



OPTIMIZATION & MODERNIZATION OF LEGACY NAVIGATION INFRASTRUCTURE

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Abstract

As increasingly advanced systems continue to emerge within the aviation industry, existing systems are expected to evolve accordingly. For this reason, both world's leading aviation authorities - the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) - emphasize a shared and consistent message: despite the rapid and exponential growth of new technologies, it remains essential to preserve and maintain the legacy navigation infrastructure. This paper begins with an introduction, followed by a brief overview of the early development of Ground-Based Navigation (GBN). I then provide clear definitions of the main types of GBN equipment, accompanied by detailed explanations of their function and relevance. Afterward, I outline the methodology used in this study, describing the different phases of work that contributed to the results. Subsequently, I present and compare the current state of GBN equipment in Portugal, considering the characteristics of Portuguese airspace previously described. Finally, it will be discussed also the potential optimization and modernization of this infrastructure - exploring whether these systems should be integrated, upgraded, or gradually phased out, according to truthful literature.

Keywords

Air Traffic Service, Air Traffic Management, Legacy Navigation Infrastructure, Ground-Based Navigation, Navigation Aid, Global Positioning System, Inertial Navigation System, Microwave Landing System, Very High Frequency Omnidirectional Range, Distance Measuring Equipment, Instrument Landing System.

1. Introduction

As a famous quote says, "If you already arrived at the airport, it means that the chance of surviving the next few hours has increased exponentially."

It happens that the scenario has not always been like the one we have nowadays. It is because of Air Traffic Management (ATM) that it is possible to have thousands of aircraft flying at the same time, using the same routes and airports, taking off and landing within moments of each other - all of this with an incredibly low failure rate. Even though the first ever flight happened in 1903, it was only during the First World War that Air Traffic Control (ATC) was born. During the last year of the war, the first commercial airline was established, connecting England and Belgium to fulfil military purposes. In the first years of the following decade, 30 commercial airlines were established around the globe. By 1920, the first ever ATC tower was erected at London Croydon. From then on, Civil Aviation Traffic Officers were able to provide navigation, traffic, and weather information to pilots over the radio. (S. Golstein, 2023)

In the early days, pilots used to fly 200 to 500 feet above the ground to navigate using roads as reference. Fire was also commonly used to help pilots follow certain routes or assist them in landing the aircraft. As air travel increased, air controllers would stand in the field and wave flags to communicate with pilots. As time went by, these methods were quickly replaced by others, such as the installation of runway lights to help pilots land the aircraft when weather conditions were not ideal. (A. Novak, 2008)

A long time has passed and, with the advance of technology, there is no important word than 'safety.' This has been achieved through the continuous international cooperation on aviation safety carried out by the 193 countries that work together through ICAO, the International Civil Aviation Organization. Together, these countries have committed to reaching the global safety target of zero fatalities by 2030 – something unimaginable in the previous century. (ICAO, n.d.)

Next, I intend to explain the role of GBN in daily aircraft operations. Despite the advance of numerous and very important technologies, all supported and validated by the responsible institutions, it is crucial to take into consideration the importance of this type of navigation, so that its value is not forgotten.

2. Early days of ground-based navigation

Although briefly introduced earlier, it is essential to clearly understand how contemporary ground-based navigation systems operate. However, achieving this understanding first requires tracing their historical foundations. For this reason, this section presents a concise overview of the origins and early evolution of Ground-Based Navigation (GBN), establishing the context necessary to appreciate its current role and technological progression.

2.1. Non-radio methods of navigation

Navigation offered three main methods, excluding the radio aid, to help and successfully complete the mission: fly as safe as possible. There were pilotage, celestial navigation and dead reckoning. This last will be more developed than the other two later in this paper. Starting with the first method: pilotage. This is referred to as the natural ability of the human being to find, better or worse, certain tracks by remembering certain places, spots or marks. In order to aid the aviators, they served themselves with the most basic human abilities, like the vision and the smell. As referred to before, they used vision (and, consequently, memory) to locate familiar places/marks; but also the smell - if they were flying near the sea or near the land, they could use also the smell to take out some information (not that used, because aviators were confined inside a tight cockpit, what disabled them to use this sense in a proper way). It is important to say that pilotage was not that useful if the weather conditions were not ideal or if the aircraft was flying in open waters, because of the lack of visual references. (Doug Davis, 2021)

