspects of previous models, for example, light materials, solar energy, and the ability to stay at a high altitude for a long time, Horus A has gone to raise the bar with new features. These are intended to facilitate the complex applications of monitoring, communication, and science.

One of the main reasons why Horus A stands out is that it has been upgraded in many areas, especially the payload capacity. What this implies is that such a platform could allow the incorporation of a variety of more sophisticated devices that have different features such as high-resolution sensors, communication relays, and maybe even radar. This increase in efficiency not only makes it possible for the platform to cover more tasks, but it also extends the range of applications to which the system can be applied, from the surveillance of civil infrastructure to the performance of long-term intelligence surveillance and reconnaissance (ISR) missions for defense purposes.

Moreover, enhanced solar collection and energy storage technologies also played a vital role in the increase of the drone's onboard power. Simply put, these two technologies make it possible for the drone to have a night flight and, in general, to be able to execute long missions with very high power demands.

One of the very important aspects is that the Horus A platform has successfully passed a series of major regulatory milestones. To be more specific, this platform was recently approved by the FAA and the U.S. Army to conduct flight tests in the national airspace of the United States. This is a very important turning point, if we take into account the quite intricate rules for unmanned, high-altitude vehicles. Actually, these official authorizations granted to Horus A just confirm that it is a HAPS vehicle which, among the very few can be performed in the open at a safe, efficient and lawful manner.

Details about the performance and the mission are still unknown, but some initial signs suggest that the Horus A has already been test flown for the military. It is possible to assume that a defensive strategy using Horus A is in the works. This is consistent with the worldwide trend of utilizing high-altitude platforms for continuous, almost real-time, and easy communication or data storage, mainly in the situations where there is no infrastructure or it is not trustworthy.

Horus A represents a significant leap forward in the evolution of solar-powered HAPS, potentially marking a gradual shift from the experimental phase to truly practical technology. The development of Horus A not only signifies progress but also demonstrates the skill and adaptability of unmanned solar aircraft, confirming the inevitability of the stratospheric platform function. As the demand for flexible, long-endurance aerial vehicles continues to increase in both civil and military sectors, the Horus A project stands out as a crucial first step in the journey toward realizing scalable high-altitude unmanned systems.

2.8 Comparative Overview of Modern HAPS Platforms

To contextualise the evolution described in the previous subsections, it is useful to compare the main characteristics of the modern HAPS platforms developed over the last two decades. Although each programme was designed for a specific mission set and operated under different regulatory environments, all share a common aerodynamic lineage that can be traced back to early pioneers such as Helios.

Platform	Wingspan	Mass	Operational Altitude	Endurance	Propulsion	Distinctive Features
Zephyr (AALTO/Airbus)	~25 m	~75 kg	18 – 21 km	30-60 days	Solar-eletric	Most mature multi-week stratospheric performance
PHASA-35 (BAE Systems)	35 m	~150 kg	~20 km	Target 180 days	Solar-eletric	Modular design; scalable payload
Sunlider (AeroVironment /HAPSMobile)	78 m	>2 000 kg	~19 km	Multi-day	Solar-eletric	High payload; advanced powertrain
Horus A (AeroVironment)			~18 km	Multi-day	Solar-eletric	Next-generation payload capacity
Thunderhead Balloon (Aerostar)			~18 km	300+ days	Solar + wind navigation	Longest-duration stratospheric platform to date

Table 2.1 - Comparative Overview of recent HAPS

This comparative overview shows a clear evolution from experimental demonstrators to operationally credible platforms, with Zephyr and Thunderhead representing the most advanced endurance achievements in fixed-wing and balloon systems respectively.

2.9 Aerodynamic and Environmental Challenges in Stratospheric Flight

Although each project achieved significant milestones, all faced the fundamental aerodynamic and environmental challenges inherent to the stratosphere:

Low Air Density

At altitudes above 60,000 ft, air density is less than 10% of sea level. Large wingspans, low wing loading and efficient propulsion are therefore essential to generate sufficient lift.

Structural Flexibility and Aeroelasticity

High-aspect-ratio wings, essential for efficient flight, are inherently flexible. Aeroelastic coupling, gust response and flutter risks remain central engineering challenges.

Wind Shear in the Tropopause Region

The ascent and descent phases are often more dangerous than cruise. Sharp wind gradients in the tropopause can induce structural loads and destabilise lightweight airframes.

Energy Constraints

Solar-powered HAPS depend on:

- high photovoltaic efficiency
- favourable sun angles
- sufficient battery mass for night flight
- strict energy management

Winter, high latitudes and cloudy environments remain difficult operational scenarios.

Thermal Extremes

Batteries and avionics suffer severe performance degradation at -40°C to -70°C , requiring constant thermal management that consumes part of the energy budget.

These constraints help explain the difficulties encountered in Helios (structural failure), Sunlider (limited altitude), and PHASA-35 (weather-sensitive ascent).

2.10 Technology Readiness Level (TRL) Assessment

Assessing the maturity of HAPS technology requires examining the readiness of each subsystem:

Subsystem	TRL	Justification
Aerostructures	7–8	Multi-week endurance flights validated (Zephyr)
Solar Power Systems	6–7	High efficiency but weather-dependent
Energy Storage (Batteries)	6	Limited low-temperature cycle data
Avionics & Autonomy	6–7	Mature but not fully certified globally
Command-and-Control Links	6	Reliable but not integrated into aviation standards

Table 2.2 - TRL Assessment

The overall system TRL for current HAPS platforms sits between 6 and 7, indicating a transition between demonstration and early pre-operational capability—consistent with the missions carried out by Zephyr, Sunlider and Thunderhead.

2.11 Synthesis and Transition to Regulatory Context

The historical and technological progression of HAPS—from early solar demonstrators like Helios to long-endurance platforms such as Zephyr and Thunderhead—highlights both the enormous potential of stratospheric aviation and the persistent challenges that prevent routine operations. As these platforms increasingly demonstrate multi-day or even multi-month endurance, the regulatory and governance framework required to integrate them safely into higher airspace becomes critical. The next chapter therefore

examines the current international regulatory landscape and identifies the structural gaps that must be addressed to support future HAPS operations.

3. Regulatory Framework

With the rising prominence of HAPS from just being experimental prototypes to becoming feasible operational tools for civil and other defense applications, the question of regulatory integration also becomes increasingly important. The intricacy of HAPS conquering the space above the usual aviation traffic and yet remaining below the satellite orbital altitudes has raised the need for new rules yet to be incorporated into the available civil aviation regulations. Different safety, security, and defense activities, and the operation of telecommunications and environmental monitoring can be undertaken with the help of UAVs. However, they should be flown in compliance with the law through clear regulations, structured management, and cross-border cooperation.

Although HAPS are still operating in a regulatory grey zone, several institutions have recently begun to recognise the need for a structured framework for higher airspace operations. ICAO, EASA and FAA have each published preliminary guidance or concept papers addressing high-altitude unmanned aircraft, but none of them currently provide a complete or harmonised set of rules. This fragmentation results partly from the long regulatory cycles typical of international aviation governance: ICAO amendments often require five to seven years to progress from initial proposal to formal adoption, meaning that any future HAPS-specific standards will not become operational for several years.

Currently, there are no necessary or available international regulations for HAPS operations in the stratosphere. This concern remains within the purview of various regulations from different aerial sources, and those regulations are limited in this context. As a result, the circumstances only permit the extremely challenging task of achieving long-endurance, unmanned, solar-powered systems operating in the upper layers of the atmosphere in a real-world environment.

3.1 Current Regulatory Situation

HAPS, like all other aircraft, are mandated by ICAO to strictly follow the laid-out rules, especially those related to take-off, climb, descent, and landing, which usually take place within controlled airspace. Defining the airspace in terms of classes, ICAO Annex 11 indicates that the airspace is comprised by seven classes (A to G), with Classes A through E labelled controlled and Classes F and G uncontrolled. Flight operations inside the controlled space are possible by following strictly the rules of the Air Traffic Services (ATS) such as, for example, the flight plan, the transponder operation, and coordination with the Air Traffic Control (ATC).

In the European region, the rules that are in place for the regulatory environment are handled through EASA by documents like the Standardised European Rules of the Air (SERA). Notably:

- SERA.6001 mandates that aircraft operating in Classes A to D must have explicit ATC clearance and maintain continuous air-ground communication.
- SERA.4001 requires a filed flight plan in advance of operations, particularly when subject to Air Traffic Flow Management (ATFM).
- SERA.8020 obliges aircraft to follow their filed flight plan, except in emergencies or under direct ATC instruction.

- SERA.13001 enforces the use of Secondary Surveillance Radar (SSR) transponders for aircraft so equipped, ensuring situational awareness and identification.

Additionally, ICAO Annex 6 primarily provides rules for airworthiness and flight preparation that also encompass HAPS in an indirect manner. One of these conditions is the cockpit coverage of adequate instrumentation, navigation, and energy systems, in addition to topics such as atmospheric conditions, oxygen systems, and emergency procedures, which concern all flights at altitudes where atmospheric pressure and temperature differ significantly from those encountered in standard commercial aviation.

While the ICAO does not generally ban flights beyond FL600, the upper sky (above 18 km, approximately 60,000 feet) is usually assigned for military and research usage, and there is also no established flight operation for civil UAVs, hence higher. So, an HAPS mission that aims to fly in such places has to get permission from the national aviation authorities. Following that, it is often the case that this type of authorization needs to be made through the case-by-case method, which, in turn, is very costly of time and energy, as it may require the operator to get in touch with the relevant authorities.

It is important to note that the three main regulatory spheres—ICAO at global level, EASA within the European region, and the FAA in the United States—currently follow different approaches to higher-altitude operations. While ICAO provides no altitude ceiling and treats anything above FL600 largely as uncontrolled, EASA has explicitly recognised the need for a HAO framework within its roadmap for 2030. In contrast, the FAA relies almost entirely on waivers, experimental certificates and mission-tailored authorisations, which is why most stratospheric flights in the United States proceed on a case-by-case basis.

