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GALILEO
EGNOS
NAVIGATION MADE IN EUROPE

EUROPEAN RADIO NAVIGATION PLAN 2023

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Contents

1 INTRODUCTION

Services dependent on **Position, Navigation and Timing (PNT[1])** have been since long an **engine for economic growth**. They also play a key role in the society and across multiple sectors and support critical infrastructures. Whilst the dependency on PNT services is growing in civil and commercial applications, they are also playing an increasing role in defence, security, and safety of life operations.

PNT services are mainly based today on radio navigation systems and notably on the services provided by the **Global Navigation Satellite Systems (GNSS**). The use of GNSS has spread across many sectors, grounded on the evolution of the existing constellations and the appearance of new ones. Today, around 10% of the European Union (EU) GDP relies on the use of **GNSS services**, and the trends suggest that this will continue increasing. In all, there is significant potential for industry in and across many sectors to better exploit GNSS services and to avail of, and benefit from, the superior performance that GNSS offers.

PNT terrestrial systems have played for many years a key role either in combination with, or independently from GNSS. However, the uptake and evolution of GNSS solutions opens the possibility to decommission or **rationalise some terrestrial-based PNT systems**. This would permit cost savings on the installation, operation, and maintenance of the terrestrial infrastructure. It would also release the associated electromagnetic radio spectrum.

GNSS signals, however, are vulnerable to natural and artificial interference, and to intentional attacks like jamming and spoofing. Thus, for critical applications or critical infrastructure protection, it is broadly accepted that GNSS, even in a multi-constellation and multi-frequency environment, should not be the unique source of PNT information. For those applications, an **alternative PNT** solution (back-up but also complementary) should be developed and maintained, not necessarily based on radio frequency technologies.

In the European Union (EU), the European Commission (EC) manages the **European Global Navigation Satellite Systems (EGNSS)** Galileo and EGNOS. **Galileo** is EU's autonomous GNSS under civil control, offering state-of-the-art PNT services to users worldwide. **European Geostationary Navigation Overlay System (EGNOS)** is the EU augmentation system that improves (accuracy, integrity) existing navigation signals generated from Global Positioning System (GPS), and Galileo in the future. EGNOS enables the use of GNSS signals in safety-of-life applications, most notably in the aviation sector.

The **use of GNSS services is multiple**. To name a few, GNSS services are currently used to improve traffic flows and vehicle efficiency, help track parcels and shipments by providing added-value logistic solutions, facilitate civil protection operations in harsh environments, speed up rescue operations and provide critical tools to coastguard and border control authorities. GNSS is also a formidable instrument for the timestamping required in financial transactions, scientific research in areas like meteorology, atmospheric science, geophysics, and geodesy and for key critical economic activities.

Although the use of GNSS is increasing, the services offered by **GNSS** are **not yet fully exploited** in all market sectors. Furthermore, the use of autonomous, unmanned and remotely controlled vehicles is experiencing an exponential growth. Considering the role that GNSS services can play in all these market sectors, there is a clear need for the EU to take full advantage of the benefits that Galileo and EGNOS can offer and facilitate their adoption sector by sector.

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[1] Acronyms are defined in APPENDIX F: ACRONYMS, including those in figures and tables.

1.1 Context of the European Radio Navigation Plan (ERNP)

The context at the time of writing this version of the European Radio Navigation Plan (ERNP) – year 2023 – plays a significant role in the ambition, the scope, and the objectives of this version of the ERNP. The major contextual elements for this edition of the ERNP are the following ones:

1. The **Space Strategy for Europe**, published in 2016, requested the European Commission to 'release a European radio navigation plan to facilitate the introduction of global navigation satellite system applications in sectoral policies'. On this basis, a first version of the ERNP was published in 2018.

   The current document, which is the second version of the ERNP, still has as main objective to 'facilitate the introduction of Galileo and EGNOS applications in different market domains'.

2. The **European Court of Auditors** issued in **2021** a **Special Report** on the EU Space programmes Galileo and Copernicus and the need to further boost the update of their data and services.

   The recommendation 4c on the better use the regulatory framework to support the uptake of EU space services, requests the European Commission 'to define time schedules for each relevant market segment, where regulation or standardisation can facilitate the use of Galileo and closely monitor them'. Hence, the objective of this version of the ERNP is to address this recommendation.

3. There is an **increased importance of PNT services, mainly based on GNSS**, for the economy and society. This increased importance is not only related to positioning and navigation services but also to timing services (key for finance, power grids, communication, etc). This trend will continue to grow in the following years.

   Space services and data are an **important enabler for the digital transformation** of the economy and society and empower digital innovations such as autonomous vehicles, smart solutions and 5G/6G wireless telecommunication networks.

4. **There is an increased number of disruptions of GNSS services** due to the relatively low power of the GNSS signals. Simple low-cost devices can cause deliberate interference to frequencies used by GNSS with the intention to disrupt GNSS signal reception (i.e., 'jamming') and jammers with much higher power that can impact on a much wider area. GNSS services can also be 'spoofed' with false information leading to errors in the PNT solution. Finally, GNSS services may suffer from severe degradation of performance due to space weather events or system failures.

   At the same time, there is **increased awareness of the GNSS interference and measures to improve the resilience of GNSS signals are proposed** (e.g., European Union and United States cooperation on satellite navigation with focus on service resilience).

   This version of the ERNP will discuss both how GNSS services are becoming more resilient (i.e., Galileo new services including authentication) and how other technologies could deliver PNT services even upon GNSS disruptions.

5. **PNT services are fundamental for emerging applications and some emerging technology will deliver PNT services too.**

   Examples of the former is the use of **GNSS in the positioning** of Low Earth Orbit (LEO) multi-constellations (required to control the constellation) or space objects (required for a Space Traffic Management system) or the use of **GNSS for** 5G and 6G technologies **sub-microsecond** worldwide

timing accuracies. Examples of the latter are **LEO constellations aiming to deliver PNT** services and future capabilities of **5G and 6G networks targeting the delivery of accurate PNT** services.

This version of the ERNP will discuss the emerging technology that is related to PNT services.

6. **Strategic PNT autonomy**: Strategic autonomy is a policy objective of the European Union under the von der Leyen Commission. The EU is taking steps to reinforce the European strategic autonomy in various domains such as the EU's economic and financial strategic autonomy or the Strategic Compass for Security and Defence. The Strategic Compass calls for the adoption, by the end of 2023, of an **EU Space Strategy for security and defence**.
7. Last but not least, the **EU Space Programme Regulation (EU) 2021/696** defining the services of the European satellite navigation systems and the **European Commission's Priorities for 2019-2024** where PNT services and GNSS in particular contribute majorly (e.g., European Green Deal, Europe fit for the digital age).

1.2 Purpose of the ERNP

Considering the above contextual information, the purpose of this edition of the ERNP is the following:

1. **Provide relevant information on PNT systems and services**, their use, typical performance, strengths, weaknesses, developments, trends, challenges, opportunities, etc.

   The intention of this version of the ERNP is to provide synthetic and summarised information of PNT systems and services and to further refer to public sources for more detailed information.
2. **Facilitate the uptake of the European GNSS (Galileo and EGNOS) services** by:
   - Providing detailed information on EGNSS (European GNSS) current and future services and their added value with respect to other PNT/GNSS services.
   - Recommending, per each sector, actions to be implemented at EU level for the uptake of EGNSS in the various market domains (e.g., legislation, standards).
3. Raise awareness and recommend actions to be taken to **increase the resilience of PNT services in the EU.**

1.3 Scope of the ERNP

The following aspects are within the scope of the current edition of the ERNP:

1. Most relevant **space based and terrestrial PNT** systems and services, including those which are not radio frequency based.
2. **Current use and expected future-use** of the PNT system and services.
3. **Emerging PNT systems and services** (LEO, 5G, sensor-fusion, etc.) as far as they are to play a major role on PNT.

It is not in the scope of the current ERNP version to describe the systems and technologies which are not used primarily for positioning, navigation, or timing, such as for instance surveillance systems (e.g., radars, cameras).

1.4 Objectives of the ERNP

Considering the context, purpose and scope presented in the previous sections, the current version of the ERNP has the following objectives:

1. **Introduce PNT** and highlight its important **role in society,** the **economic benefits** it creates and the **potential impact of PNT disruptions** if/when they exist, notably on Critical Infrastructure.
2. Provide an overview on **PNT user needs** in the various market sectors.
3. Explain the **challenges of PNT/GNSS** and the **trends and opportunities** for PNT/GNSS services**.**
4. Provide an overview of the **major PNT systems** and services, including conventional, GNSS and emerging systems, with their current and future use and typical performance, developments, strengths, and weaknesses. Provide information on the **interoperability and compatibility** of PNT systems and services.
5. Provide an overview on the relevant **international policies** related to PNT.
6. Provide **detailed information of the European GNSS services** (Galileo and EGNOS) highlighting their added value with respect to other GNSS services and including future planned services.
7. Explain the **European Union policies** related to PNT, including the on-going activities to facilitate the introduction of the European GNSS in EU policies.
8. Recommend, per market sector and when relevant:
    - **Actions to facilitate the introduction of EGNSS**, including Regulations and Standards.
    - **Actions to increase the resilience of PNT services**.
9. Provide a **medium-term vision** on how PNT should evolve in the European Union.

1.5 Structure of the ERNP

The current version of the ERNP will be structured as follows:

- Section 1 covers the Introduction and includes the context, purpose, scope, the objectives, and the structure of the document.
- Section 2 discusses the PNT Landscape covering the objectives 1 to 5 and includes an introduction to PNT, its role in society, economic benefits, PNT user needs per market segment, challenges, trends and opportunities, the overview of the major PNT systems and services, their interoperability and compatibility and the main international PNT policies.
- Section 3 discusses the EU PNT covering the objectives 6 to 8 and includes the EU Space Programme, the main services provided by the European GNSS systems Galileo and EGNOS and the current EU policies related to PNT per market segment together with the additional actions that would facilitate the uptake of Galileo and EGNOS services and/or increase the resilience of PNT services. It also includes the EU cooperation activities on GNSS.
- Section 4 provides the medium-term view of the EU PNT covering the objective 9.
- The various appendixes provide detailed information of the various aspects described in the document.