Secondly, there is the celestial navigation, used since the ancient times by diverse cultures. Greek and Arabs used the astrolabe which allowed them to, after some calculations, discover the time and latitude of certain objects. During the 19th century, almanacs, the sextant and accurate clocks were precious. The first contained the exact location of key celestial objects at regular times above the earth, the second was able to measure the angle of the object above the earth and the third served as proof to see if the observers obtained the measurement at the precise time noted in the almanac. (Doug Davis, 2021)

Finally, and concerning the purpose of this paper, the most important of the non-radio methods of navigation, the one called dead reckoning. Inertial Navigation Systems (INS) emerged when engineers discovered that high-precision sensors, together with increasingly capable computers, could handle dead-reckoning calculations automatically; faster and more accurately than a human, and in three dimensions. Nowadays, it is commonly used as a complementary backup to Global Navigation Satellite System, GNSS, in nearly all navigation applications. (Doug Davis, 2021)

2.2. Ground-Based Navigation

For many years, the GBN has been extremely useful in the daily aircraft operation. In fact, and according to FAA, the GBN provides very useful aid, commonly used to make the operation the most efficient and effective, with the objective of meeting operational needs. Next, it will be presented some types of GBN, like ILS, VOR, DME and NDB.

2.2.1. Instrument Landing System - ILS

The Instrument Landing System (ILS) consists of a set of equipment installed on the ground at airports, situated near the runways. Its function is to provide pilots with accurate information about their lateral and vertical position relative to the runway, in order to aid the landing. This system has 3 categories (CAT I, II and III) according to the sensitivity they provide. (M. Durgut, 2020)



Figure 1. Instrument landing System

This equipment consists of two separate infrastructures. Both systems work on their own, but their information is combined in the cockpit to provide the pilot with precise guidance in both the lateral and vertical planes. On the left, there is the Localizer (LOC), transmitting VHF signals between 108.1 MHz and 112 MHz and providing aircraft with lateral guidance; very useful to help the pilots to align the nose of the aircraft with the center of the runway. On the right side, we have the Glide Slope (GS) that transmits UHF signals between 329.15 MHz and 335.0 MHz to give vertical guidance to the pilot. (FAA, n.d.) Besides these two main structures, there is also a marker device (located on the approach line) and approach lights.

That's with the precious help of these infrastructures that the aircrafts do a descent to the decision altitude, at a time when the pilot must be able to see the runway and decide: either he lands or declares a missed approach. (A. Novak, 2008)

2.2.2. Very High Frequency Omni-Directional Range – VOR

The Very High Frequency Omni-Directional Range, or VOR, is a navigation aid that gives aircraft directional guidance to an airport by indicating their bearing from 0 to 360 degrees through visual instruments. It operates within the 108 to 118 MHz frequency band. (Djunaedi, 2024)



Figure 2. Very High Frequency Omni-Directional Range

Numerous VORs suffer from reduced signal performance due to nearby obstacles that partially block their transmissions. This can be caused not just by natural encroachments, like the existence of tall trees, but also with the presence of synthetic

obstacles (radio towers, overhead transmission lines, wind farms, among others). Using a DVOR configuration mitigates signal-in-space issues that occur when obstacles reflect the VOR signal. (A. Novak, 2008)

2.2.3. Distance Measuring Equipment – DME

Distance Measuring Equipment is an international standardized pulse-ranging equipment system for aircraft, operating between the interval of 960 to 1215 MHz. When the ground station is collocated with a VOR station, the resulting combination forms the standard ICAO rhotheta short- range navigation system. (Kayton and Fried, 1997). The rho (distance from the facility) is supplied by the DME and the theta (azimuth bearing from magnetic north) is supplied by VOR/DVOR.