These differences illustrate why operators planning long-endurance HAPS missions often must navigate three incompatible regulatory philosophies depending on the jurisdictions involved.

Authority	Regulatory Scope for Higher Airspace / HAPS	Key Documents & Tools	Current Approach	Main Limitations
ICAO	Global regulatory framework for international civil aviation; does not provide detailed rules for operations above FL600.	<ul style="list-style-type: none"> • ICAO Doc 10171 – <i>Manual on Higher Airspace Operations (HAO)</i> • Annex 2, Annex 6, Annex 11, PANS-ATM 	Conceptual and strategic guidance. ICAO acknowledges the need for a new regulatory layer for higher airspace but is still in early stages of development.	<ul style="list-style-type: none"> • Very long regulatory cycles (typically 5–7 years). • Does not define a legal boundary between airspace and outer space. • No specific standards for unmanned persistent operations in the stratosphere.
EASA	Regional regulator for EU Member States; covers UAS, airworthiness, ATM, and flight operations.	<ul style="list-style-type: none"> • SERA (Standardised European Rules of the Air) • EASA High Altitude Operations (HAO) roadmap (2030+) • Part-UAS, Part-21 	Structured, medium-term development of a dedicated High-Altitude Operations framework. Emphasis on future certification pathways and integration in ATM systems.	<ul style="list-style-type: none"> • No HAPS-specific certification basis yet. • Dependent on ICAO harmonisation for international flights. • Operational approvals still handled case-by-case.
FAA	National regulator for the United States; responsible for experimental aircraft, UAS, and special airspace missions.	<ul style="list-style-type: none"> • FAA Part 91 (general operations) • Experimental Certificates • Special Airworthiness Certificates • Mission-specific waivers 	Predominantly case-by-case authorisation for HAPS missions. FAA prioritises operational permissions over long-term standardisation.	<ul style="list-style-type: none"> • No dedicated regulatory category for stratospheric unmanned platforms. • Heavy reliance on waivers slows large-scale deployments. • Lack of integration with military high-altitude operations.

Table 3.1 - Comparative overview of HAPS-related regulatory approaches (ICAO, EASA, FAA)

In practical terms, ICAO focuses on conceptual guidance, EASA is developing a structured method toward future certification and ATM integration, and the FAA prioritises operational approvals over long-term rulemaking. While none of these approaches currently deliver a complete solution, together they highlight a global trend: the recognition that stratospheric operations require a dedicated regulatory treatment distinct from both conventional aviation and low-altitude drones.

3.2 Challenges for HAPS

One of the main regulatory problems encountered by HAPS is that of an undefined legal regime of the upper airspace. Between the upper limits of controlled commercial aviation and the internationally recognized boundary of outer space (usually defined by the Kármán line at 100 km of altitude), there is a layer of airspace that still lacks applicable rules, yet the use of new aerial technologies keeps rising.

The "grey area" in question is confined between the Kármán line that is taken as the start of space at 100 km and the FL600 defining the upper limit of controlled airspace (Classes A to E). Hence, the work zone for HAPS remains this non-controlled space, as shown in Figure 2, which depicts the principal layers of the atmosphere with their respective regulatory classifications.

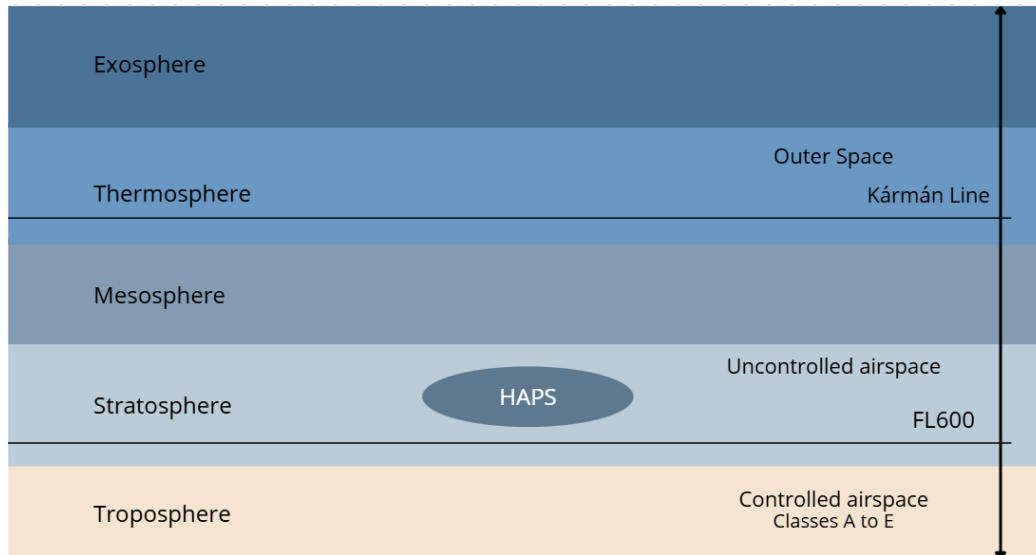


Figure 3.1 Representation of airspace layers and the operational region of HAPS between controlled and uncontrolled airspace.

HAPS are typically operated in the stratosphere, which is an area that is not usually used and does not have civil aviation regulations. This situation indicates that these aircrafts will be not only available at a particular altitude but also at the lower level, which varies greatly in each area concerning performance, mission duration, and flight dynamics.

Due to their nature HAPS are also most often called under the same UAS (Unmanned Aircraft System) regulations. Nevertheless, the existing rules were mostly written with the expectation of short-distance drones running at low altitudes, and they do not fit the characteristics of HAPS platforms that require high altitude, large scale, long endurance, and autonomy. As an example, there is no ATM (Air Traffic Management) system at present that can take over the control of continuous unmanned operations in the stratosphere, nor any provisions for HAPS to interoperate smoothly with the military, the launch of rockets, or hot-air balloons.

The situation is even more confusing due to the absence of agreements on the vertical line that separates the atmosphere from outer space, which is a matter of state sovereignty, liability, and jurisdiction. In the absence of precisely defined borders, it is still unclear where legal issues crop up. For example, whether HAPS are obligated to observe the aviation law strictly or, depending on the altitude, they can still enjoy some parts of the space law.

Other key regulatory challenges include:

- The absence of dedicated certification pathways for the airworthiness and operational approval of HAPS;
- The need for a new ATM concept to manage mixed traffic (manned/unmanned, civil/military) across all layers of airspace;
- The requirement for civil-military coordination mechanisms, particularly in regions where national security may be impacted by persistent aerial platforms;

- Emerging issues in cybersecurity, command and control (C2) links, and data protection associated with long-endurance, autonomous missions.

Unless a dedicated and comprehensive regulatory framework is developed – one that probably involves coordination among ICAO, EASA, national authorities, and even space agencies – HAPS operators will still find themselves in a fragmented regulatory landscape full of administrative burdens and operational uncertainties.

4. Future Regulatory Pathways

With the technology of HAPS improving and their operational relevance expanding, the inadequacy of the existing aviation regulatory frameworks is becoming more and more visible. These systems have revealed the capability of continuous, unmanned flight in the stratosphere for weeks or even months without interruption, carrying out tasks traditionally performed by ground-based, airborne, and even satellite systems (EASA, 2023; Pohling et al., 2023). Nevertheless, the altitude they operate at, the outline of the mission, and their unmanned characteristics make them beyond the scope of rules aimed at conventional civil aviation. The consequence is a legal and procedural space where, if not addressed promptly, the safe and scalable deployment of HAPS may be jeopardized.

To solve this, global regulators are in the process of acknowledging the need for a different airspace management model that outlines and controls the peculiarities of Higher Airspace Operations (HAO) in the new airspace. These initiatives are in the infancy phase, nevertheless, they signify a major milestone in the history of airspace management and also indicate a wide agreement that the upper regions of the sky cannot be left legally uncertain or functionally unrecognized anymore (EASA, 2023; ICAO, 2022).

4.1 Higher Airspace Operations (HAO) Initiatives

The increasing deployment of such platforms as HAPS, high altitude balloons, reusable suborbital launch vehicles, and near-space aircraft has led authorities to the idea of creating a separate airspace segment – sometimes called higher airspace – that usually starts at FL600 (18 km \cong 60,000 feet) and goes up to the point where space begins (EASA, 2023; ICAO, 2022). In this vertical corridor, the conventional ATM rules are no longer feasible, and the new performance-based, technology-neutral regulations are very much required.

In June 2023, EASA published a comprehensive regulatory roadmap for HAO. The roadmap, clearly stating that a new regulatory environment for the management of the airspace beyond the traditional civil aviation is necessary, also indicates that it is necessary to create such a system that allows for the new entrants, which are not only HAPS, but also suborbital spaceplanes, long-endurance balloons, and reusable launch systems, to be present in the airspace (EASA, 2023).

This document outlines four primary areas of focus for future regulation:

1. **Airworthiness and Certification** – Setting up special licensing processes to accommodate the unique characteristics of high-altitude, unmanned, solar-electric aircraft, which greatly differ from both satellites and drones.
2. **Airspace Integration and ATM Frameworks** – Built highly scalable and secure infrastructure that enables blended traffic coordination at the stratosphere and has capacity for unmanned operations that have long flight durations.
3. **Cybersecurity and Communications** – C2 links that are secure and safe are operated under agreed upon standards, and highly reliable and resilient to attacks communication networks are created, which is essential for the functioning of autonomous flights over international territories.
4. **Civil-Military Coordination** – Drafting new procedures for cooperative use of airspace between civil HAPS operators and military authorities, taking into consideration the highly sensitive nature of the operation.