1.6 Comments to the ERNP

Comments to the ERNP are welcome and will be considered for the next update of the document: mailto:DEFIS-GNSS-ERNP@ec.europa.eu.

2 PNT LANDSCAPE

This section discusses the PNT landscape and covers the objectives 1 to 5 introduced in section 1.4. It allows the reader to get relevant summary information on PNT systems, services, user needs, challenges, trends, and opportunities and PNT international policies. It sets the basis for the following section where the EU PNT will be discussed.

The section will:

- Introduce PNT (section 2.1).
- Describe the role of PNT / GNSS in society (section 2.2).
- Assess the economic benefits of PNT / GNSS (section 2.3).
- Summarise user needs per market segment (section 2.4).
- Describe the PNT / GNSS challenges (section 2.5).
- Describe the PNT / GNSS trends and opportunities (section 2.6).
- Summarise the major PNT systems and services (section 2.7).
- Describe the importance of interoperability and compatibility (section 2.8).
- Summarise the major International PNT policies (section 2.9).

The section intends to provide an overview of the above-mentioned topics while providing the public references for further detailed information.

2.1 Introduction to PNT

PNT (Position, Navigation and Time) describes a combination of three distinct yet integral capabilities:

- Positioning is the ability to determine one's location and orientation in two or three dimensions. This position is referenced to local or, most commonly, a global coordinate system such as Galileo Terrestrial Reference Frame (GTRF), European Terrestrial Reference Frame (ETRF) or International Terrestrial Reference Frame (ITRF).
- Navigation is the ability to determine a path between current and desired position (relative or absolute), as well as navigate this path by applying corrections to course, orientation, and speed.
- Timing is the ability to acquire and maintain time either locally or globally (for example Coordinated Universal Time, or UTC). This also includes time transfer service.

The main feature of the modern PNT is the ability to **accurately determine and maintain both position and time in the global reference frame** (GTRF, ETRF, ITRF etc. for position and UTC for timing), anywhere in the world, noting that different PNT systems will have different geographical ranges, from global to regional and local.

Throughout the document, the following key concepts will be used:

- **User performance indicators** typically used when assessing PNT services performance:
    - Availability: the percentage of time the position, navigation or timing solution can be computed by the user. Values vary greatly according to the specific application and services used, but typically range from 95% to 99.9%.
    - Accuracy: the difference between true and computed user solution (for position or time).
    - Integrity: the measure of trust that can be placed in the correctness of the position or time estimate provided by the receiver.
    - Continuity: the ability to provide the required performances during an operation without interruption once the operation has started.
- **Other relevant performance indicators** for PNT receivers:
    - Time To First Fix (TTFF): a measure of a receiver's performance covering the time between activation and output of a position within the required accuracy bounds.
    - Robustness to spoofing and jamming: a qualitative rather than quantitative parameter that depends on the type of attack or interference the receiver is capable of mitigating.
    - Authentication: the ability of the system to assure the users that they are utilising signals and/or data from a trustworthy source, and thus protecting sensitive applications from spoofing threats.

2.2 Role of PNT in society

Facing global challenges such as the digital revolution, climate change and global pandemics, the economy and society relies more than ever on innovative solutions which can deal with big data, mitigate natural and human-made disasters and diseases, and strengthen a global supply chain that underpins our daily lives. **PNT and GNSS play a vital role in contributing to these innovative solutions** through thousands of applications that are emerging or already in use by citizens, governments, international organisations, NGOs, industry, academia and researchers around the world (European Union Agency for the Space Programme – EUSPA EO and GNSS Market Report 2022). The overall installed base of GNSS devices will grow from 6.5 billion units in 2021 to 10.6 billion units in 2031. The lion's share of the installed base is dominated by the Consumer Solutions segment.

Apart from those market driven forces, the environment sustainability plays an important role. The **European Green Deal** aims for a climate-resilient society in an age when some European economies are still heavily reliant on coal and fossil fuels. This initiative is considered one of the most consequential legislative efforts in the history of the European Union, comprehensive of every aspect of society and the economy and across all policy areas. Arguably the best-known objective of the European Green Deal consists of cutting carbon dioxide net emissions to zero by 2050, and already by 55% by 2030 (compared to 1990 levels). And while Europe has already cut a quarter of its emissions since the 1990s, this is still not enough to reach the stated 2030 and the 2050 objectives. **EU Space data and services contribute to the European Green Deal** through positioning, navigation and timing used, for instance, in smart farming, as well as for reduction of road, maritime and aviation emissions through route optimisation. Moreover, the EU provide funding and support for entrepreneurs using Copernicus and Galileo data, which predominantly results in financing 'green' applications, while stimulating the relevant markets.

Another important driving factor of our society is the **digital transformation**, which Europe has envisaged within the 2030 timeframe. **Spatial information is profiling as an integrator**, paving the way for a common, open, and innovative digital infrastructure, rather than a simple point location enabler for applications. Artificial Intelligence (AI)-based analysis of big-data promises to revolutionise the use of satellite data for tasks that include quantification of global urbanisation, the nourishment of the world's population, as well as improving the management of natural hazards or pandemics.

More satellites and more frequencies will bring a wealth of advantages. Dual frequency is already required for carrier phase-based algorithms (Real Time Kinematic (RTK), Precise Point Positioning (PPP) and PPP-RTK) and triple frequency can further improve the performance of the phase ambiguity resolution algorithms in terms of the maximum separation from a reference station (for RTK and Network RTK), the reliability of the solution and the time required to obtain and validate this solution.

However, **cyberattacks, including Radio Frequency Interference (RFI) of GNSS signals** is one of the most relevant aspects to be considered. GNSS jamming incidents are reported in increasing numbers, most of them caused by so-called 'privacy protection devices' (illegal in most countries). GNSS spoofing incidents are also increasing, though less frequently. GNSS services should be able to response to these threats by including monitoring and **authentication capabilities** as a necessary building block of the overall application security, without prejudice to other techniques.

Finally, it is fundamental to consider PNT services through the system of systems **'sensor fusion'** perspective, the paradigm for autonomous driving and other demanding applications, increasing integrity, availably and accuracy of the service. Indeed, future evolution is expected to take place at the level of effectiveness of sensor fusion techniques. The vision is not to have one technology as the 'primary' means of PNT but rather a combination of all the relevant existing PNT technologies.

2.3 Economic benefits of PNT / GNSS

PNT and GNSS have become a ubiquitous utility for millions of people across Europe. Many aspects of our daily lives are facilitated by invisible GNSS signals from space – from checking the status of our early morning commute to watching our favourite TV shows before bed.

EUSPA analysis on the socio-economic benefits provided by GNSS[2] shows **total GNSS economic benefits of total EUR 2 trillion** in European territory (defined as the EU27 plus the United Kingdom (UK), Norway, and Switzerland) over the period of analysis (1999-2027). In addition to this, over the same period more than 100 000 high-paying, highly skilled jobs were also estimated to be attributable to GNSS across Europe in the downstream and upstream industries.

Reports focusing on the United Kingdom and United States (US) estimate both the economic benefits produced by GNSS in the relevant economy and the economic losses expected as a result of a temporary outage of GNSS. For loss estimates, the relevant counterfactual in each application is technology that is available for immediate deployment in the event of an outage (rather than against any theoretically feasible technology, as in the case of benefits), meaning loss and benefit estimates vary significantly. The results of the UK, US, and EU studies are summarised in the next table.

Table 1 –Summary of reported economic benefits and losses

Study focus	Economic benefits (annual)	Economic loss	Economic loss (per day)
UK	GBP 6.7 billion	GBP 5.2 billion (5 days)	GBP 1.0 billion
US	USD 300 billion	USD 30.3 billion (30 days)	USD 1.0 billion
Europe	EUR 69.0 billion	Not Available	Not Available

The discrepancies in the reported values suggest that **careful analysis** of the European states would be required **before extending or generalising the findings to the European context**. Some of the important differences that would have to be considered include geographical differences such as population density, cultural differences reflected in population attitudes and legal frameworks, study methodology differences such as scope of analysis (i.e., economic sectors considered, or satellite constellations included in analysis) and choice of counterfactuals, infrastructure differences with implications for resilience or available technology and time period differences that impact estimated total impacts and averaged 'daily' values.

It is important to note that the RAND report argues that **cost of GNSS outage might be overstated**, possibly by orders of magnitude, as for many industries backups are already operational.

In summary and despite the differences and opinions reported above, we can affirm that GNSS provides **annually hundreds of billions of euro** to the worldwide **wealth**, while a few-days GNSS outage could imply an **economic loss** of up to several **billions of euro per day** worldwide.