Figure 3. Distance Measuring Equipment

2.2.4. Non-Directional Beacon

A Non-Directional Beacon (NDB) is a ground- based radio transmitter that operates on low frequencies and helps instrument approaches at airports. It sends out a signal in all directions, which is picked up by the Automatic Direction Finder (ADF) onboard the aircraft. Using the ADF, the pilot can identify the direction of the beacon in relation to the aircraft. To navigate with it, the pilot simply tunes the NDB's frequency, and the ADF needle will point toward the station. (Goodhue, 2025)



Figure 4. Non-Directional Beacon (NAV Portugal, 2025)

3. Methodology

Considering the topic of this paper, the main goal was to understand what role legacy navigation infrastructure still plays in today's aviation environment. With so many new systems being developed and introduced, it's easy to assume that this

older equipment is becoming less relevant. Because of that, the goal is understanding how these traditional navigation aids actually fit into the current reality, and whether their importance is truly disappearing or if they still hold a meaningful place in the overall system.

3.1. Research

Since the topic addressed in this paper is not among the most widely explored in existing research, especially when compared to other, I quickly realised the need to engage in deeper investigation. To do so, I consulted several important, reliable and high- quality studies that significantly contributed to the development of this paper. My research process involved using platforms such as Google Scholar, ResearchGate and Web of Science, among others. In addition, I frequently accessed the website of the Portuguese ANSP, NAV Portugal, as well as the Portuguese Aeronautical Information Publication (AIP). These resources proved to be particularly valuable, as they allowed me to understand in detail the current intentions and strategic directions of my country regarding certain topics - information that I could not find in any other source. Beyond these references, I also analysed the SESAR Master Plan 2025 and the ATM Master Plan 2015. Both documents were extremely useful and constructive for the preparation of this work, especially because they enabled me to align my research with current European trends and long-term developments in the field. Finally, and after gathering and reviewing all the material that I had collected, the next step was to cross-compare the entire information. This process was essential to synthesise the findings and ultimately produce a coherent, meaningful and worthwhile piece of work.

4. Portuguese aeronautical infrastructures

4.1. Portuguese Air Space

Portugal, despite his small size as a country, has an enormous air space. The Portuguese air space is, nowadays, one of the bigger when compared to the size of the country. It is currently divided in two different zones, covering: the Lisbon RIV and Santa Maria RIV – RIV stands for, in Portuguese, Região de Informação de Voo, that can be translated to Flight Information Region (FIR).

The first mentioned FIR aims to cover all the Portuguese continental area plus the Madeira archipelago. The second one covers all the area around the Azores archipelago, until the middle of the Atlantic Ocean. According to NAV Portugal, the Portuguese Air Navigation Service Provider (ANSP), the Lisbon FIR covers an area of 660 thousand square kilometres, which includes the Lisbon Control Center plus six control towers, which are situated in six airports: Cascais Airport, Faro Airport, Funchal Airport (in Madeira Island), Lisboa Airport, Porto Airport and Porto Santo Airport, this last one situates also in the archipelago of Madeira.

Secondly, there is the Santa Maria FIR. This one is even bigger than the other mentioned above: it covers a total area of, approximately, more than 5.1 million square kilometres. It includes, also, the Oceanic Control Center and four control towers, located in four airports in Flores, Horta, Ponta Delgada

and Santa Maria. These islands mentioned are part of the Azores Archipelago. (NAV Portugal, 2024) Finally, and just for comparison, Portugal just has a total land area of 92.212 square kilometres.



Figure 5. Lisbon (right) and Santa maria (left) FIRs.

4.2. Ground-Based Navigation in Portugal (2015 – 2025)

Over the last 10 years, the navigation infrastructure in Portugal has changed quite noticeably. Some of the older systems that had been in place for decades have been updated, replaced, or even removed, while other, more reliable and modern, have been introduced. These changes reflect the normal evolution of aviation needs and the continuous effort to keep the Portuguese network safe, efficient, and aligned with current operational practices. Looking at what has been added, what has disappeared, and what has been improved provides a clear picture of how the overall system has adapted to today's requirements. According to the Portuguese ANSP, Portugal has every GBN equipment mentioned above, all over its territory. Starting with the first ground-based equipment referred in this paper, the ILS.