In line with these objectives, the Specific Operations Risk Assessment (SORA) framework developed by Joint Authorities for Rulemaking on Unmanned Systems (JARUS) and adopted by EASA serves as the primary mechanism for approving high-altitude platform operations within the 'specific' category. Nikodem and Kaltenhäuser (2020) describe SORA as a structured, risk-based assessment methodology, while also highlighting its limitations for HAPS. Originally designed for conventional unmanned systems such as multi-rotor or medium-sized fixed-wing drones, SORA requires interpretive adaptations to address HAPS-specific features, including extremely high altitudes, long-endurance missions, and complex airspace transitions.

Moreover, Nikodem and Kaltenhäuser (2020) note that within the SORA framework, operations exceeding certain risk thresholds—such as those with a Ground Risk Class greater than 7—fall outside its standard scope. For such missions, particularly those over inhabited areas or disaster zones, special approvals are required rather than standard SORA-based authorization. This limitation highlights a regulatory gap that HAO initiatives aim to address.

The authors further propose that future regulatory approaches incorporate 4D-operational volumes—predefined spatial and temporal blocks—and Unmanned Traffic Management (UTM) systems to enable safe, coordinated flight paths in sparsely trafficked high-altitude airspace. Such strategies would minimize conflict risk and provide structured integration of HAPS operations, especially since traditional tactical mitigations, such as real-time ATC interventions, become ineffective at these altitudes (Nikodem & Kaltenhäuser, 2020).

At the global level, ICAO has also confirmed the trend of HAO at the 41st Assembly, which took place in July of 2022. The assembly focused on the role of collaboration among regulators, governments, and international organizations in the provision of safe, efficient, and just use of higher airspace. In addition, ICAO has unleashed a call to its members to be the co-creators of the global consistent standards to be implemented while the work is being conducted in this sphere, thus highlighting the need for the international coordination of the unregulated space of the law (ICAO, 2022).

These initiatives are specially valuable because there is a growing commercial market for high-altitude platforms in various industries such as telecommunications, observing the Earth, disaster management, and security. But on the other hand, such activities would put the ecosystem in a great danger and might end up being illegal or inconsistent or even banned if there are no regulations to guide them. The situation would be challenging if the HAPS were used in several jurisdictions or transnational airspaces (EASA, 2023; Pohling et al., 2023).

There is no doubt that the higher atmosphere definition and management have become inevitable rather than optional if we want to have a sustainable and expandable future with stratospheric flight. The first steps that EASA and ICAO have taken are important progress, however, the erection of a comprehensive regulatory framework would still have to require more collaboration, ingenuity, and foresight — especially if the number and diversity of the high-altitude operators keep growing.

4.2 Space vs. High-Altitude Operations

The most inconspicuous aspect of air to space law is an issue of HAPS operations. The core of the problem is the question of whether there is a distinction or the same between the airspace and the outer space. Commercial air traffic below FL600 is very well

regulated, and space activities are managed under the terms of special treaties (for example, the Outer Space Treaty of 1967 (United Nations, 1967) but the space between the two is still legally and conceptually unclear.

It is not that the question about where the airspace is over and space is beginning has never been resolved in international law. The Kármán line (at the height of 100 kilometers) is a place that is most often mentioned as a boundary of space, however, this is a scientific convention and not a legal obligation. As a result, states are still allowed to assert that they retain control over their airspace to an unlimited height which as a result causes uncertainty for HAPS operators (McDowell, 2018).

The uncertainties in the law lead to a number of relevant challenges:

- **Jurisdictional Clarity:** HAPS systems that drift across borders — especially balloons or solar-powered UAVs on long-duration missions — may inadvertently violate the airspace that other countries have rights to along with which there may be no clear rules of engagement or notification protocols.
- **Regulatory Overlap:** Some activities at very high altitudes might cause a way of overlapping regulations that is similar to the space sector ones, especially regarding licensing, liability, and insurance, but the craft is not going out of the Earth's atmosphere.
- **Safety and Liability:** Due to the fact that there is no clear altitude range that is set as a limit, therefore, there is no legal framework available, which clearly states who is responsible in case of an accident, collision or data leakage, during an incident with a high-altitude vehicle (McDowell, 2018).

Practically speaking, the difference between high-altitude aviation and space flights has a very direct impact on certification, supervision, and international cooperation. To illustrate, a HAPS vehicle at the altitude of 70,000 feet is obligated to follow aviation laws, including the use of ATC, the making of a flight plan, and radio communications; however, it might also have to have self-defense equipment, be under the control of the export authorities, or be in the process of military coordination if the payload and the mission require so (EASA, 2023; Pohling et al., 2023).

The situation is getting even more complicated because of the “near space” or “higher airspace” concept that was featured in the Nikodem & Kaltenhäuser article. Controlled airspace is generally designated up to FL600 or FL660 depending on the state or country, however, there is not a single upper limit for national airspace that is agreed upon globally. The HAPS that function at altitudes between 20 and 25 km (65,000 to 82,000 feet) are right in this uncertain area of the sky (Nikodem & Kaltenhäuser, 2020).

Nikodem and Kaltenhäuser (2020) indicate some of the operational difficulties in this area, such as the fact that tactical air traffic control is no longer possible because of the sparse infrastructure and limited detectability of high-altitude vehicles. Detectability of these vehicles is very limited, especially if they are military ones. This also makes the need for regulatory clarity doubly important. They claim that trustworthy detectability (for example, through transponders), continuous communication with ATC, and emergency descent procedures that are agreed upon in advance should be the main parts of the future frameworks.

In addition, to go up or down, HAPS still have to cross several ICAO airspace classes (A to D), that normally call for Visual Flight Rules (VFR) or Instrument Flight Rules (IFR) observance – both of which are very hard or even not possible for the unmanned HAPS. The writers propose that HAPS could carry out their flights utilizing other procedures,

where they have less equipment and rely more on the situation awareness of the remote pilot and the strategic deconfliction (Nikodem & Kaltenhäuser, 2020).

The growing number of platforms that can conduct both civil and military missions, makes it even harder to distinguish air and space operations. This dual characteristic of the platforms not only extends the problem but also increases the necessity of having consistent legal terms and operational standards, which take into consideration the confidential nature of the situation and the technical differences of the vehicles working in the upper atmosphere (EASA, 2023; ICAO, 2022).

Ultimately, the governance of high-altitude operations will be influenced not only by innovation, but also by the readiness of the global community to create an agreement on the changing traditional boundaries, both in terms of the sky and the law. With the increasing number of HAPS and other stratospheric vehicles, the authorities need to implement a more accommodating, multi-level, and universally consistent regulatory framework – which not only acknowledges the stratosphere as a transition area between the domains but also as a space where operations can be conducted.

5. Technical and Operational Challenges

HAPS represent a transformative leap in aerospace technology—merging the endurance and reach of satellite systems with the flexibility and responsiveness of unmanned aerial vehicles. These platforms can be independent in the upper atmosphere for a very long time (several weeks to months) and carry on activities such as environmental monitoring, disaster response, maritime surveillance, telecommunication, and many more. But the development of their functionality to the extent of maturity attracts a whole bunch of complex technical and operational problems, most of which are about the limitations of the present civil aviation infrastructure and regulatory paradigms.

As HAPS start to take a significant position in the global aerospace ecosystem, it is necessary to know and deal with these difficulties not only from technical point of view but also in terms of airspace integration, safety assurance, and mission resilience. The rest of this chapter describes the challenges in detail. It particularly concentrates on those areas where the new challenges overlap with the current airspace management systems and risk-assessment methodologies. In addition, it focuses on the engineering necessities needed to establish a dependable, secure, and scalable installation.

5.1 Regulatory Implementation Gaps and Framework Limitations

The main challenge facing the implementation of HAPS is among others the lack of a regulatory framework that is truly suitable for the purpose. The Specific Operations Risk Assessment (SORA), a document created by JARUS and accepted by EASA as an acceptable means of compliance in the 'specific' risk category, has become the primary tool for UAS risk assessment. Nevertheless, SORA was initially intended for the unmanned systems which are conventional in nature and operate at lower altitudes and for shorter periods of time, like small to medium rotary or fixed-wing drones (Nikodem & Kaltenhäuser, 2020).

By extending SORA to HAPS, its weaknesses become obvious. Many of the mitigation measures that it suggests, such as ground risk buffers, impact-energy reduction devices, and emergency response plans, are not only impractical but also inappropriate in scale for vehicles that are operating at altitudes of about 20 km. Just as an example, a one-to-one ground risk buffer would mean that there should be no human activity within a 20 km radius under the area of the HAPS flight path (Nikodem & Kaltenhäuser, 2020). Furthermore, conventional impact mitigation (e.g., parachute deployment) fits awkwardly with ultra-lightweight, solar-powered designs that are limited in mass and energy budgets (Nikodem & Kaltenhäuser, 2020).

Because of this, those who want to get the mission approvals for HAPS in the specific category are very often forced to make an interpretive use of SORA, together with justifications and negotiations with local aviation authorities. In situations where the risk that cannot be eliminated is still very high – for instance, when flights are done over crowded places or during the spread of disasters – issuance of special permits might be necessary, apart from the standard procedure of regulation (Nikodem & Kaltenhäuser, 2020). This regularity mismatch represents a significant challenge for everyday activities, highlighting the immediate need for creating HAPS-specific risk assessment methods that are consistent with the particular features of these vehicles and their operations.

Given that HAPS integration requires coordinated action across civil aviation authorities, defence institutions, international regulatory bodies, and industry partners, understanding the distribution of responsibilities among these actors becomes essential. To clarify how the proposed hybrid governance model (EASA + EUROCONTROL + national authorities) aligns with the existing institutional landscape, the following stakeholder map summarises the key organisations involved and the roles they typically play in regulatory development, certification, operational management, and civil-military coordination.