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[2] To assess the economic benefits generated by GNSS in Europe, the study compared the quality of services enabled by GNSS with a counterfactual case where the next-best technologically feasible solution had been developed instead. In many cases these hypothetical solutions have not actually been developed at the required scale – due in large part to the low cost, high performance, and wide availability of GNSS

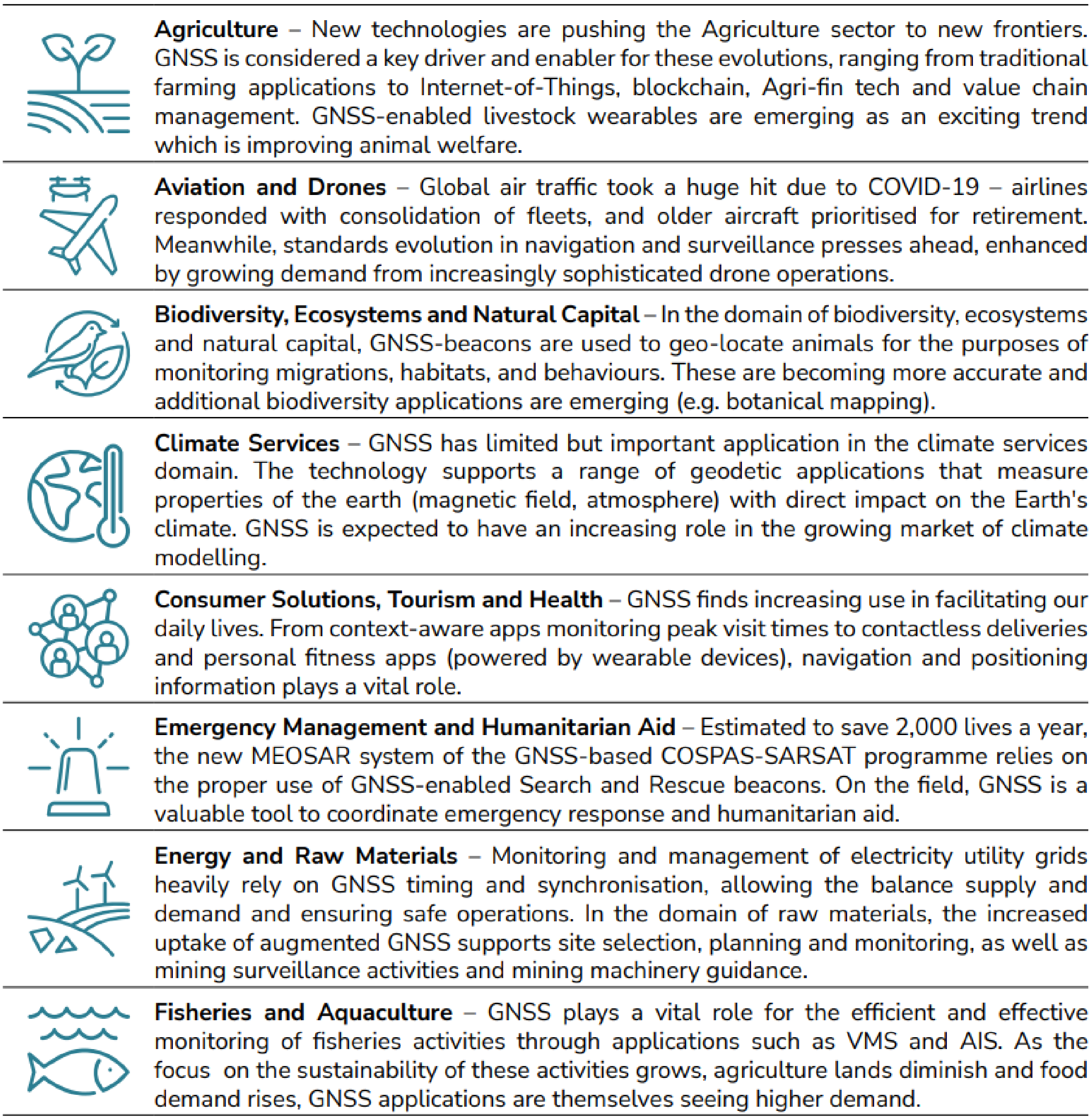
2.4 PNT user needs

The user needs for PNT services are widely described in the **EUSPA user needs and requirements reports**. These reports include a market overview, trends, user requirements analysis and specifications for various market segments.

In addition, the **EUSPA EO and GNSS Market Report 2022** provides a detailed description of the use of PNT/GNSS services in various market domains and an overview of the main applications.

Other non-EU documents provide similar information, such as the US report Economic Benefits of the Global Positioning System (GPS) and the US Federal Radionavigation Plan.

Figure 1 provides an overview of the role and trend of GNSS across various market segments.



Agriculture – New technologies are pushing the Agriculture sector to new frontiers. GNSS is considered a key driver and enabler for these evolutions, ranging from traditional farming applications to Internet-of-Things, blockchain, Agri-fin tech and value chain management. GNSS-enabled livestock wearables are emerging as an exciting trend which is improving animal welfare.

Aviation and Drones – Global air traffic took a huge hit due to COVID-19 – airlines responded with consolidation of fleets, and older aircraft prioritised for retirement. Meanwhile, standards evolution in navigation and surveillance presses ahead, enhanced by growing demand from increasingly sophisticated drone operations.

Biodiversity, Ecosystems and Natural Capital – In the domain of biodiversity, ecosystems and natural capital, GNSS-beacons are used to geo-locate animals for the purposes of monitoring migrations, habitats, and behaviours. These are becoming more accurate and additional biodiversity applications are emerging (e.g. botanical mapping).

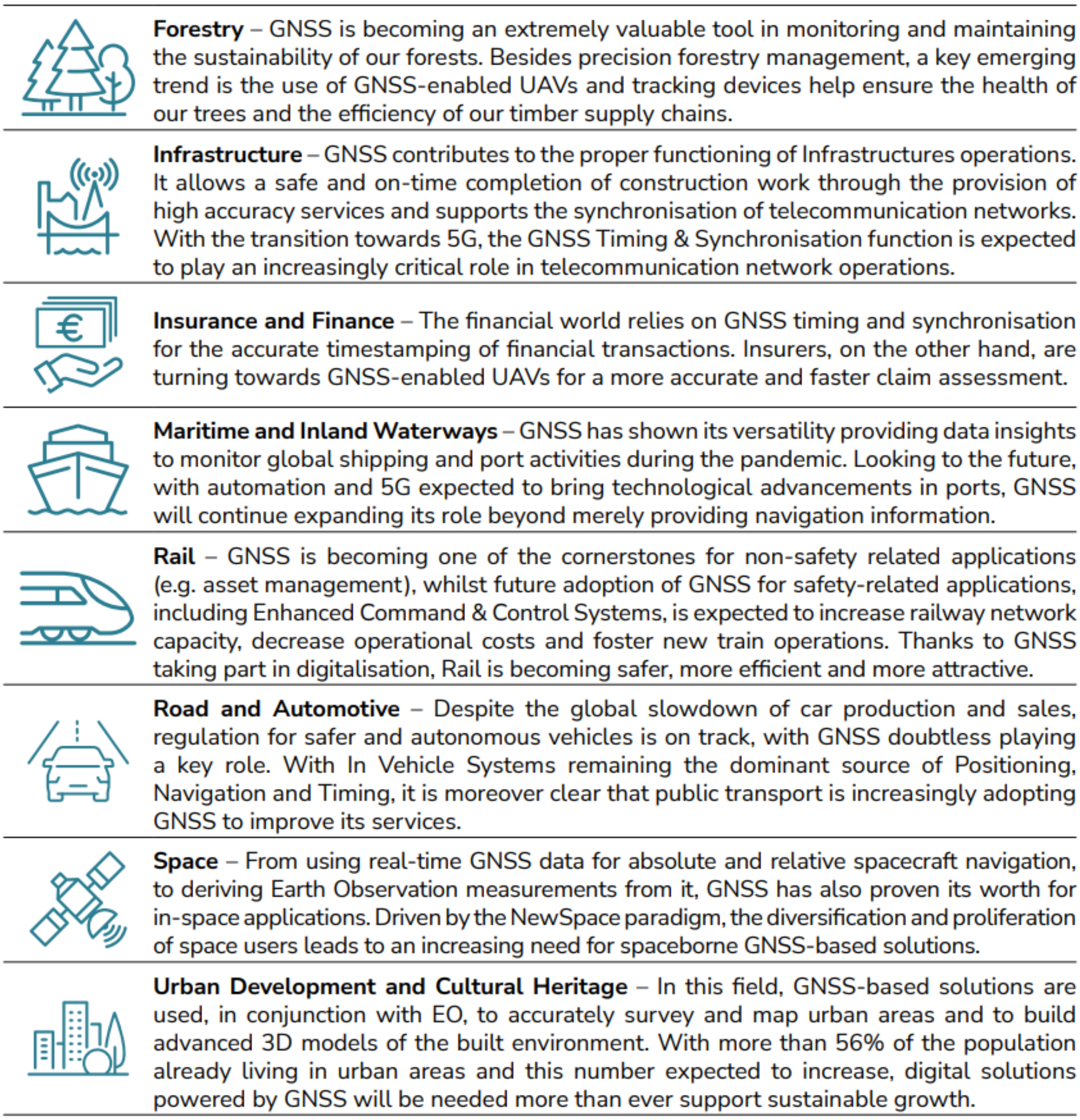
Climate Services – GNSS has limited but important application in the climate services domain. The technology supports a range of geodetic applications that measure properties of the earth (magnetic field, atmosphere) with direct impact on the Earth's climate. GNSS is expected to have an increasing role in the growing market of climate modelling.

Consumer Solutions, Tourism and Health – GNSS finds increasing use in facilitating our daily lives. From context-aware apps monitoring peak visit times to contactless deliveries and personal fitness apps (powered by wearable devices), navigation and positioning information plays a vital role.

Emergency Management and Humanitarian Aid – Estimated to save 2,000 lives a year, the new MEOSAR system of the GNSS-based COSPAS-SARSAT programme relies on the proper use of GNSS-enabled Search and Rescue beacons. On the field, GNSS is a valuable tool to coordinate emergency response and humanitarian aid.

Energy and Raw Materials – Monitoring and management of electricity utility grids heavily rely on GNSS timing and synchronisation, allowing the balance supply and demand and ensuring safe operations. In the domain of raw materials, the increased uptake of augmented GNSS supports site selection, planning and monitoring, as well as mining surveillance activities and mining machinery guidance.

Fisheries and Aquaculture – GNSS plays a vital role for the efficient and effective monitoring of fisheries activities through applications such as VMS and AIS. As the focus on the sustainability of these activities grows, agriculture lands diminish and food demand rises, GNSS applications are themselves seeing higher demand.