This navigation aid has been, in the past decade, replaced and updated for new one, to respect the demands of ICAO:

- ILS installation on runway 10 in Faro Airport, in 2015;
- ILS replacement on two runways in Lisbon Airport, in 2019. The previous equipment had been in use since 2004;
- ILS replacement on runway 17 with newer equipment at Porto Airport in 2020. The previous equipment had been in use since 2000.
- ILS installation on runway 35 at Porto Airport, in 2020.
- ILS replacement at São Miguel Airport and in Santa Maria Airport, in 2020.
- ILS installation at Montijo Airport, in 2020.
- Replacement of the antenna system and radio-signal distribution for the Localizer and Glide Path components of ILS on runways 02 and 20 at Lisbon Airport in 2022, to ensure continued CAT III operational capability.

It is important to highlight that, as of 2025, Portugal has ten airports equipped with Instrument Landing Systems. This is particularly notable given that ILS is a long-established

technology, implemented many decades ago. Despite the emergence of more modern navigation and landing systems, ILS continues to demonstrate its value and reliability, showing no signs of being phased out in the next decades.

Another example of GBN equipment that has followed the same path as the ILS is the VOR/DME. Over the past decade, Portugal has made a clear effort not only to install additional stations but also to replace older ones with newer and more reliable equipment. This has been important to ensure good coverage across the entire territory and to maintain a robust network of navigation aids where they are most needed. (Online EAIP – NAV Portugal AIS, 2025)

- In 2015, it was replaced one navigation station VOR/DME, at Espichel;
- In 2016, it was replaced four navigation stations VOR/DME at Nisa, Viseu, Porto and Horta Island;
- In 2018, it was replaced one navigation station VOR/DME at Santa Maria Island;
- In 2022, it was replaced three navigation stations VOR/DME at Funchal Island, Cascais and Porto Santo Island.

The same observation made for ILS also applies to VOR/DME systems. Even though, like ILS, VOR/DME has been in use for many decades, it remains a cornerstone of the global navigation infrastructure.

Nowadays there is, across the Lisbon Flight Information Region, a total of 14 radio navigation aids of various types are installed. Concerning the Santa Maria FIR, there are 16 such aids distributed across the archipelago: five in Santa Maria Island, five in São Miguel Island, three in Horta Island, and three in Flores Island. (NAV Portugal, 2024)

Besides, a comprehensive redesign of the CNS systems implemented in the control towers aimed at fully enabling the provision of Air Traffic Control services. Over the past decade, these CNS systems have undergone continual modernization and incremental upgrades, ensuring they remain aligned with evolving international standards, technological advancements, and operational requirements. This ongoing renewal process has strengthened system reliability, improved performance, and enhanced the overall safety and efficiency (AIP's, 2015-2025)

5. Optimization & modernization

Europe's air traffic system is reaching a turning point. The skies are getting busier every year as the number of flights continues to grow, yet safety remains exceptionally high. Although, the system is struggling to follow. Six years ago, just before the COVID-19 pandemic, air traffic hit a record of nearly 11 million flights. (European Union, 2025)

By 2024, and even with the war in Ukraine since the beginning of 2022, many European countries were already having more flights than before the pandemic, and forecasts suggest traffic will keep rising, eventually reaching around 16 million flights by 2050. At the same time, the airspace will become even more complicated to manage as new kinds of aircraft are being developed, like zero-emission planes, military and non-military

drones, not forgetting high-altitude vehicles. (European Union, 2025)

As a crucial component of the Single European Sky (SES), the European ATM Master Plan serves as Europe's roadmap for modernising air traffic management. It defines the goals, direction, and main priorities for achieving a fully digital European sky, with the objective of making Europe the most efficient and environmentally sustainable airspace in the world by 2045. In that year, it will be expected that every flight will be managed in the most efficient way from departure to arrival, supported by seamless communication between aircraft, air traffic control, and all ground systems. European ATM pretends to eliminate unnecessary fuel consumption and also enhance its impact on non-CO₂ emissions, noise reduction and local air quality. The system will be flexible and robust, capable of adjusting to changing traffic levels and supporting an increasingly diverse range of aircraft; all while maintaining the highest standards of safety and security. Air traffic management will also be fully connected with other modes of transport, creating a truly integrated transport network. (European Union, 2025)

5.1. Strategic Deployment Objectives (SDOs)

The focus here is on Europe's deployment priorities, introducing the strategic deployment objectives. These objectives represent a set of high-priority actions, or essential operational changes, that must be implemented between 2025 and 2035. They are crucial for delivering the overall vision and performance targets and are built on SESAR Solutions that are either already mature or expected to reach that level by the next year. (European Union, 2025)

The SDOs were selected following a prioritisation process that evaluated the relevance and readiness of the supporting SESAR Solutions. The selection was then based on four criteria: the critical role they can play in addressing climate-neutral aviation, capacity and scalability, safety criticality and the uptake of innovative air mobility.