5.2 Transition Through Controlled Airspace

Another important operational problem is very much in the nature of a vertical movement of HAPS in the whole controlled airspace during the going up and coming down. Usually, going up and coming down are the most sensitive parts of a flight as a result of passing through the different airspace classes therefore it might be necessary to undergo ICAO classes A to D. Each of these classes has a very strict separation standards and necessary equipment requirements. Operations within these classes in the context of international aviation law normally require compliance with either IFR or VFR (Nikodem & Kaltenhäuser, 2020).

To address the problem, scientists suggest that the airspace should be limited or temporarily separated in the area where the HAPS are climbing and descending (Nikodem & Kaltenhäuser, 2020). Moreover, the practical implementation of this concept is definitely possible, however, it still leads to increased management burdens for airspace and may cause disturbances in normal traffic. In addition, the process of setting up and managing such corridors is always subject to rules agreed upon by civil and/or military authorities, which is an obstacle to achieving flexibility in real-time and quick mission deployment.

This challenge is really made worse by the fact that the descent phases might take place in emergency or energy-saving situations (such as controlled glides to save power at night), thus actually raising the requirement for exact coordination and set flight corridors to be used.

5.3 Communications, Control, and Detectability

Dependable and safe communication with ATC is essential for an aircraft to be safely integrated into managed airspace. Nevertheless, HAPS are under very strict restrictions with regard to weight, energy, and space, which restrict their capability to transport traditional avionics suites (Nikodem & Kaltenhäuser, 2020). To give an example, civil aviation standards require the use of double-redundant VHF radios and other transceivers – standards that are not only unnecessary but also often not suitable for HAPS that are light and powered by solar energy.

As a means of finding a middle ground, it has been suggested that HAPS use single VHF units together with secure satellite or cellular networks, thus retaining the necessary dual-channel communication but in a more minimalist form (Nikodem & Kaltenhäuser, 2020). Although such a choice may be in line with the functional equivalency provisions, the acceptance of local authorities and the existence of agreed operational concepts would still be required. Moreover, keeping the situational awareness intact through telemetry and remote monitoring is very important, especially during the phases of the flight within or near controlled airspace.

Another challenge is related to detectability. High-altitude airspace is less crowded, but military and high-performance civil aircraft may still be operating in these areas. Not all of these vehicles are fitted with systems that can detect those without transponders. To reduce the risk of conflicts, HAPS need to have surveillance equipment that is compatible, for example, transponders and operators need to keep talking with ATC about their position and their plan, not only in places where they have ATC services but also in places where there are no services (Nikodem & Kaltenhäuser, 2020).

5.4 Emergency Procedures and Platform Reliability

Emergency procedures, and more specifically emergency descent protocols, introduce additional operational challenges. HAPS, unlike crewed aircraft, cannot directly interact with the pilot or ATC for an emergency, so they have to rely on remote pilot commands or pre-programmed procedures. Such a situation makes the systems that enable status monitoring, anomaly detection, and communication with ATC during emergencies very important (Nikodem & Kaltenhäuser, 2020).

HAPS missions with very long endurance, possibly 100 days or more, require that reliability is demanded of all critical systems to a very high degree. These platforms, which have no full type certification, still, however, must be able to operate with failure rates below 10^{-4} per flight hour if they are to be feasible (Nikodem & Kaltenhäuser, 2020). Meeting this level of reliability means using cutting-edge materials, designing systems that can tolerate faults, and carrying out environmental tests to confirm the ability to cope with extreme temperature changes, UV radiation and low pressure in the stratosphere.

5.5 The Case for Strategic Traffic Management

Finally, conventional tactical ATM systems are inappropriate for the near-space region where HAPS operate. ATC's real-time, reactive control is limited by restricted radar coverage, communication delay, and the low number of vehicles at high altitudes. Therefore, scholars suggest that the 4D-operational volumes – space-time intervals in which a particular vehicle is operated, are used so that the vehicle is continuously monitored and there will be no conflicts in the air through strategic planning (Hsieh et al., 2020; Nikodem & Kaltenhäuser, 2020).

These methods are consistent with the new ideas of Unmanned Traffic Management (UTM) and U-Space that talk about automation, pre-coordination and multi-source surveillance integration. Through the use of 4D operational volumes and UTM services, HAPS missions can keep the space safe and stick to the known plan even in the less regulated parts of the sky.

Not only do these obstacles reveal the requirement that substantial changes in regulatory frameworks, operational procedures, and technology development, which all must be coordinated, are needed to really benefit from HAPS. These issues are not just problems for the experts to solve by technical means only, but also to rethink in a new way of how the space above the earth at such height and how the certification of unmanned systems and their integration into civil aviation is carried out.

Developing the regulations to not only recognize the risk profiles tailored for HAPS but also the action taken to reduce the risk, the utilization of more sophisticated engineering solutions to overcome the barriers of communication, visibility, and reliability, and the

invention of pragmatic traffic management like 4d-operational volumes and harmonized UTM systems will be the next step. Only by such coordination can vast potential of safe, reliable, and scalable high-altitude platform operations be unlocked, leading to the continued presence of stratospheric services that will help disaster response, environmental monitoring, communications, and global connectivity for a long time.

6. Strategic Roadmap for the Integration of HAPS

The earlier chapters got into the details of the technological evolution of HAPS (chapter 2), the regulatory framework in place or that does not exist for their activities (chapter 3), as well as the future pathways being explored at the global level (chapter 4). Chapter 5 dealt with the technical and operational issues that have emerged and need to be resolved for the demonstration of HAPS.

This chapter is no longer about descriptive analysis and literature review but rather presents the innovative, organized strategic roadmap for the implementation of HAPS in space.

The main goal is to show real ways, key phases, and administration systems that could make it easier for the world community to work together in exploiting HAPS to the maximum while at the same time ensuring safety, security, and the peaceful settlement of regulations.

By means of this roadmap, the chapter aims to outline a practical course of action for the regulators, industry players, and policymakers to transition from fragmented, experimental applications to a single, operating ecosystem that not only is efficient in providing uninterrupted connectivity, but also in environmental sensing and disaster response locally, regionally, and globally.

6.1. Introduction

HAPS have made almost unbelievable technical progress over the past several years, with record-breaking endurance and coverage capabilities for prototypes and early commercial platforms. The regulatory environment in the area, however, is still quite green, which results in a patchwork of situation-dependent authorizations and, therefore, significant operational uncertainties.

Moreover, the challenges that were both technical and operational in the case of the stratosphere inclusion are also outlined in Chapter 5. Some of these challenges include certification gaps, limitations of managing the airspace, and the required coordination between the civil and military sectors that necessitate a thoughtful, coordinated, and multi-dimensional approach.

This chapter's main goal is to build a step-by-step plan which:

- Specifies unambiguous routes for the integration of regulatory, technological and operational integration;
- Uncovers main milestones and schedules to steer the coordinated development;
- Considers the governance models for the international collaboration and the standard-setting;
- Evaluates the dangers and compromises that come with other plans of action;
- Facilitates decision-making based on facts by means of an organized examination (SWOT).

In addition, this chapter strengthens the link between the strategic pathways proposed and the regulatory and technological realities previously identified, ensuring that each proposed action is justified by concrete dependencies, institutional responsibilities, and realistic implementation timelines derived from ICAO and EASA cycles.

This roadmap is not meant to dictate a single, inflexible answer; rather, it provides a versatile, multi-tiered approach that acknowledges that simultaneous development in several areas is necessary while at the same time the structured framework for harmonizing stakeholder efforts, deacrising risks, and being sure that HAPS can fulfil their revolutionary promise for world communication, monitoring, and research enables this.

To support this, explicit references to technological maturity levels (TRL), risk mapping, and civil–military coordination requirements are incorporated throughout the chapter, ensuring a more operationally grounded and less conceptual roadmap compared to earlier sections.

6.2. Strategic Pathways and Milestones

After inspecting the regulatory framework in Chapter 4 and the technical and operational problems in Chapter 5, this chapter portrays a plan as a method of the strategy pathways to the secure use of HAPS in the atmosphere above the earth.

The suggested pathways are designed to deal with the regulatory confusion, gaps and the lack of technological maturity which have been outlined earlier. A number of indicative milestones and timelines are also included in each of the paths to show the stages and the involvement of various actors needed for the successful implementation of these changes.

In the acknowledgement that the complex operational, regulatory and technical challenges discussed in chapter 4 and 5 cannot be solved by one strategy only, this roadmap is a layered, parallel approach preference. The idea is to have several paths operating in parallel while mutually learning and supporting each other.

To reinforce methodological rigor, the selection of these pathways follows three criteria: (1) direct relevance to the regulatory gaps identified in Chapter 4; (2) alignment with technological and operational constraints highlighted in Chapter 5; and (3) coherence with ICAO and EASA regulatory development cycles.

Additionally, each pathway now explicitly identifies technological dependencies, indicative TRL levels, and the institutional actors responsible for implementation, ensuring a stronger link to the roadmap.

6.2.1 Pathway 1: Incremental Integration Using Existing Frameworks (2025–2030)

In Chapter 4.1 it was stated that the current ways of getting approval are based on the idea of changing the systems that exist such as the Specific Operations Risk Assessment (SORA). Even though SORA was initially created for short-range, low-altitude operations (Chapter 5.1), it is still the only viable solution for quick implementation.

This pathway is therefore dependent on short-term technological readiness (typically TRL 6–7 for HAPS prototypes) and on the capacity of national authorities to interpret SORA consistently. It also represents the lowest-barrier entry point for early operational testing, making it a crucial foundation for gathering real-world performance and safety data that will later support Pathways 2, 3 and 4.

Milestones:

- 2025: Harmonized guidance material for interpreting SORA for HAPS, coordinated by EASA.
- 2026: Establishment of national-level procedures to streamline case-by-case approvals.
- 2028: Integration of lessons learned into updated risk assessment frameworks.

Responsible Entities: primarily EASA and national aviation authorities, with ICAO supporting harmonisation at international level.