Forestry – GNSS is becoming an extremely valuable tool in monitoring and maintaining the sustainability of our forests. Besides precision forestry management, a key emerging trend is the use of GNSS-enabled UAVs and tracking devices help ensure the health of our trees and the efficiency of our timber supply chains.

Infrastructure – GNSS contributes to the proper functioning of Infrastructures operations. It allows a safe and on-time completion of construction work through the provision of high accuracy services and supports the synchronisation of telecommunication networks. With the transition towards 5G, the GNSS Timing & Synchronisation function is expected to play an increasingly critical role in telecommunication network operations.

Insurance and Finance – The financial world relies on GNSS timing and synchronisation for the accurate timestamping of financial transactions. Insurers, on the other hand, are turning towards GNSS-enabled UAVs for a more accurate and faster claim assessment.

Maritime and Inland Waterways – GNSS has shown its versatility providing data insights to monitor global shipping and port activities during the pandemic. Looking to the future, with automation and 5G expected to bring technological advancements in ports, GNSS will continue expanding its role beyond merely providing navigation information.

Rail – GNSS is becoming one of the cornerstones for non-safety related applications (e.g. asset management), whilst future adoption of GNSS for safety-related applications, including Enhanced Command & Control Systems, is expected to increase railway network capacity, decrease operational costs and foster new train operations. Thanks to GNSS taking part in digitalisation, Rail is becoming safer, more efficient and more attractive.

Road and Automotive – Despite the global slowdown of car production and sales, regulation for safer and autonomous vehicles is on track, with GNSS doubtless playing a key role. With In Vehicle Systems remaining the dominant source of Positioning, Navigation and Timing, it is moreover clear that public transport is increasingly adopting GNSS to improve its services.

Space – From using real-time GNSS data for absolute and relative spacecraft navigation, to deriving Earth Observation measurements from it, GNSS has also proven its worth for in-space applications. Driven by the NewSpace paradigm, the diversification and proliferation of space users leads to an increasing need for spaceborne GNSS-based solutions.

Urban Development and Cultural Heritage – In this field, GNSS-based solutions are used, in conjunction with EO, to accurately survey and map urban areas and to build advanced 3D models of the built environment. With more than 56% of the population already living in urban areas and this number expected to increase, digital solutions powered by GNSS will be needed more than ever support sustainable growth.

Figure 1 – Role & key trends of GNSS across markets (Credit: EUSPA EO and GNSS Market Report 2022)

2.5 PNT / GNSS Challenges

GNSS signals, which are received with very low power level, are **vulnerable** to radio-frequency interference (RFI) and to natural phenomena (e.g., ionospheric scintillation) which can lead to disruption of GNSS services. Such phenomena can be **deliberate** (**jamming and spoofing** attacks) but can also be **unintentional** (spurious radiation of other radio devices, GNSS multipath propagation).

Although GNSS vulnerabilities are now commonly acknowledged, the **trust** of PNT-based systems or applications goes beyond GNSS and must encompass the **end-to-end-application**, which is only as safe or secure as its weakest component. GNSS is not necessarily the easiest part to attack for maleficent actors: it might be easier or cheaper to hack the output of a receiver to report fake positions than to spoof the incoming GNSS signals. This is for instance how maritime Automatic Identification System (AIS) report positions thousands of km away from the vessel's true position, which is today out of reach of any spoofer.

The International Telecommunications Union issued in July 2022 the Circular Letter CR/488 for the prevention of harmful interference to Radio Navigation Satellite Service Receivers. International Civil Aviation Organization (ICAO) Assembly Resolution A41-8C encourages States to take actions to ensure the resilience of Communication/Navigation/Surveillance and Air Traffic Management (CNS/ATM) systems and services, invites ICAO to obtain more resilient positioning and timing services and encourages standardisation bodies and industry to develop appropriate interference detection, mitigation, and reporting capabilities for the aircraft on-board, satellite- and ground-based CNS system components.

The Radio Equipment Directive 2014/53/EU (RED) establishes the essential requirements that PNT-based devices have to fulfil in order to be placed on the EU market. The RED is the EU legal act that obliges the manufacturers of radio equipment, including GNSS transmitters and receivers, to make an efficient use of the radio spectrum. In other words, RED-compliant products avoid the production of harmful interferences, that constitute the elements that may affect the radio navigation services. The use of harmonised standards in support of the RED developed by the European Standardisation Organisations provides with presumption of conformity to the legal requirements.

Additionally to the measures established in the harmonised standards that reflect the state of the art of the technology, there are today several measures to that may be used to **protect against GNSS jamming and spoofing**:

- **Ensure a clean RF environment** and the use of frequency bands allocated by the International Telecommunication Union is the very first layer of protection for GNSS users.
- **Authenticate the GNSS signals**: GNSS authentication is achieved by incorporating specific features that cannot be predicted or forged by malicious actors in the broadcast signals. A receiver enabled for authentication can interpret these features to distinguish genuine signals from imitations. This can be done at two complementary levels: at the data level, to authenticate the broadcast navigation messages and the range level, to authenticate the measured ranges to the satellites.
- **Use multiple sources of positioning information** to cross-check the solution with independent measurements. This can be done by using multiple constellations and possibly multiple frequencies and/or by complementing GNSS solution with other technologies (as an example, smartphones typically contain many sensors than can be used to provide redundant positioning or movement information).

- **Use a better antenna set up:** adaptive antennas (CRPA) can be a very efficient tool against jamming or simpler configurations (2 antennas) can provide direction of arrival information, which is very useful in detecting incoming spoofing signals.
- **Implement dedicated receiver techniques:** for instance, those based on the monitoring of the signal power or carrier to noise density ratio (C/N0), time of arrival (TOA) discrimination, distribution checks of correlator outputs and consistency checks among different measurements such as ephemeris data, clock offset change or code and carrier Dopplers.
- **Implement Signal Quality Monitoring (SQM) techniques**: originally designed for multipath detection and waveform deformation monitoring, can be used to identify the deformation of the correlation function of typical spoofing attacks. The challenge for spoofing detection and rejection is to discriminate between true signals and unwanted signals. Multipath detection has the same objective and similar techniques are therefore proposed.

  Novel innovative approaches to the correlation process, such as the 'Supercorrelator', claim the capability to separate line of sight and non-line of sight signals during the correlation process, providing multipath mitigation, anti-spoofing, and signal arrival-angle determination. As powerful as they are, such methods are currently implemented only in sophisticated high-grade receivers, but **not widely available in other GNSS chipsets**.

Associated to the low power of GNSS signals, GNSS solutions are mostly unavailable in some environments, such as indoors, underground, or urban canyons. In those environments a mix of technologies (e.g., **hybridisation of GNSS or sensor fusion**) is used to achieve seamless PNT.

Indoor penetration together with high availability, low power consumption and short Time-To-First-Fix (TTFF) are the key requirements for the high-volume market (e.g., consumer solutions, Internet of Things (IoT), automotive solutions, drones, robotics).

Further information can be found in the EUSPA Market Report 2022 and EUSPA Technology Report.

2.6 Trends and Opportunities

The following trends are observed for PNT and GNSS services:

1. **Multi-constellation, multi-frequency is the new norm**

   The four global systems (GPS – US, Galileo – EU, GLONASS – Russia and BeiDou – China), the regional systems (QZSS – Japan and IRNSS – India) and the various SBAS (US, EU, etc.) amount to **100+ satellites**, that thanks to international coordination, have open signals, compatible frequency plans, common multiple access schemes (with GLONASS adding CDMA to its legacy FDMA scheme) and modulation schemes (e.g., Galileo E1 and GPS L1C). This facilitates the design of multi-constellation GNSS chipsets and receivers, to the benefit of end users.

   Furthermore, all global and regional constellations broadcast **open signals in common multiple frequency bands** and SBAS will emulate them with plans to upgrade services to multiple frequencies and multiple constellations in the coming years.

   In addition to the baseline interoperable open signals, each global/regional constellation provides specific services through dedicated signals and frequencies. This is the case of governmental services such as Galileo Public Regulated Service (PRS) or GPS Precise Positioning Service (PPS), as well as value-added services (e.g., Galileo High-Accuracy Service (HAS), QZSS L6 or BeiDou short messaging service).

   Dual-frequency receivers offer significant advantages over single-frequency receivers in terms of achievable accuracy, but also in terms of improved resistance to interference (owing to frequency diversity). Historically, dual-frequency use has been limited for many years to professional or governmental users and to expensive L1 + L2 receivers. The advent of four full GNSS constellations that provide high quality open signals in the E5 frequency band has been a game changer, and has triggered widespread availability of E1 + E5 dual frequency chipsets for the mass market

2. **Receivers, processing methods and antennas are continuously evolving for better performance**

   The evolution of receiver design is enabled by **technological developments** in the **semiconductor industry**, including **increased processing power** to support more GNSS channels, and the development of **low-cost sensors** that allows tighter coupling with different technologies and brings positioning to GNSS-deprived locations. Simultaneously, market pressures exert a pull towards increased accuracy, improved performance in all environments, reduced time-to-first-fix (TTFF) and robustness against jamming or spoofing.

   GNSS errors are usually reduced via two modelling methods: the Observation Space Representation (OSR) provides a single compound ranging correction as observed in a nearby (real or virtual) reference station, while in the State Space Representation (SSR) method, the various error sources are estimated separately by a network of continuously operating reference stations (CORS) before being sent to the receiver. Some parameters (e.g., environmental delays for PPP) are estimated inside the receiver rather than from CORS networks. The PPP-RTK method combines elements from both methods and provides scalable accuracy to all user segments, from mass market to high-accuracy. The **emergence of high-accuracy mass market applications** shows a strong potential for widespread utilisation of PPP-RTK.

   Geolocated IoT devices require the availability of position fixes for very low energy consumption. For this reason, there has been a push to significantly **reduce GNSS energy consumption** over recent years, resulting in rapid advancements in receiver technology (with sub 10 mW consumption in continuous tracking mode at 1 Hz) and the use of several innovative techniques. This includes mature solutions such as assisted GNSS (A-GNSS) or long-term ephemeris predictions, as well as novel hybrid approaches leveraging the connectivity intrinsic to the IoT.