- Alerts for reduction of collision risks on taxiways and runways;
- Optimising airport and Terminal Manoeuvring Area, TMA, environmental footprint;
- Dynamic airspace configuration;
- Increased automation support;
- Transformation to Trajectory-based Operations (TBO);
- Virtualisation of operations;
- Transition towards performance of Air-Ground Connectivity (Multilink);
- Service-oriented delivery model (Data-driven and Cloud-based);
- CNS Optimisation, Modernisation and Resilience;
- Enable Innovative Air Mobility (IAM) and drone operations.

Even though all those 10 objectives are equally important, this paper will give more emphasis to the 9th objective due to its topic. The objective itself aims to optimise, modernise and increase the resilience and interoperability of Communication, Navigation and Surveillance in Europe, building on top of ongoing deployment activities, in particular the ones already included in Commission implementing regulations (PBN – Performance-Based Navigation, datalink). (European Union, 2025)

5.2. Infrastructure and how it can be optimized

The objective of deployment is to deliver benefits as soon as possible, while keeping investments smart, cost-effective and well-coordinated. To achieve this, different actors need to align their plans and timing, with support from EU funding to help make that happen. Since automation, integration and harmonisation are central to the future vision, it's important to establish common standards early and involve a wide range of public and private stakeholders from the very beginning - even during the R&D stage (Research and Development stage). This broad collaboration lays the groundwork for a smooth and successful rollout across the entire network. (European Union, 2015)

CNS technologies, both on the ground and onboard aircraft, are a key technical foundation for many of the future operational improvements and new procedures in the ATM system. The performance expectations for these systems are becoming more complex, and they will increasingly be viewed as part of a single, integrated air-and-ground CNS environment. Where it makes sense, different areas communication, navigation and surveillance may move towards shared or common infrastructure components. (European Union, 2015)

At the same time, CNS systems and infrastructure, both airborne and ground-based, will adopt a more business-oriented approach, aiming to use resources more efficiently and deliver the required capabilities in a cost-effective and spectrum-efficient way. These considerations are reflected in the CNS roadmaps, which defines the technologies and infrastructure needed to support the evolution of the SESAR Target Concept. (European Union, 2015) According to the SESAR Master Plan 2025, these are the specific objectives about CNS optimisation and modernisation:

- Implemented a secured surveillance functionality that enables detection and, when possible, mitigation of security threats that could affect the surveillance chain;
- Implement minimum operational work (MON);
- Rationalise ILS and implement efficiency measures/methods for more cost-effective maintenance of ILS, providing a link between ICAO and national CNS provision;
- Optimise surveillance, leveraging terrestrial and space-based information.

5.3. Future of legacy navigation infrastructure

Legacy navigation infrastructure, such as VOR, DME, NDB, and ILS, remain widely used around the world, and most aircraft

carry the necessary equipment to use them. Because GNSS signals can be vulnerable to interference, it has been recognized that some traditional radio navigation systems, or an alternative navigation service, must be maintained as a backup to GNSS. (ICAO, 2016)

Managing operations during a GNSS interruption will depend mainly on the use of signals from other constellations or on applying pilot and ATC procedures, supported by onboard inertial systems and selected conventional navigation aids. If a broad GNSS outage occurs in a region, switching back to conventional aids and procedures may reduce airspace capacity or flight efficiency. However, when signal loss affects only one GNSS constellation, switching to another may allow the same PBN performance level to be preserved. (ICAO, 2016)