Key Dependencies: development of consistent risk-classification criteria; availability of reliable Command and Control (C2) links; initial detect-and-avoid concepts adapted to stratospheric climb and descent.

Rationale:

This route allows early performance capability and real-world data collection as regulatory systems are changing. It also reduces the risk of technological inertia but at the same time, if not properly coordinated, it could deepen the divisions of local approaches and thus have a negative impact on the situation (as pointed out in Chapter 4.2).

Additionally, reliance on SORA alone presents the risk of maintaining a fragmented approval landscape. For this reason, this pathway is explicitly linked to the early phases of the roadmap (Figure 6.2), where incremental approvals serve as a bridge until the HAO framework (Pathway 2) reaches maturity.

6.2.2 Pathway 2: Higher Airspace Operations (HAO) Regulatory Framework (2025–2032)

Chapter 4.1 has shown that the EASA 2023 roadmap and the ICAO's 41st Assembly have acknowledged the requirement for a specific regulatory strategy for Higher Airspace Operations.

This pathway represents the structural regulatory transformation needed to move HAPS from experimental activities into routine cross-border operations. Unlike Pathway 1, which functions within existing frameworks, Pathway 2 requires the creation of a legally recognised operational domain above FL600, including airspace classes, coordination rules, and interaction models between civil and military authorities.

Milestones:

- 2025: Setting up of joint working groups by EASA and ICAO.
- 2026–2028: Prepare and trial the operations of HAO airspace management, civil-military coordination protocols, etc.
- 2030: Implementation of ICAO-agreed international standards.
- 2032: Complete functional integration of HAO framework into air transport system of countries.

Responsible Entities: ICAO (global standard setting), EASA (regional implementation), EUROCONTROL (ATM coordination), and national defence ministries (civil–military agreements).

Technical Dependencies: development of interoperable high-altitude surveillance; validated performance envelopes for ascent/descent; reliable C2 continuity above 60,000 ft.

Regulatory Dependencies: alignment with ICAO rulemaking cycles (normally 3-year Assembly periods) justifies the 2030–2032 timeframe.

Rationale:

This route directly links to the basic regulatory void which was mentioned in Chapter 4.2. Defining a new portion of the airspace with specialized regulations also extends a period of legal certainty and allows for safe operation, which is in line with the high-altitude ATM ideas presented in Chapter 5.5.

Furthermore, Pathway 2 is the backbone of the entire roadmap, since Pathways 3 and 4 ultimately depend on having a legally recognised operational environment in which their technical and procedural outputs can be applied.

6.2.3 Pathway 3: Technological Certification and Airworthiness Standards (2025–2030)

Chapter 5.1 and 5.4 have identified that the absence of specific certification standards for HAPS vehicles which resulted in operators having to find ways to get approval from authorities that are not suitable for stratospheric flight.

This pathway addresses the “hardware gap”—the lack of performance, safety, and reliability standards tailored to vehicles operating for weeks at 20–25 km. A crucial element is the progression of HAPS technologies from experimental TRL 6–7 to pre-operational TRL 8–9 by 2030, enabling certification under dedicated specifications rather than ad hoc exemptions.

Milestones:

- 2025–2026: Industry–regulator joint working groups agree on performance requirements for HAPS airframes and systems.
- 2027: Release of specific EASA and ICAO certification specifications for high-altitude, long-endurance unmanned aircraft.
- 2030: First certifications of HAPS vehicles under dedicated standards.

Responsible Entities: EASA (CS-HAPS or equivalent), ICAO (global technical provisions), industry consortia (design data), and test-range operators.

Technical Dependencies: structural and aerodynamic validation at stratospheric conditions; energy-storage and solar array reliability; endurance-class propulsion; C2 redundancy.

Rationale:

This pathway is crucial to secure the protection, trustworthiness, and compatibility of HAPS equipment. It also helps the risk reduction objectives outlined in Chapter 5 by offering unambiguous design and operational requirements adapted to the environment of the stratosphere.

Certification also acts as a prerequisite for scalable UTM integration (Pathway 4), since performance-based airspace separation requires predictable aircraft behaviour and

validated failure modes. This explicit dependency is reflected in the roadmap timeline in Figure 6.2.

6.2.4 Pathway 4: High-Altitude Unmanned Traffic Management (UTM) Integration (2025–2035)

In chapter 5.5 it was pointed out that the traditional tactical ATM is not suitable for HAPS operations, recommending instead the use of strategic, pre-coordinated 4D-operational volumes and UTM-inspired systems.

This pathway focuses on building the operational infrastructure required for large-scale HAPS fleets. Unlike traditional ATM, high-altitude UTM must be predominantly strategic, relying on pre-allocated airspace blocks, automated deconfliction, and long-term mission planning. The development horizon (2025–2035) aligns with the expected pace of digital ATM reform across ICAO and EUROCONTROL.

Milestones:

- 2025–2026: Pilot studies of high-altitude UTM corridors with predefined operational volumes.
- 2028: Creation of interoperable, global UTM protocols for higher airspace.
- 2032: Launch of local UTM services for HAPS integration.
- 2035: Complete global harmonization of high-altitude UTM corridors.

Responsible Entities: ICAO (global UTM architecture), EUROCONTROL (network-level integration), national ANSPs (implementation), and industry (automation systems).

Technical Dependencies: reliable transponders above FL600; automation algorithms for long-endurance conflict prediction; integration with civil–military mission planning.

Rationale:

Such an approach makes it possible to integrate HAPS into the airspace in a safe, predictable, and scalable manner, thereby lowering the chances of conflicts with other high-altitude operators and at the same time providing support for complex multinational missions.

By design, Pathway 4 cannot reach operational maturity before Pathways 2 and 3 progress significantly; this interdependency is explicitly reflected in the timeline presented in Section 6.6.

6.2.5 Integrative Roadmap Summary

Instead of suggesting a linear, single-solution style of thinking, this roadmap outlines parallel, mutually reinforcing pathways. The problems that were identified in Chapters 4 and 5 are perfectly clear that:

- Incremental use of existing frameworks (Pathway 1) is necessary for short-term operational deployment and learning but cannot replace dedicated HAO regulation (Pathway 2).
- Airworthiness and certification standards (Pathway 3) are requirements for safe scaling, however, their success depends on their integration into the suitable ATM and UTM systems (Pathway 4).

These pathways will require joint efforts from several stakeholders, including ICAO, EASA, national aviation authorities, military agencies, industry consortia, and technology developers, for their implementation.

Furthermore, the coordination logic of the roadmap follows a clear structure:

- Pathway 1 enables early deployment and knowledge capture (2025–2028).
- Pathway 2 establishes the legal airspace foundation (2025–2032).
- Pathway 3 ensures technical reliability and certification (2025–2030).
- Pathway 4 creates long-term operational scalability (2025–2035).

This staged dependency structure ensures that technological, regulatory, and operational risks are progressively reduced rather than concentrated at the final deployment stage.

By outlining specific goals for the period of 2025–2035, this roadmap provides a methodical, achievable roadmap for moving HAPS beyond the experimental stage to the phase of the systems that are not only safe and reliable but also commercially viable for the whole world to use for connectivity, surveillance, and environmental monitoring.

6.3 Advantages, Disadvantages, and Risks of Alternative Strategies

Building on the strategic pathways outlined in Section 6.2, this section discusses the advantages, disadvantages, and corresponding risks of undertaking each pathway either individually or jointly. This examination has been made to tackle the issues of integration that were highlighted in Chapters 4 and 5, where the main barriers to making HAPS both safe and scalable were found to be the disjointed and uncoordinated approaches.

To strengthen the analytical depth of this section, the assessment below now incorporates explicit criteria: (1) regulatory feasibility, (2) technological maturity and TRL progression, and (3) operational scalability. The comparison also establishes clearer links to the roadmap milestones introduced in Section 6.2 and Section 6.6.

6.3.1 Advantages and Disadvantages of Individual Pathways

Each tactic is unique with its own positives but also negatively impacts if one is selected only:

- **Pathway 1: Incremental Integration Using Existing Frameworks**
 - *Advantages:* Enables direct operational ability; harnesses hands-on skills; lesser initial regulatory burden.
 - *Disadvantages:* Depends on changed, flawed frameworks (e.g., SORA) that do not correspond to high-altitude, long-duration flights; threat of conflicting national interpretations.
 - *Risks:* Fragmented approval landscape, possible safety gaps, restricted scalability.

This pathway shows the highest short-term feasibility but the lowest strategic alignment with long-term TRL progression and HAO regulatory development.

- **Pathway 2: Higher Airspace Operations (HAO) Regulatory Framework**

- *Advantages:* Provides legal clarity for an extended period of time; makes cross-border collaborations easier; allows the resolution of civil-military conflicts.
- *Disadvantages:* Requires very detailed negotiations; the process of development and implementation can take a long time.
- *Risks:* Starting the implementation too late may result in operators being in a regulatory no-man's land; there is a possibility that national standards will be divided if a global consensus is not reached.

This pathway has medium feasibility but the strongest alignment with the 2030–2035 vision described in the roadmap.

- **Pathway 3: Technological Certification and Airworthiness Standards**

- *Advantages:* Safety and reliability assured; increases industry trust; lessens ad hoc approval processes.
- *Disadvantages:* High development expenses; time-consuming standard-setting.
- *Risks:* Technology moves faster than regulation if standards lag behind; uneven international adoption might lead to market barriers.

It directly influences the risk-mapping phase of the roadmap and is essential for reaching TRL 8–9 before 2030.

- **Pathway 4: High-Altitude Unmanned Traffic Management (UTM) Integration**

- *Advantages:* Allows safe, reliable, and scalable operations; facilitates strategic planning through 4D airspace volumes; minimizes the risk of airspace conflicts.
- *Disadvantages:* Demands new infrastructure and changes in procedures; integration with existing ATM systems is complicated.
- *Risks:* Difficulties in interoperability with systems of other countries; cyber attacks.