Antennas are a critical part of any receiver design. The best chipsets and most sophisticated signal processing cannot compensate for poor antenna performance. While this importance has long been recognised in high-accuracy segments, other segments including the mass market are only now fully embracing this topic. Indeed, the widespread availability of dual frequency receivers is opening new possibilities, but antennas are a limiting factor for the overall performance.

3. **5G/6G enables ubiquitous connectivity and can contribute to positioning**

   Mobile technology has historically evolved from a people-to-people platform (3G) towards a people-to-information connectivity (4G). **5G** is the first mobile system designed to connect everything. 5G is expected to unleash a Massive Internet of Things (MIoT) ecosystem and critical communications applications, where networks can meet the communication needs of billions of connected devices, with the appropriate trade-off between speed, latency, and cost. **6G**, currently under development, is expected to support applications beyond current mobile use scenarios, such as virtual and augmented reality (VR/AR), ubiquitous instant communications, pervasive intelligence, and the evolution of Internet of Things (IoT).

   Contrary to previous radio networks generations, where positioning was only an add-on feature, **for 5G** mobile radio networks **the positioning is seen as an integral part of the system** and will play a key role, enabling a wide range of location-based services and applications. A key feature technology of 5G positioning is represented by wide band signals in the Frequency Range 2 (FR2), which consists of the operational frequencies that have been allocated to 5G in the mmWave region (above 24 GHz). These wide signals (up to 500 MHz bandwidth) are suitable for better time resolution but also accurate digital beamforming, which in turn enable highly accurate Time of Arrival (ToA) and Direction of Arrival (DoA) estimation especially in direct line-of-sight conditions. Independent 5G infrastructure can also act as an alternative source of PNT, as long as infrastructure does not depend on GNSS.

   It is expected that **complementing EGNSS with 5G** will be the core of future location engines for many applications in the Location Based Service (LBS) and IoT domains, with a significantly improved location performance in cities. With failsafe wireless connections, faster data speeds and extensive data capacity, 5G can provide the connectivity backbone required to enable **cooperative positioning** as well as the safe operation of driverless cars, drones, mobile robots and, more generally, the world of Autonomous Things.

   In the future, **6G** aims to achieve **centimetre-level positioning accuracy** thanks to the use of intelligent reflective surfaces, massive antenna arrays and advanced beamforming and promises to serve applications such as drone delivery, asset tracking, health care monitoring, precision agriculture and autonomous vehicles.

Further detailed information can be found in the EUSPA GNSS User Technology Report.

2.7 PNT systems and services

Historically, **conventional PNT systems**, based on terrestrial / ground-based infrastructure, have played a key role in enhancing and strengthening PNT, services, either in combination with, or independently from GNSS. There are different conventional systems, all making use of different physics principles to serve a special purpose, being the main one to provide an accurate and reliable position and timing solution which enables to navigate from one point in space to another in a safe manner, determining the position and providing derived information such as the speed and the course, to arrive to the desired destination.

Today, modern **PNT systems and services are underpinned by GNSS** thanks to their capacity to maintain world-wide position and time without incomparable performance. The availability of GNSS services is changing at a very fast pace and will continue to do so in the short and medium term. The last years have seen four GNSS (GPS, GLONASS, Galileo and BeiDou) being declared operational to provide global PNT services with multi-frequency capabilities. In addition, ground and space-based augmentation systems improve the performance of the GNSS signals for specific users and typically regionally or locally.

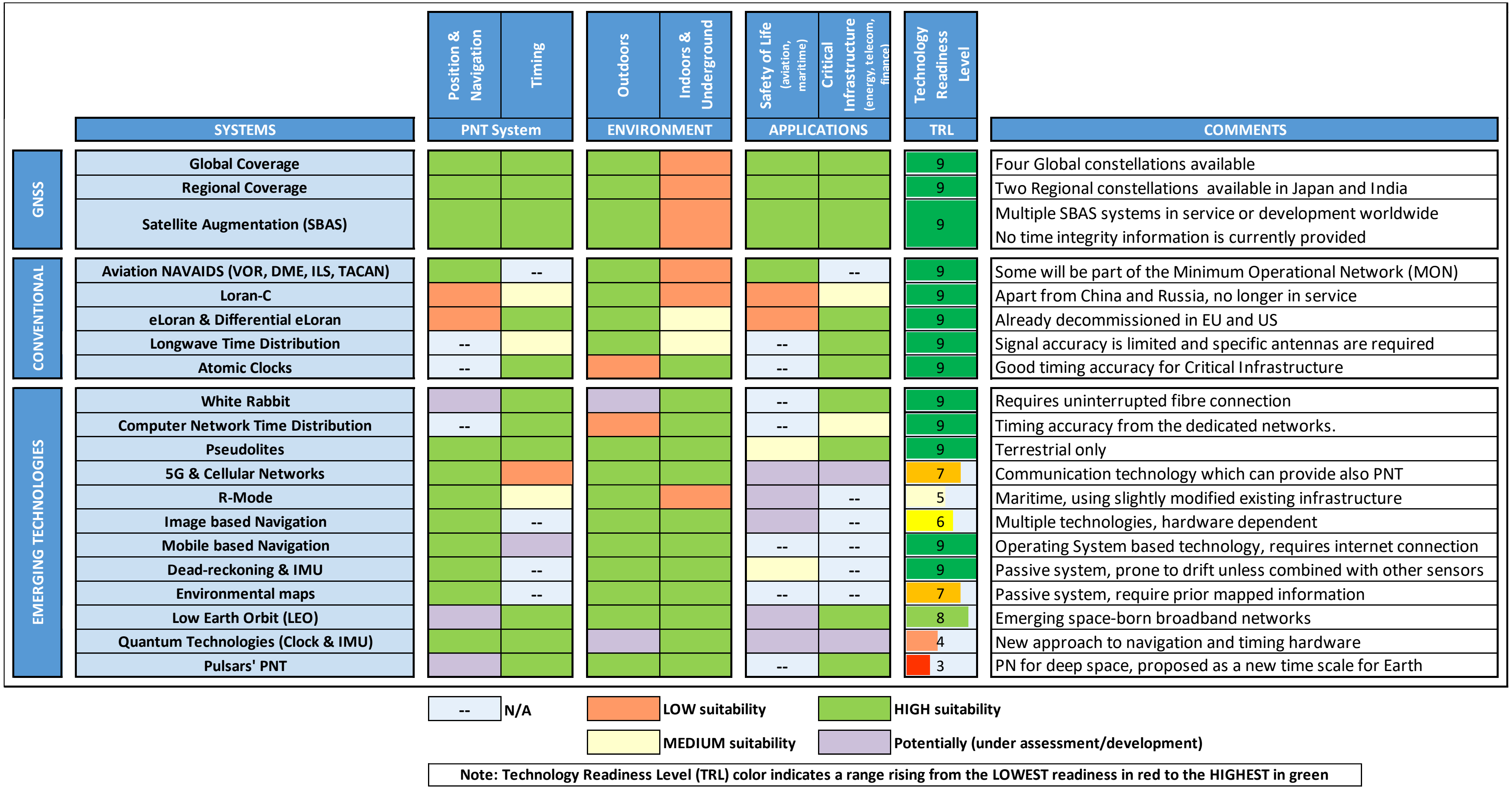
This panoply of interoperable GNSS services will allow **rationalisation** and even **decommissioning** of **conventional terrestrial PNT systems** which will generate maintenance and operational costs savings and electromagnetic spectrum rationalisation. For certain critical applications, like aviation, electricity or banking sectors or civilian emergency services, a backup navigation infrastructure will still be necessary to provide basic guidance capability in case of a GNSS malfunction or outage.

However, and despite is unbeatable success, GNSS services have also certain weaknesses linked mainly to the low power signals which can be easily interfered. This calls for the existence of **Alternative PNT** systems and services able to provide PNT capabilities independently from GNSS (normally with degraded performance). Moreover, Alternative PNT services can also complement GNSS services where GNSS signals are not available (e.g., indoors, underground) thanks to higher signals power. The combination of GNSS and Alternative PNT services enable **resilient PNT services** which are those PNT services that continue operating even upon the loss of GNSS services or in environments where GNSS solutions are not available.

Alternative PNT services can be provided by conventional PNT systems and/or by the so-called **emerging / new generation PNT systems**, which provide PNT services which typically have either lower performance than those of GNSS or with limited coverage or increased cost.

2.7.1 Overview of PNT Systems

All the PNT systems have as their main purpose to provide **accurate and reliable position and timing information** to enable the user device to obtain its location or navigate from one point to another or get synchronised to a time reference. Depending on the technology and nature of the different PNT systems, their suitability to deliver position, navigation or timing information to a specific application may vary. Figure 2 provides an overview on the different PNT systems when classified as **GNSS**, **Conventional** and **Emerging** technologies. The suitability is shown by colours, providing an indication of how each system behaves, depending on several factors such as its performance or deployment feasibility. When a system does not provide a certain functionality, it is indicated with a N/A. This helps in identifying which PNT systems could be more suitable for a particular environment or application, having in mind that other criteria such as for example geographic range, vulnerability to space weather or cost are not considered in this overview. These PNT systems will be described in the following sections with further detailed information provided in APPENDIX A: PNT Systems.