As PBN becomes the standard for area navigation, DME stands out as the most suitable conventional aid to support these operations (assuming aircraft have onboard DME multilateration capability), as it is already integrated into multi-sensor avionics for this purpose. DME networks and coverage will therefore need to be improved accordingly. Likewise, the continued widespread use of ILS will ensure that, where installed, it remains a viable alternative for approach and landing in the event of a GNSS failure. (ICAO, 2016)

Today's single-frequency GNSS offers the most accurate globally available positioning service. Although it generally delivers very high availability, it still lacks sufficient resilience to certain vulnerabilities - especially radio frequency interference and ionospheric disturbances caused by solar activity. Because a fully resilient solution has not yet been achieved, it remains essential to maintain a terrestrial navigation infrastructure that is robust enough to ensure safe and continuous aircraft operations. (ICAO, 2016)

5.4. Cost-Efficiency Analysis of Legacy Navigation Infrastructure

To assess whether legacy ground-based navigation (GBN) infrastructure should be maintained, rationalized or replaced, a cost-efficiency evaluation was performed using a multi-criteria analytical framework based on three pillars:

- Economic efficiency (CAPEX + OPEX)
- Operational performance (availability, continuity, coverage)
- Resilience contribution (backup capability during GNSS degradation)

The analysis compares:

- ILS vs GNSS/GBAS approaches,
- VOR/DME vs DME/DME positioning networks,
- NDB vs alternative backup solutions.

5.4.1. Cost Structure Definition

(A) Capital Expenditure (CAPEX) Includes:

- Equipment acquisition

- Installation and calibration
- Civil works and site preparation
- Flight inspection certification

(B) Operational Expenditure (OPEX) Includes:

- Preventive maintenance
- Corrective maintenance
- Flight inspection cycles
- Energy consumption
- Spectrum and regulatory compliance

Table 1. Typical ranges (indicative European averages 2015 -2025)

System	CAPEX (approx.)	Annual OPEX
ILS CAT I	1.0 – 1.5 M€	120 – 180 k€
ILS CAT III	2.0 – 3.5 M€	200 – 350 k€
VOR/DME	0.8 – 1.5 M€	80 - 150 k€
Standalone DME	0.4 – 0.6 M€	50 – 100 k€
NDB	0.2 – 0.5 M€	30 – 65 k€
GBAS	2.5 – 4.0 M€	150 – 250 k€

Cost per Operational Benefit Metric (COCU)

$$COCU = \frac{\text{Total Lifecycle Cost}}{\text{Coverage area} \times \text{Operational Availability}}$$

Where:

- Lifecycle cost = CAPEX + (OPEX × 20 years)
- Coverage area = effective service radius
- Availability = system availability (e.g., 99.9%)

This enables comparison between:

- Wide-area enroute systems (VOR/DME)
- Precision approach systems (ILS)
- Satellite-based systems

A comparative cost-efficiency assessment indicates that ILS remains operationally indispensable in high-density environments and for CAT II/III precision approaches, where its independence from satellite vulnerability ensures high resilience. However, due to significant lifecycle and maintenance costs, ILS is economically unjustified at low-traffic regional airports. GNSS/GBAS solutions offer greater scalability and lower per-runway infrastructure requirements, yet their exposure to radio frequency interference and jamming limits their suitability as a standalone solution in resilience-critical environments. Regarding en-route navigation, VOR infrastructure is progressively less cost-efficient due to higher maintenance demands and reduced relevance in performance-based navigation (PBN) airspace. In contrast, an optimized DME network provides a more economically sustainable alternative, supporting DME/DME positioning, enhancing spectrum efficiency, and aligning with multi-sensor avionics architectures.

This rationalization approach is consistent with the Minimum Operational Network (MON) concept.

Finally, although NDB systems exhibit low capital and operational costs, their limited accuracy and vulnerability to atmospheric interference render them operationally inefficient within modern PBN frameworks. A gradual phase-out strategy is therefore recommended, retaining installations only where terrain constraints or redundancy requirements justify minimal backup capability.

Overall, a hybrid architecture combining selective ILS retention, DME network optimization, and GNSS-based primary navigation represents the most cost-efficient and resilience-balanced solution.