This pathway is the most operationally transformative but depends heavily on the timely completion of Pathways 2 and 3, as reflected in the roadmap timeline.

6.3.2 Risks of Relying on Only One Strategy

In the fifth chapter, it was stated that the HAPS integration is a multi-dimensional problem which involves management, technical, and legal complications. It means that a mere focus on only one of these aspects will not be enough without considering others.

- Dependence on incremental integration alone is like digging oneself deeper into fragmented national approvals that don't really solve the issues of safety, certification, or traffic management.
- Concentrating solely on HAO frameworks without any nearby alternatives would mean deployments that are delayed, and as a result, the industry would be less developed, and operational learning would be insufficient.

- The supply of certification standards being on the top without a supportive ATM procedure would not give a proper answer to the problem of airspace integration in critical ascent/descent phases.
- Working solely on UTM solutions will not bring any benefits if the vehicles are not certified for performance or if they have not been given the green light by the regulators for routine operations.

These risks explicitly justify the multi-pathway design of the roadmap: they highlight that technical, regulatory, and operational readiness must evolve in parallel. Each isolated strategy creates bottlenecks identified earlier in the TRL analysis and risk-mapping requirements.

6.3.3 Advantages and Risks of Combined Strategies

On the other hand, several parallel routes are certainly good but some put some control problems:

- *Advantages:*
 - Gradually empowers the implementation with the advancement of sustainable development.
 - By offering regulations that are clear and transparent, industry investments are drawn.
 - Allows the gathering of knowledge and gradual enhancement based on the initial operational experience.
 - Minimizes the safety and security hazards by using multilayered, compatible mitigation measures.
- *Disadvantages and Risks:*
 - More complicated situation in the management of international, regional, and national stakeholders.
 - The possibility that the absence of clear governance may lead to overlapping or repeated efforts.
 - Risk of contradictory timelines or objectives between entities responsible for the initiative.
 - Necessitates continuous availability of resources and dedication from various stakeholders.

This combined approach matches the structure of the roadmap in Section 6.6, where pathways interact through defined dependencies, responsible actors (ICAO, EASA, EUROCONTROL), and TRL progression milestones.

6.3.4 Synthesis

The analysis is consistent with the main point that HAPS integration is not suitable for a single linear approach. A multi-layered, multi-pathway approach is needed to solve the interconnected regulatory, technical, and operational problems that are mentioned in Chapter 4 and 5.

On the other hand, this kind of approach requires intentional management and scheduling in order to reduce the chances of division, repetition, and lack of coordination. These risks highlight the need for a very clear outlining of the function responsibilities and working together of different organizations such as the ICAO, the EASA, governmental authorities, industry consortia and ATM, as will be shown in Section 6.4.

6.4 Governance Models: Single Entity vs Multi-Entity Coordination

An essential feature of the strategic roadmap addressed in Section 6.2 is the governance model that oversees the administration of HAPS integration. As Chapters 4 and 5 have indicated, the lack of a particular set of rules for regulation, along with scattered national strategies, creates a significant obstacle to the deployment of HAPS in a safe, scalable, and efficient manner.

This part analyses the two main models of governance that deal with the process of managing the creation and implementation of the necessary administrative, procedural, and technical frameworks:

- (1) A new dedicated international body with centralized single-entity governance, for example, a specific global agency to govern aviation emissions, would be created.
- (2) Distributed multi-entity management that makes use of the current organizations, such as ICAO, EASA, national authorities, and industry consortia.

The purpose of this section is to understand the advantages, disadvantages, and risks associated with these models by comparing them and to provide some basis for the roadmap's practical recommendations.

To strengthen the alignment with the roadmap, this section also clarifies the roles of the principal stakeholders—ICAO, EASA, EUROCONTROL, national authorities, defence institutions, and industry—since their coordinated interaction is essential for implementing the strategic pathways described in Section 6.2 and the 2025–2035 timeline in Section 6.6.

6.4.1 Single Entity Governance Model

This model is about creating a new independent global organization or a specialized agency that will be responsible for the development, coordination, and enforcement of HAPS-specific rules and standards.

Advantages:

- Offers regulatory standards that are uniform and consistent across all areas.
- Makes the certification, airworthiness, and operational approval processes simple.
- Enables effective interchange of data, favourable practices, and operational experiences.
- Reduces the potential for regulatory fragmentation or conflicting national requirements.

Disadvantages:

- Extensive political and administrative hurdles stand in the way of establishing a new international organization.
- A significant amount of time and effort is needed just to discuss the mandate, organization, and financing.
- Possible of bureaucratic inertia that hampers the agency's ability to quickly adjust to technological advances.

- Potentially the loss of the ability to easily adapt to security issues or special requirements of the local region.

Risks:

- Delays in setting up might result in the whole industry staying in a state of legal ambiguity for a long period.
- Unequal participation or influence by states with divergent priorities.
- Potential for duplication of work with existing organizations if mandates are unclear.

This model would, in principle, support a fully harmonised implementation of Pathways 2, 3 and 4, but its slow establishment contrasts with the time-critical nature of the 2025–2035 roadmap and the need for early TRL progression and operational learning.

6.4.2 Multi-Entity Coordination Model

This model focuses on collaborative governance, which means it makes use of the current organizations like ICAO, EASA, national aviation authorities, military agencies, and industry consortia to manage regulatory development and operational integration.

Advantages:

- Develops further by incorporating knowledge, the credibility of the institution, and regulatory frameworks.
- Quicker first-time usage, through already established ways of managing relations.
- Ability to adapt solutions to local or country-specific situations.
- Promotes partner commitment as the sharing of tasks between known stakeholders.

Disadvantages:

- Requires a lot of coordination, so there will be no duplication or gaps.
- Increased possibility of different rules, certification standards, and operational procedures being set that may not be consistent.
- Possibility of overlapping jurisdictional claims or disagreements.
- Requires strong communication, negotiation, and conflict-resolution mechanisms.

Risks:

- Fragmented regulatory environment persists if coordination fails.
- Slower harmonization across borders, complicating multinational operations.
- Challenges in balancing civil and military priorities without formalized processes.

This model directly supports the progression of all four pathways by distributing roles: ICAO leading international standard-setting, EASA managing regional regulation and certification, EUROCONTROL coordinating ATM/UTM aspects, and national authorities enabling operational approvals.

6.4.3 Comparison and Integration

Chapters 4 and 5 pointed out that the regulatory and operational difficulties of HAPS integration are deeply transnational. High-altitude operations often go across borders and involve overlapping civil, military, and commercial interests.

In light of this, neither governance model offers a perfect solution by itself:

- A single-entity approach gives the impression that it is very clear and consistent but it comes up with many practical and political problems that are quite difficult to overcome.
- On the other hand, a multi-entity approach is more realistic at present, however, it has a danger of inefficiencies, duplication, or regulatory fragmentation if there are no coordination mechanisms that are strong enough.

Essentially, a mix-and-match approach of the two could be the most effective way to manage the HAPS business:

- Using global bodies such as ICAO to provide global policies and limited procedures for continuous.
- Allowing regional agencies such as EASA to give a set of regional regulations and different instructions according to the specific needs of each region.
- Giving the national authorities the implementation and enforcement of standards, while still being able to cooperate on civil-military use and security issues.
- Making industry and research sectors collaboration easier to provide sufficient technological preparedness and practical feasibility, through the formation of a working group or the gathering of like-minded parties.

This integrative model is fully consistent with the cross-pathway dependencies identified in Section 6.2, particularly the regulatory–technical coupling between certification (Pathway 3) and UTM/ATM harmonisation (Pathway 4).

6.4.4 Implications for the Roadmap

This study strengthens the case for intentional, continuous teamwork across different institutional levels in order to fulfill the multi-pathway roadmap introduced in Section 6.2.

In order to prevent the situation where stakeholders are working in a fragmented or even conflicting way, they should give priority to:

- Setting up clear and unambiguous roles and responsibilities for ICAO, EASA, national authorities, and industry groups.
- Developing formal ways to coordinate, which will include not only joint working groups but also data-sharing frameworks.
- Agreeing on the process for civil–military coordination so that both sides can calmly and peacefully solve the security and sovereignty issues.
- Ensuring that the governance has the ability to continue being good not only for the described period but also for the future is in place.

These implications reinforce the structured sequencing in the 2025–2035 roadmap, in which each major milestone (standards, HAO procedures, certification, UTM corridors) depends on the coordinated action of the responsible institutions. The framework therefore provides governance stability needed to support technological evolution, TRL advancement, and safe multinational operations.

6.5 SWOT Analysis

To understand the complexities of using HAPS in the stratosphere, this section presents a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis.

The SWOT format was chosen mainly because it allows for a systematic assessment of the internal and external conditions that may affect the performance of the proposed plan. Although it is primarily qualitative and relies on interpretative judgment, SWOT still provides a clear framework for identifying key issues, trade-offs, and new questions.

To ensure analytical coherence with the strategic pathways in Section 6.2, each factor included in the SWOT matrix follows explicit selection criteria: (1) relevance to technological feasibility, (2) regulatory impact, (3) operational scalability, and (4) alignment with the 2025–2035 roadmap timeline.

Additionally, the factors are hierarchized according to their expected influence on HAPS integration, providing a clearer prioritisation structure.

6.5.1 Methodological Considerations

SWOT analysis is a strategic planning tool that is widely known in policy design and technology management as a means to get insights into four categories (Gurel & Tat, 2017):

- Strengths: internal advantages supporting success
- Weaknesses: internal limitations or challenges
- Opportunities: external conditions that can be leveraged
- Threats: external risks or barriers

This method gives a very flexible and yet structured way to review an initiative's position against its environment, making it especially suitable in situations with multi-actor, multi-pathway like HAPS integration (Pickton & Wright, 1998).