	SYSTEMS	PNT System: Position & Navigation	PNT System: Timing	ENVIRONMENT: Outdoors	ENVIRONMENT: Indoors & Underground	APPLICATIONS: Safety of Life (aviation, maritime)	APPLICATIONS: Critical Infrastructure (energy, telecom, finance)	TRL: Technology Readiness Level	COMMENTS
GNSS	Global Coverage	🟩	🟩	🟩	🟧	🟩	🟩	9	Four Global constellations available
	Regional Coverage	🟩	🟩	🟩	🟧	🟩	🟩	9	Two Regional constellations available in Japan and India
	Satellite Augmentation (SBAS)	🟩	🟩	🟩	🟧	🟩	🟩	9	Multiple SBAS systems in service or development worldwide No time integrity information is currently provided
CONVENTIONAL	Aviation NAVAIDS (VOR, DME, ILS, TACAN)	🟩	--	🟩	🟧	🟩	--	9	Some will be part of the Minimum Operational Network (MON)
	Loran-C	🟧	🟨	🟩	🟧	🟧	🟨	9	Apart from China and Russia, no longer in service
	eLoran & Differential eLoran	🟧	🟩	🟩	🟨	🟧	🟩	9	Already decommissioned in EU and US
	Longwave Time Distribution	--	🟨	🟩	🟨	--	🟩	9	Signal accuracy is limited and specific antennas are required
	Atomic Clocks	--	🟩	🟧	🟩	--	🟩	9	Good timing accuracy for Critical Infrastructure
EMERGING TECHNOLOGIES	White Rabbit	🟪	🟩	🟪	🟩	--	🟩	9	Requires uninterrupted fibre connection
	Computer Network Time Distribution	--	🟩	🟧	🟩	--	🟨	9	Timing accuracy from the dedicated networks.
	Pseudolites	🟩	🟩	🟩	🟩	🟨	🟩	9	Terrestrial only
	5G & Cellular Networks	🟩	🟧	🟩	🟩	🟪	🟪	7	Communication technology which can provide also PNT
	R-Mode	🟩	🟨	🟩	🟧	🟪	--	5	Maritime, using slightly modified existing infrastructure
	Image based Navigation	🟩	--	🟩	🟩	🟪	--	6	Multiple technologies, hardware dependent
	Mobile based Navigation	🟩	🟪	🟩	🟩	--	--	9	Operating System based technology, requires internet connection
	Dead-reckoning & IMU	🟩	--	🟩	🟩	🟨	--	9	Passive system, prone to drift unless combined with other sensors
	Environmental maps	🟩	--	🟩	🟩	--	--	7	Passive system, require prior mapped information
	Low Earth Orbit (LEO)	🟪	🟩	🟩	🟩	🟪	🟩	8	Emerging space-born broadband networks
	Quantum Technologies (Clock & IMU)	🟩	🟩	🟪	🟩	🟪	🟪	4	New approach to navigation and timing hardware
	Pulsars' PNT	🟪	🟩	🟩	🟩	--	🟩	3	PN for deep space, proposed as a new time scale for Earth

-- **N/A**

🟧 **LOW suitability**

🟩 **HIGH suitability**

🟨 **MEDIUM suitability**

🟪 **Potentially (under assessment/development)**

Note: Technology Readiness Level (TRL) color indicates a range rising from the LOWEST readiness in red to the HIGHEST in green

Figure 2 – Overview of PNT systems classified as GNSS, Conventional and Emerging

Figure 3 provides an overview of the PNT systems when classified as space and terrestrial systems:

- **Space PNT** systems include constellations of Medium Earth Orbit satellites (MEO) providing GNSS services (section 5.1), Geostationary satellites (GEO) providing GNSS augmentations (section 5.1.3.1) and also the emerging mega constellations of Low Earth Orbit satellites (LEO) (section 5.3.10).
- **Terrestrial PNT** systems include conventional PNT systems such as navigation aids for aviation and maritime or atomic clocks (section 5.2), GNSS augmentation systems such as differential or PPP systems (section 5.1.3.2) and emerging technologies such as 5G, quantum of environmental maps (section 5.3).

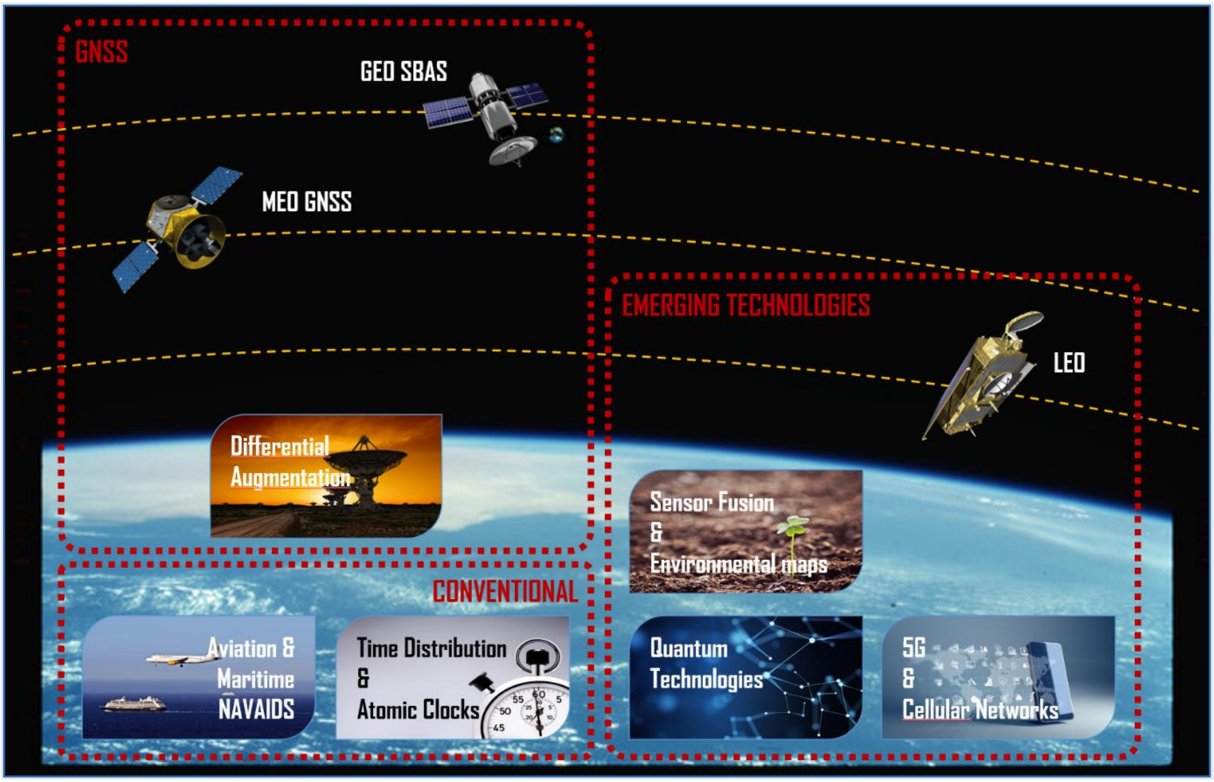


Figure 3 – PNT systems classified as Space and Terrestrial

2.7.2 Global Navigation Satellite Systems (GNSS) & Augmentations

Global Navigation Satellite System (GNSS) is a PNT infrastructure that allows users with a compatible receiver to process signals coming from satellites and determine the position, velocity, and time (PVT). Depending on their coverage, we distinguish between:

- Satellite Navigation Systems – Global coverage**:** Galileo (EU), GPS (USA), BeiDou (China), GLONASS (Russia).
- Satellite Navigation Systems – Regional coverage**:** QZSS (Japan), IRNSS (India).

GNSS performance can be improved by **augmentation systems**, which can be classified as:

- **Space-based**: those where the GNSS corrections are transmitted to users through satellites, and which provide *wide-area* augmentation information (i.e., continental scale).

  One type of these systems is the Satellite Based Augmentation Systems (SBAS) which provide services for aviation and where the following exist today: EGNOS (EU), WAAS (USA), MSAS (Japan), GAGAN (India), KASS (South Korea), ANGA (Central Africa), SouthPAN (Australia and New Zealand), BDSBAS (China) and SDCM (Russia).

  Another type of these systems is Precise Point Positioning (PPP) which enable real-time cm-level positioning accuracy by broadcasting GNSS corrections for a model of the GNSS satellite errors. PPP typically requires tens of minutes to achieve the final position accuracy.

- **Terrestrial-based**: those where the GNSS corrections are transmitted to users through terrestrial means (ground stations or Internet). They typically provide augmentation information to a *local area* (i.e., tens of km) but some also provide wide-area information through Internet (i.e., PPP).

  Some examples of the *local-area* systems are:

  - Ground Based Augmentation Systems (GBAS) which provide services for aviation with augmentation information including integrity (see section 2.1).
  - Differential GNSS (DGNSS) with augmentation information aimed to improve the accuracy of the user position and which is based on the processing of code GNSS measurements.
  - Real-time kinematic (RTK) which enable real-time cm-level positioning accuracy within few seconds thanks to the processing of phase GNSS measurements.

  Finally, trying to combine the best of the RTK and PPP worlds, PPP-RTK systems have appeared in recent years combining RTK quick initialisation times with the wide-area range of PPP.

- **Receiver-based**: those where the user receiver incorporates augmentation information from navigation sensors. An example of these systems is the Aircraft Based Augmentation Systems (ABAS), where the most widely used is Receiver Autonomous Integrity Monitoring (RAIM).

Detailed information on the various GNSS systems and augmentations is provided in APPENDIX A: PNT Systems while Galileo and EGNOS services will be discussed in detail in section 3.2 and 3.3 respectively.

The next figures provide an overview of the current GNSS and SBAS systems with some of their main characteristics and timeline.