Resilience Cost Multiplier

A resilience weighting factor (RWF) was introduced:

$$\text{Adjusted Cost} = \frac{\text{Lifecycle Cost}}{\text{Resilience Contribution Score}}$$

Where Resilience Contribution Score (1–5) evaluates:

- GNSS independence
- Failure isolation capability
- Capacity preservation during outage

Table 2. Typical scoring for navigation system in Portugal

System	Resilience score
ILS	5
DME	4
VOR	3
VOR/DME	4
NDB	2
GNSS	2 (due to vulnerability)

This demonstrates that although ILS has higher cost, its resilience-adjusted cost becomes competitive.

Considering the specific characteristics of Portuguese airspace—particularly the extensive Santa Maria oceanic FIR, the high operational reliance on GNSS, and the projected growth in traffic density—a balanced and resilience-oriented CNS strategy is required. Maintaining ILS capability at major airports such as Lisbon, Porto, and Faro remains operationally justified due to traffic volume and precision approach requirements. At the same time, the rationalisation of the VOR network and the expansion of DME-based positioning coverage represent cost-efficient measures aligned with modern PBN operations. Preserving a Minimum Operational Network (MON) backbone ensures continuity of operations in the event of a GNSS disruption.

From a purely economic standpoint, maintaining the entire legacy navigation infrastructure is not cost-optimal. However, from a system resilience and safety perspective, selective retention of critical assets is essential. The most efficient long-term solution is therefore a hybrid CNS architecture in which satellite navigation serves as the primary layer, supported by a rationalised DME network, retained ILS precision capability at

key airports, a minimal VOR backbone where operationally justified, and the gradual retirement of NDB systems. This approach supports both cost-efficiency and operational robustness, while remaining consistent with SESAR Strategic Deployment Objective 9 and broader European ATM digitalisation goals.

6. Conclusion

Aviation navigation in Portugal has evolved within the broader global transformation of air traffic management, progressing from early non-radio techniques to a complex system of ground-based and satellite-based technologies that sustain operations across both the Lisbon and Santa Maria Flight Information Regions. This evolution reflects not only technological advancement but also Portugal’s commitment to maintaining high safety standards within one of Europe’s most geographically distinctive airspace structures—characterised by a vast oceanic FIR, significant transatlantic traffic flows, and growing operational density.

Although Global Navigation Satellite Systems (GNSS) constitute the primary navigation source across Portuguese airspace, particularly in the oceanic environment of the Santa Maria FIR, their vulnerability to radio-frequency interference, jamming, and spoofing represents a non-negligible operational risk. In this context, legacy ground-based navigation systems—including ILS, VOR, DME, and, to a lesser extent, NDB—retain strategic importance as resilience layers within the national CNS architecture. Their independence from satellite signals and proven operational continuity during GNSS disruptions provide critical safeguards for both continental and island operations.

The analysis of the Portuguese navigation infrastructure between 2015 and 2025 demonstrates that modernization efforts have not aimed at full replacement of legacy systems, but rather at selective upgrading and rationalisation. ILS installations at major airports such as Lisbon, Porto, and Faro remain operationally justified due to traffic volume and precision approach requirements, while the gradual optimisation of the VOR network and the reinforcement of DME capabilities align with performance-based navigation (PBN) implementation. Within Portugal’s specific operational context, maintaining a Minimum Operational Network (MON) backbone is essential to ensure continuity of service during potential GNSS outages, particularly given the strategic relevance of transatlantic routes.

From an economic standpoint, full preservation of all legacy systems across the territory would not be cost-optimal. However, from a safety and resilience perspective—especially considering Portugal’s oceanic responsibilities—selective retention and performance-based rationalisation are justified. The most suitable long-term approach for Portugal is therefore a hybrid CNS architecture in which GNSS remains the primary navigation layer, supported by an optimised DME network, strategically retained ILS installations at high-traffic airports, a reduced but functional VOR backbone, and the phased withdrawal of NDB systems.

Such a strategy ensures operational continuity, preserves safety margins, and supports capacity growth while aligning with the European ATM Master Plan and SESAR Strategic Deployment

Objective 9. In the Portuguese context, modernization of legacy navigation infrastructure is not merely a technological choice, but a strategic necessity to safeguard national and transatlantic airspace operations in an increasingly complex and satellite-dependent aviation environment.

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