Strengths of the Method:

- Gives a simple, easy to understand layout for multi-factor evaluation
- Invites integrative thinking about technological, regulatory, and institutional aspects
- Enables dialogue between different stakeholders

Weaknesses of the Method:

- Doesn't have quantitative rigor or weighting of factors
- Subjective judgments may be different from one analyst to another
- Can be too simple for complicated interdependence situations

In spite of these drawbacks, SWOT as a tool is still quite good for early-stage strategic planning, mainly in the case of very new fields like HAPS, where uncertainty is high and no single authority governs the full operational environment (Gurel & Tat, 2017; Pickton & Wright, 1998).

To reinforce the robustness of this analysis, each SWOT element is linked in Section 6.5.4 to the corresponding strategic pathway and roadmap phase, ensuring continuity between problem identification, strategy design and implementation planning.

6.5.2 SWOT Matrix for HAPS Integration Strategy

Below is a consolidated SWOT matrix summarizing key findings from the preceding sections:

Strengths (ranked by strategic impact)	Weaknesses (ranked by severity)
Long-endurance capability at lower cost than satellites	Regulatory uncertainty and lack of dedicated frameworks
Reduces reliance on ground infrastructure	Fragmented national approvals under existing frameworks
Flexible deployment for emergency response and remote connectivity	High certification and development costs
Environmentally sustainable (solar-powered, low emissions)	Vulnerability to weather during ascent/descent
Supports persistent surveillance and monitoring	Limited payload capacity compared to LEO satellites
Opportunities (ranked by expected value)	Threats (ranked by probability and impact)
Expanding connectivity in underserved regions	Fragmented or conflicting international regulations
Disaster response and humanitarian missions	Airspace conflicts with manned and military aviation
Environmental and scientific data collection	Cybersecurity and command/control vulnerabilities
Cost-effective alternative to satellite constellations	Commercial non-viability (e.g., Project Loon precedent)
Enabling dual-use (civil–military) cooperation	Delays in establishing international standards

Table 6.4 SWOT analysis of HAPS Integration Strategy.

6.5.3 Analysis of SWOT Results

The SWOT analysis supports the strategic value proposition of HAPS as a disruptive technology that can help solve the most problematic issues of global connectivity, disaster response, surveillance, and environmental monitoring. The strengths and opportunities of HAPS directly energize the commitment to the regulatory and technological courses of action, which are presented in Section 6.2.

On the contrary, weaknesses and threats that are pointed out indicate the significance of:

- Settling the issue of regulatory ambiguity through agreement at the global level (Pathway 2).

- Setting up safety and security certification standards for the compliance of the implementation of safe and reliable operations (Pathway 3).
- The introduction of continuous and stable air traffic management and UTM as a tool for the avoidance of conflict (Pathway 4).
- Establishing structures that lead the way for the smooth running of multi-entity participation and the overall reduction of the fragmentation (Section 6.4).

Not solving these problems and not being aware of the risks can lead to a history of commercial failures being repeated, and thus cause safety to be compromised.

This interpretation also clarifies which weaknesses must be mitigated early (e.g., regulatory uncertainty), which opportunities can guide investment priorities (e.g., underserved connectivity), and which threats require coordinated action in the roadmap (e.g., cybersecurity, international standards).

It also reinforces that strengths alone cannot justify operational deployment without the regulatory and technical enablers defined in Pathways 2 and 3.

6.5.4 Implications for Strategic Planning

By methodically categorizing internal and external factors, the SWOT analysis facilitates evidence-based decision-making regarding the proposed roadmap in this chapter.

It outlines that a multi-pathway, coordinated approach is crucial, not just for exploiting HAPS' outstanding strengths and prospects, but also for dealing with the challenges brought by technology, regulation, and the market that are still at hand.

Consequently, this review reaffirms the necessity for integrated planning, purposeful leadership, and international collaboration.

Most importantly, the SWOT matrix directly informs the sequencing of the roadmap:

- Weaknesses 1–2 justify the early focus on incremental approvals (Pathway 1) and creation of HAO standards (Pathway 2).
- Weakness 3 and Threats 2–3 justify the push for certification and safety standards (Pathway 3).
- Threats 1 and 5 strengthen the case for long-term UTM harmonisation (Pathway 4).
- Strengths and Opportunities inform which applications are most viable in the early phases (2025–2030) and which require mature frameworks (2030–2035).

This ensures coherence between the analytical foundation (SWOT), the strategic response (pathways), and the operational plan (roadmap).

6.6 Recommended Roadmap and Timeline

The preceding analysis in Section 6.2 outlined four strategic pathways essential for enabling the safe, scalable, and sustainable integration of HAPS into stratospheric operations. Each pathway addresses specific regulatory, technical, and operational gaps identified in Chapters 4 and 5, while collectively they provide a comprehensive framework for future development.

This section consolidates those pathways into an integrated, time-phased roadmap that specifies key milestones over the 2025–2035 planning horizon. The roadmap emphasizes the need for parallel progression, highlighting that no single strategy alone can resolve the multifaceted challenges posed by HAPS integration. Instead, progress

must occur simultaneously across regulatory harmonization, certification standards, operational procedures, and airspace management systems.

The timeline shown in Figure 6.2 below illustrates a multi-pathway strategy. It indicates significant events along four coordinated lines of effort:

- Pathway 1: Incremental Integration Using Existing Frameworks – allowing short-term missions via the consistent understanding of the risk assessment methodologies compatible with each other (e.g., SORA);
- Pathway 2: HAO Regulatory Framework – creating dedicated international rules for the stratosphere operations, concentrating on the ICAO coordination and civil-military procedures;
- Pathway 3: Technical Certification and Airworthiness Standards – specifying the performance and safety requirements that are not general but rather made for long-endurance, high-altitude unmanned aircraft;
- Pathway 4: UTM Integration – coming up with strategic, pre-coordinated ATM solutions like 4D-operational volumes for safe routine operations at high altitudes.

To increase the analytical detail and operational relevance of the roadmap, the following elements have been integrated:

- Dependencies between pathways (e.g., UTM implementation requiring prior regulatory clarity under Pathway 2);
- Technological readiness levels (TRLs) for each phase of development;
- Alignment of milestones with ICAO Air Navigation Conference cycles and EASA regulatory planning cycles;
- Risk mapping at each stage, including regulatory delays, technology immaturity, and interoperability barriers;
- Clear identification of the responsible actors for each milestone (ICAO, EASA, EUROCONTROL, national authorities, defence ministries, and industry);
- Consideration of alternative scenarios should regulatory progress or technological advances deviate from expectations.

The suggested timeline is a graph representation of the expected chronology of main organisational steps, industry developments, and international cooperation that are needed to have a large-scale operational-ready system.

By representing these milestones side-by-side, the roadmap has highlighted the necessity of coordinated action among multiple entities such as ICAO, EASA, national aviation authorities, military agencies, industry consortia, and ATM service providers.

This kind of coordination is needed to ensure the occurrence of good, safe, and efficient scenarios and thus prevent the situations mentioned in Section 6.3 and 6.4 as risks.

Figure 6.2 below shows the suggested roadmap which gives a brief on the strategic outline of the necessary steps to go from initial pilot projects to continuous globally harmonized HAPS deployment during the next 10 years. This timeline outlines the major achievements of the four strategic pathways mentioned in Section 6.2, showing the intended steps for complete operational integration.

Year	Milestone	Pathway	Entities Involved
2025	- Harmonized SORA guidance for HAPS approvals <ul style="list-style-type: none"> • TRL focus: 6-7 (prototype validation in operational environment) • Key dependency: availability of reliable C2 links for ascent/descent • Risk: inconsistent adoption across Member States 	Pathway 1: Incremental Integration	EASA, National Aviation Authorities
	- Establish HAO working groups <ul style="list-style-type: none"> • Dependency: agreement on the scope of Higher Airspace • Risk: delays in consensus at ICAO ANC cycle 	Pathway 2: HAO Regulatory Framework	ICAO, EASA, National Authorities
	- Industry-regulator working groups on certification <ul style="list-style-type: none"> • TRL baseline: 5-6 (requirement definition phase) 	Pathway 3: Certification Standards	EASA, ICAO, Industry Consortia
	- Pilot studies of UTM corridors <ul style="list-style-type: none"> • Risk: cybersecurity vulnerabilities in prototype UTM systems 	Pathway 4: UTM Integration	Industry, National Authorities, ATM Providers
2026	- National procedures for case-by-case approvals <ul style="list-style-type: none"> • Risk: divergence in operational requirements across borders 	Pathway 1	National Aviation Authorities
	- Draft HAO procedures, civil-military coordination <ul style="list-style-type: none"> • Dependency: definition of sovereignty boundaries in higher airspace 	Pathway 2	ICAO, EASA, Defence Ministries
	- Define performance requirements for HAPS <ul style="list-style-type: none"> • TRL: consolidation toward 7-8 	Pathway 3	EASA, Industry
2027	- Publish dedicated certification specifications <ul style="list-style-type: none"> • Dependency: stability of HAO regulatory structure 	Pathway 3	EASA, ICAO
	- UTM prototype services in test regions <ul style="list-style-type: none"> • Risk: technical interoperability between national systems 	Pathway 4	ATM Providers, Industry, Regulators
2028	- Integration of lessons into updated SORA	Pathway 1	EASA, National Authorities
	- Operational HAO procedures adopted	Pathway 2	ICAO, EASA, National Authorities

	<ul style="list-style-type: none"> - Development of interoperable international UTM protocols <ul style="list-style-type: none"> • TRL: UTM technologies reaching 6-7 	Pathway 4	ICAO, National ATM Providers, Industry
2030	<ul style="list-style-type: none"> - ICAO-endorsed HAO international standards <ul style="list-style-type: none"> • Dependency: adoption during ICAO Assembly and ANC cycles 	Pathway 2	ICAO, National Authorities
	<ul style="list-style-type: none"> - First certifications under dedicated HAPS standards <ul style="list-style-type: none"> • TRL: 8-9 (system qualification and operational readiness) 	Pathway 3	EASA, ICAO
2032	<ul style="list-style-type: none"> - Regional UTM services for high-altitude integration 	Pathway 4	National ATM Providers, Industry, Regulators
2035	<ul style="list-style-type: none"> - Full global harmonization of high-altitude UTM corridors <ul style="list-style-type: none"> • Scenario note: If HAO standards face delays, harmonisation may shift to 2036-2038 depending on ICAO cycles 	Pathway 4	ICAO, National ATM Providers, Industry

Table 6.5 Proposed HAPS Integration Roadmap Timeline (2025–2035).