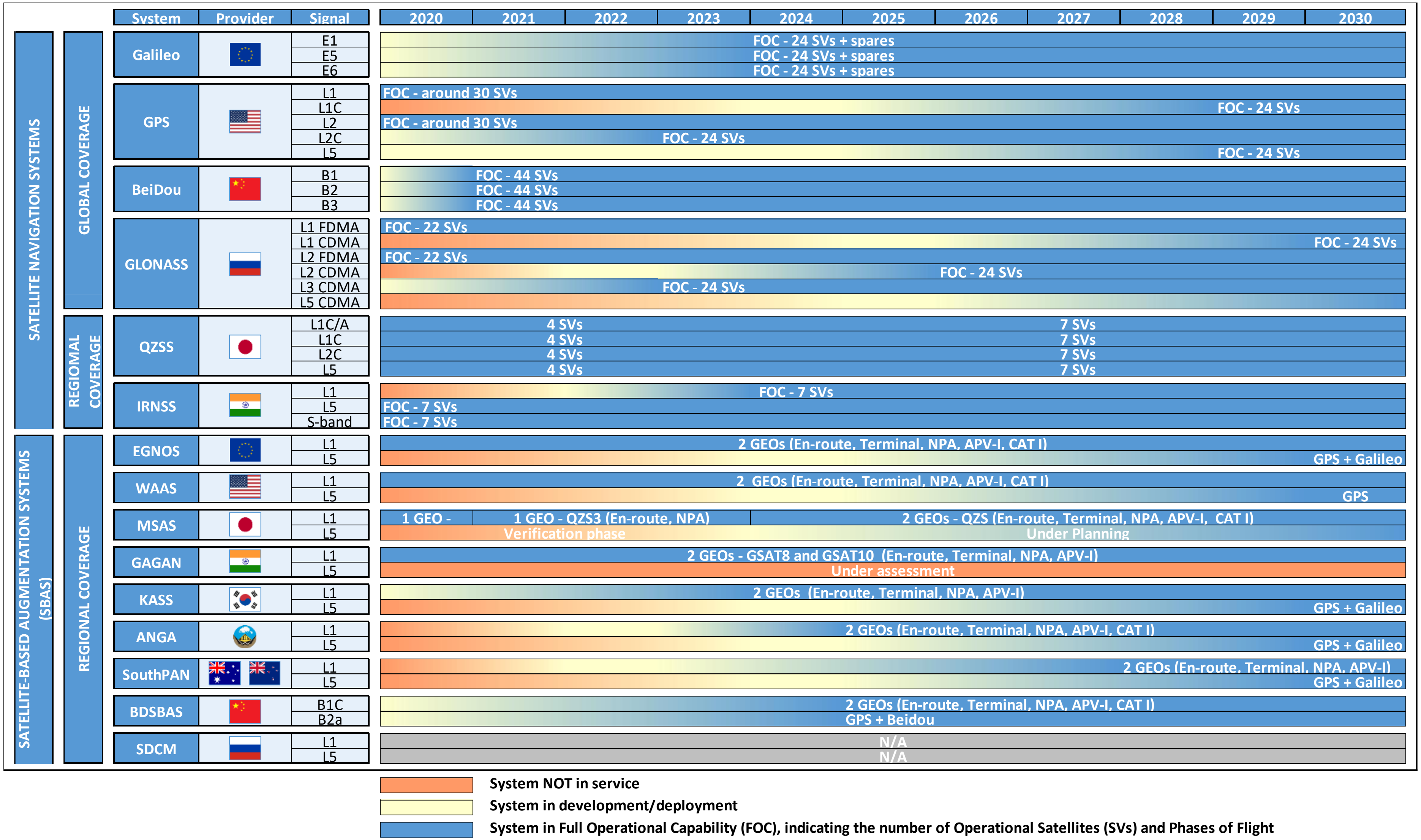


Figure 4 – Overview of GNSS Systems

2.7.3 Conventional PNT systems

Conventional PNT systems have been in operation for many years and contain mainly ground infrastructure such as antennas, supporting facilities, monitoring sites and control centres. Conventional PNT systems have the following characteristics:

- **Specific frequency bands and power** which confer the main service characteristics, including the range of the system.
- Typically, **one type of service** is provided such as the provision of bearing, distance, or a combination.
- **Unique and standardised identification at a specific site**, to ease their use with automated systems processing their signals.
- **Design based on well-known and public standards** which define the requirement specification of the system and allows to properly verify and validate the system.

Due to the increased use of GNSS and the obsolescence of some of these conventional systems and the cost to maintain them, there is a tendency for the **rationalisation** while keeping a minimum network which could support operations in the absence of GNSS.

As an **example**, the figure below, extracted from the European ATM Master Plan, shows the expected evolution of the conventional navigation systems (NDB, VOR, DME, ILS) in the **European civil aviation sector**. Several systems are planned to be rationalised or decommissioned in the next decade, a consequence of the successful deployment and ramp up of GNSS and their satellite and ground-based augmentations. The benefit of this infrastructure rationalisation includes operational **cost savings and release of the spectrum bands** occupied by the conventional systems. Nevertheless, to ensure the safe provision of the European air traffic management upon a potential GNSS outage, a **Minimum Operational Network (MON)** of conventional systems will be retained.

It is important to highlight that the evolution plans included in the ATM Master Plan are those envisaged by European Union (also reflecting the evolution plans agreed at ICAO level). However, conventional PNT systems are ultimately the responsibility of the different national authorities which may have specific policies and plans differing from the ATM Master Plan.

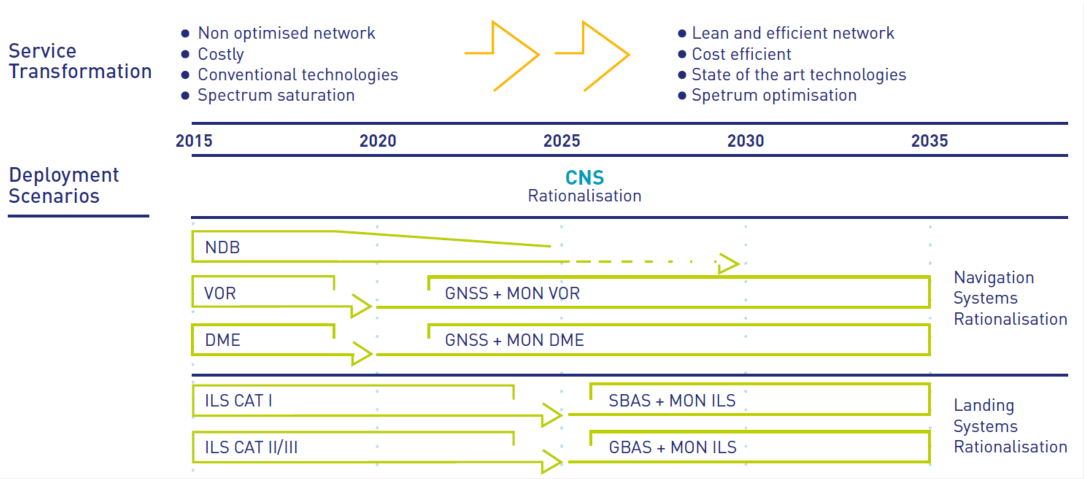


Figure 5 – Rationalisation of Conventional Navigation Aids (Credit: ATM Master Plan)

Finally, Figure 6 provide an overview of the conventional PNT systems with further information provided in Appendix A, section 5.2.

System	Frequency Band	PNT Type		Accuracy	Range	Supported NAV Spec (Aviation)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		Pos/Nav	Timing														
NDB	From 190 kHz to 1750 kHz	🟩 Bearing with respect to NDB	--	Depends on AFD on-board. ICAO minimum accuracy for NDBs is ± 5°	From 25 NM to 150 NM	--	🟦→🟧 Decommissioning proposal in the European ATM Master Plan										
VOR	From 108 MHz to 117.975 MHz	🟩 Bearing with respect to VOR	--	Within ± 2°	From 25 NM to 130 NM	RNAV 5	🟦→🟩 Rationalisation to MON										
DME	From 960 MHz to 1215 MHz	🟩 Distance to the DME	--	Around ± 200 metres (± 0,1 NM)	With VOR: from 25 NM to 130 NM With ILS: around 15 NM	RNAV 5, RNAV 2, RNAV 1, RNP 1 and A-RNP	🟦→🟩 Rationalisation to MON										
ILS	From 108 MHz to 111.975 MHz	🟩 Hor/Vert Guidance - Precision Apch	--	CAT I: ± 10.5 m (35 ft.) CAT II: ± 4.5 m (25 ft.) CAT III: ± 3 m (15 ft.)	Around 15 NM	--	🟦→🟩 Rationalisation to MON										
TACAN	From 960 MHz to 1215 MHz	🟩 Bearing and Distance	--	Within ±1° DME portion around ± 926 m (0.5 NM)	Around 200 NM	--	🟦 In operation since 1960										
Loran-C	From 90 kHz to 110 kHz	🟧	🟨	< 460 m	Long range Day: up to 600 NM Night: up to 1300 NM	--	🟧 Not in use in Europe since 2015										
eLoran and dLoran	From 90 kHz to 110 kHz	🟧	🟩	± 20 m, ± 5m for dLoran	600NM day (Night: up to 1300 NM), dLoran 30 NM (due to Differential Stations)	--	🟧 Not in use in Europe since 2015										
DCF77	77.5 kHz	--	🟨	long-term deviation (1 y) between ± 5 ms and ± 150 ms	Around 1000 NM	--	🟦 In operation since 1959										
Atomic Clocks	--	--	🟩	Better than nanosecs	No limitation	--	🟦 In operation since 1960										

-- N/A
🟧 LOW suitability
🟨 MEDIUM suitability
🟩 HIGH suitability

🟧 System NOT in service
🟩 Minimum Operational Network (MON) according to Reg. 2018/1048 PBN IR
🟦 System IN service (Full Operational Capability - FOC)

Figure 6 – Overview of Conventional PNT Systems

2.7.4 Emerging / Next Generation PNT Systems

In addition to conventional PNT systems or GNSS services, there is a panoply of **emerging or new generation of PNT systems**, which today provide services with typically lower performance than GNSS or with limited coverage or at an increased cost.