6.7 Summary

This chapter through the presentation of its evidence develops the real consequences of the mixture of HAPS in a larger context of regulatory, operational, and technological limitations. The found results corroborate the notion that despite the technology being very proficient in achieving continuous operations in the atmosphere with quite a few applications to communications, observation, and disaster response, the extent of technology deployment is still largely constrained by not completely coherent regulatory frameworks and by operational challenges that have not been solved.

During this discussion, it appeared that traditional risk assessment methods, certification procedures, and traffic management systems are not fully compatible with HAPS characteristics. These kinds of research, combined with comparative evaluations, also reveal that a gradual step-by-step progression may be possible by just slightly tweaking the present tools like SORA. However, this still heavily depends not only on the existence of international coordination but also on the achievement of certain technological developments.

The essence of the discoveries made in this chapter is that the integration of HAPS is a two-faced issue: there is, firstly, the positive in which improvement in connectivity, resilience, and monitoring capabilities become possible; and, secondly, the negative, i.e. the strong need for the regulation that is harmonized, the certification standards that are reliable, and the governance models that are innovative.

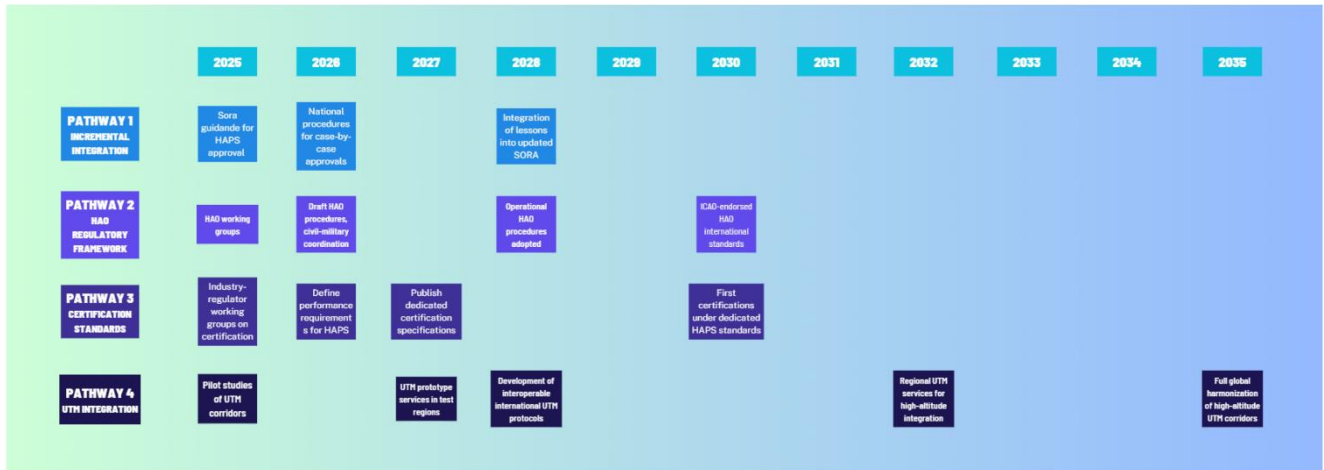


Figure 6.1 Strategic roadmap for the integration of HAPS operations (2025–2035) across four key pathways: incremental integration, regulatory framework, certification standards, and UTM integration.

HAPS mission profiles based on the four-stage design process have been discussed in the whole chapter. The four pathways presented throughout this chapter — incremental integration, regulatory development, certification, and UTM harmonization — are converging to a globally harmonized HAPS operational environment by 2035, a horizon of the chapter. Figure 3 synthesizes the chronology and interdependencies of these pathways.

Additionally, this chapter reinforces the importance of aligning strategic actions with clear dependencies, technological readiness levels (TRL), and internationally synchronized regulatory cycles. The inclusion of risk mapping across the timeline further highlights how technical, organisational, and legal uncertainties may influence the pace of integration. These enhancements provide a more robust connection between the SWOT analysis, the four strategic pathways, and the proposed roadmap, ensuring that the transition from experimental deployments to routine stratospheric operations rests on transparent, evidence-based decision-making.

Overall, the chapter consolidates the understanding that a successful integration of HAPS depends on a multi-layered, coordinated strategy supported by international cooperation, structured governance mechanisms, and continuous technological maturation. This structured roadmap provides the foundation for future research, policy development, and practical implementation in the evolution of high-altitude operations.

7. Conclusion

This research work dwelt extensively on the key areas of technology, regulations, and operations in HAPS, mainly highlighting the use of HAPS as part of the global aerospace and telecommunication infrastructures. The study had a broad coverage of the present and past legal and institutional frameworks by investigating how HAPS had changed their way since their first days and also identified the major issues that were blocking HAPS' widespread use. Besides, it briefly described the roles of EASA and ICAO in the prediction of the activities to happen in space and made further suggestions of a gradual plan to facilitate the transition from experiments to normal commercial flights.

Additionally, this study provided an integrated perspective linking technological feasibility, regulatory gaps, and operational constraints with strategic pathways for future harmonisation, enabling a clearer understanding of how HAPS could be embedded into global aviation architecture.

The main findings of this study may be listed as follows:

1. Firstly, it was found that the technology is feasible. The HAPS platforms have been able to showcase, among other attributes such as longevity, range, and adaptability, which makes them just right as either satellite auxiliaries or replacements, especially in cases of local networking, nature observation, and disaster management.
2. Yet, in contrast, the most important barrier still stands behind the fence of regulation. The insufficiently standardized global regulations for stratospheric operations and the fragmented national approval processes are causing negative effects on the deployment of new technologies in this field.
3. Moreover, the operational issues are not only able to be solved without new frameworks, but also they require the use of those frameworks. Such issues as airspace integration, undetectability, certification, and the emergency procedures scenario can only be partially solved by existing paradigms of the aviation industry, hence the need to devise innovative, HAPS-specific solutions.
4. Finally, it is necessary that the roadmap is planned and organized well. The gradual modification of the present tools such as SORA, which is expected to operate together with the establishment of HAO structures, certain standards for certification and an intelligent traffic management system must form the bulk of this.

These findings collectively answer the research questions by demonstrating that (i) HAPS technologies are already at sufficient maturity for pre-operational missions, (ii) current aviation law is inadequate for sustained stratospheric operations, and (iii) structured, multi-layered regulatory pathways are necessary to enable safe and scalable deployment.

7.1 Study Limitations

While the study provides a broad and structured framework, several limitations must be acknowledged:

- Methodological limitations: the analysis is primarily qualitative, relying on literature and regulatory documents rather than empirical flight or operational data;

- Bibliographical limitations: the field is rapidly evolving, meaning some regulatory developments, prototype test results, or guidance material may have changed after the completion of this study;
- Operational uncertainty: due to the absence of a mature HAO system, several assumptions on future airspace structures remain conceptual;
- Dependence on publicly available sources restricts insights into classified or industry-protected HAPS performance data, especially on defence-oriented systems.

These limitations do not invalidate the findings but highlight the need for continuous monitoring of technological and regulatory developments in future work.

7.2 Implications and Future Work

Looking ahead, such results must be employed in later operations as the following:

- Developing more advanced technical research that focuses on fault-tolerant systems, lightweight materials, and energy efficiency areas so that the endurance and resilience of the HAPS might be expanded further.
- Creating operational concepts for safe and controlled ascents, descents, and flight of long duration in the stratospheric flight corridors, besides designing compatible UTM systems.
- To develop not only existing but also new close international relations especially between the civil and military authorities for the purpose of avoiding the domination of security issues in the commercial and humanitarian use of space.
- Implementing pilot projects compliant with the same regulatory recommendations which would provide the necessary data to be used for standard-setting as well as risk assessment methodologies.

In addition, future research should further explore:

- the evolution of Higher Airspace Operations (HAO) frameworks beyond 2035, including long-term governance models for routine stratospheric traffic;
- the coexistence of HAPS with emerging Urban Air Mobility (UAM) and suborbital systems, ensuring multi-layer airspace integration;
- the progressive interaction between aviation law and space law as stratospheric operations approach near-space altitudes;
- quantitative models for economic viability, sustainability, and resilience of HAPS-based communication networks;
- longitudinal studies evaluating the technical maturity (TRL progression) of solar-electric HALE platforms under real-world operating conditions

7.3 Final Remarks

The future of HAPS will largely depend on the presence of well-established and harmonized regulations rather than on the mere technological possibilities. In the absence of a reliable global system, these stratosphere operations could be haphazard, risky, and perhaps not even financially sustainable over time. Therefore, the degree of progress depends on how well the actors in regulation, the industry, and international organizations manage to agree on common standards for certification, airspace integration, and governance.

Only by taking such a coordinated regulatory action can HAPS be safe, scalable and sustainable contributors to the global connectivity and security, apart from their experimental deployments.

The results of this study therefore underline the urgency of coordinated governance, the relevance of structured multi-pathway development strategies, and the significant potential of HAPS as a long-term component of global aerospace infrastructure. The proposed roadmap provides a practical foundation for future regulatory, operational, and technological efforts aimed at enabling HAPS to evolve from experimental systems into a fully integrated element of the high-altitude ecosystem

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