Figure 7 provides an overview of the emerging PNT technologies with the highest maturity and perceived importance. The technologies have been grouped mainly based on the perceived hardware similarity and include:

- Terrestrial technologies providing mature timing services with high performance.
- Radio-based technologies, be it ground-based (e.g., pseudolites, R-mode) or space-based (LEO satellites).
- Mobile navigation which is to a certain degree hardware agnostic and depends heavily on sensor fusion, machine learning and backend servers and it is a prominent technology for mass market.
- Non-radio-based technologies such as inertial systems and magnetic sensors.
- Visual, LiDAR or radar-based techniques technologies, which despite not strictly providing PNT are important in sensor fusion.
- Quantum and pulsars, which while not mature yet might offer very interesting performance in the future.

An important characteristic of these systems is their technology maturity, so-called Technology Readiness Levels (TRLs), indicated in the last column of the above figure. The methodology allocates a number ranging from '1' (basic principles observed - the lowest degree of maturity) to '9' (actual system proven in operational environment – the highest degree of maturity). The higher the TRL, the higher the readiness of the system to be used operationally.

These **emerging technologies** differentiate from the conventional aids and to a certain extend from GNSS, by:

- They are designed as part of the combined offering or sensor fusion approach.
- They do not only provide position but also create an efficient time distribution, though some might need a connection to the UTC.
- They embrace modern hardware and software development practices, leading to rapid development and over-the-air updates. This also means that all units are connected and usually do not need manual intervention after installation.
- They have capabilities for monitoring, reporting and fault identification by themselves.
- They have improved cybersecurity, integration with other systems, user experience and flexibility.

Further information on the systems themselves is provided in the Appendix A section 5.3.

System	Frequency Band	PNT Type		Accuracy	Range	Technology Readiness Level (TRL)
		Pos/Nav	Timing			
White Rabbit (WR)	--	🟪	🟩	Sub-ns / cm	Network, with repeaters up to hundreds of km	9
Computer Network Time Distribution	--	--	🟩	Sub-µsec	Network, with repeaters up to hundreds of km	9
Pseudolites	Various bands (e.g. WiFi, 921.88 – 927.00 MHz)	🟩	🟩	0.2 - 15 ns 0.005 m (carrier) - 15 m (code)	5 - 15 km	9
5G and cellular networks	450 MHz - 6 GHz and 24.25 GHz - 52.6 GHz	🟩 2D	🟩	Tens of meters Sub-µsec	Given by the network infrastructure	7
Ranging mode (R-Mode)	VHF and MF	🟩 2D	🟨	Tens of meters	250 km	5
Image based Navigation	--	🟩	--	Usually on dm level, absolute vary	Based on the system	6
Mobile based Navigation	Bluetooth and WiFi	🟩	🟪	Few meters (height accuracy allows to detect floor)	Bluetooth and WiFi usually tens of meters	9
Dead-reckoning & IMU	--	🟩	--	1m drift after 2min (high grade) 1m drift after few sec (low grade)	No limitations	9
Environmental maps	--	🟩 2D	--	Outdoor: meter to hundres of meters, indoor: < 1m	Depends on the system	7
Low Earth Orbit (LEO)	K and L bands	🟪	🟩	10 ns 10 m static	Global	8
Quantum Technologies (Clock & IMU)	--	🟩	🟩	At least one order of magnitude better than convential IMUs	No limitations	4
Pulsars' PNT	X-Ray (others not so efficient)	🟪	🟩	1000 km	Whole galaxy	3

Note: Technology Readiness Level (TRL) color indicates a range rising from the LOWEST readiness in red to the HIGHEST in green

-- N/A
🟨 MEDIUM suitability
🟩 HIGH suitability (2D indicates 2 Dimensions)
🟪 Potentially (under assessment/development)

Figure 7 – Overview of Emerging / Next generation PNT Systems

2.8 Interoperability and Compatibility

The emergence and modernisation of GNSS (including their regional and augmentation components) entail discussions on **GNSS interoperability** and **compatibility** among the different service providers.

According to the International Committee on Global Navigation Satellite Systems (ICG) '**Interoperability** refers to the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system'.

In the GNSS context, interoperability should be understood as the capability for user equipment to exploit available navigation signals of different GNSS and to produce a combined solution which generally exhibits performance benefits (e.g., better accuracy, higher availability) with respect to the standalone system solution. Interoperability is often discussed at two different levels: **system** and **signal** while interoperability at receiver level is ensured by internationally recognised standards. Further information can be found in Interoperability – Navipedia.

ICG states that '**Compatibility** refers to the ability of global and regional navigation satellite systems and augmentations to be used separately or together without causing unacceptable interference and/or other harm to an individual system and/or service.'

Two aspects are often considered when assessing compatibility:

- Radiofrequency compatibility (RFC), including factors of cross-correlation properties and affordable receiver noise floor.
- Spectral separation between authorised signals and other signals, and if overlapping is unavoidable, then close discussion among providers is undertaken to guarantee the required service.

Further information can be found in Compatibility – Navipedia.

International cooperation is fundamental to ensure interoperability and compatibility of GNSS signals (e.g., signal structures, messages, carrier frequencies, codes, and modulations) and is conducted from an early stage of development while receiver standards are key to ensure the interoperability and compatibility at receiver level.

Similarly to GNSS, interoperability, compatibility and standards development is necessary for other PNT services (e.g., standards are being developed by IEEE for Resilient PNT user equipment).

2.9 International PNT policies

Recognising the importance of PNT services, national PNT policies exist internationally for the major world economies. An overview of those PNT policies is provided in this section.

The US Federal Radio Navigation Plan (FRP) is the official source of positioning, navigation, and timing (PNT) policy and planning for the US Federal Government. The FRP contains chapters covering Roles and Responsibilities, Policy, representative PNT User Requirements, Operating Plans, and the National PNT Architecture, as well as appendices covering System Parameters and Descriptions, PNT Information Services, and Geodetic Reference Systems and Datums.

In 2018, the US published a National Timing Resilience and Security Act and in 2020 an 'Executive Order on Strengthening National Resilience through Responsible Use of PNT Services' with the purpose to 'foster the responsible use of PNT services by critical infrastructure owners and operators'. Amongst the many actions, the Executive Order called for the implementation of a GNSS-independent source of Coordinated Universal Time. In 2020, the US Department of Transport conducted the testing of 11 selected alternative PNT technologies, with the objective to assess complementary and backup PNT technologies to GPS. The campaign tested both position and time, providing a quantified ranking for the various analysed technologies.

The Russian Radio Navigation Plan, published in 2019 and agreed to by representatives from 11 nations[3] discuss position and timing requirements for different users. The Plan shows a significant concern with disruption of signals from Global Navigation Satellite Systems (GNSS) such as GPS and its Russian equivalent GLONASS and provides for how Russia — and its allies — are making users safer by integrating space and terrestrial systems into a more robust and resilient positioning, navigation, and timing (PNT) architecture. It also confirms a mobile terrestrial PNT capability, likely for military use.

In case of interference, the Plan suggests the creation of a system to monitor GNSS frequencies and identify disruptions, the use of multiple GLONASS frequencies and the integration of GLONASS, GPS and terrestrial systems within users' receiver: 'one of the ways to integrate ground and space Radio Navigation Systems is integration of systems like 'Seagull' [Loran] and GLONASS. Integrated systems 'Seagull'/ GLONASS may in the future used as the main systems for route stages navigation.'

Despite **China** having not published a Radio Navigation Plan yet, their approach has been presented on number of conferences and symposia. China plans to build the world's first comprehensive PNT architecture (e.g., resilient and robust). This architecture is described as a multi-source PNT system that will be 'more ubiquitous, more integrated, more intelligent'. Centred around BeiDou satellites at Medium Earth Orbit (MEO), it will incorporate a wide variety of other PNT sources such as a LEO PNT constellation, Loran-C stations, inertial sensors, and systems like quantum navigation that have yet to be developed.

In the UK, a Marine Navigation Plan was released in 2016 focusing on the use of PNT services for maritime navigation. In 2017, a report assessed the economic impact to the UK of a five-day disruption to GNSS at GBP 5.2 billion and in 2020, the UK announced the creation of a **National Timing Centre** to ensure additional resilience to GNSS services for accurate timing by means of a network of atomic clocks housed at secure locations.

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[3] Russian Federation, Republic of Azerbaijan, Republic of Armenia, Republic of Tajikistan, Republic of Belarus, Turkmenistan, Republic of Kazakhstan, Republic of Uzbekistan, Kyrgyz Republic, Ukraine, Republic of Moldova.

3 EU PNT

This section discusses the PNT in the European Union covering the objectives 6 to 8 introduced in section 1.4. It aims to provide **detailed information** on the main services provided by the European GNSS systems **Galileo and EGNOS**, to summarise per market segment the **current EU policies** related to PNT and the additional actions that would facilitate EGNSS services and/or increase the resilience of PNT services.

The section will:

- Introduce the EU legal framework for the EU Space Programme (section 3.1).
- Describe the Galileo current services and plans for future services highlighting their added value with respect to other GNSS services (section 3.2).
- Describe the EGNOS current services and plans for future services (section 3.3).
- Describe the EU policies related to PNT, including the on-going activities to facilitate the introduction of EGNSS in EU policies (section 3.4).
- Provide recommendations to facilitate the introduction of EGNSS services (section 3.4).
- Provide recommendations to increase the resilience of PNT services (section 3.4).
- Describe the EU cooperation activities on satellite navigation (section 3.5).

3.1 EU Space Programme 2021 – 2027

In April 2021, the Council and European Parliament adopted a Regulation (EU) 2021/696 establishing the new EU Space Programme for the years 2021 to 2027. The regulation calls for the EU Space Programme to ensure:

- high-quality, up-to-date, and secure space-related **data and services**.
- greater **socio-economic benefits** from the use of such data and services, aimed at increased growth and job creation in the EU.
- enhanced EU **security and autonomy**.
- a stronger role for the EU as a **leading actor** in the space sector.

The regulation simplifies the previous EU legal framework and governance system and standardises the security framework. It includes the following EU Space Components:

- **Galileo**: EU's own global navigation satellite system, providing highly accurate global positioning data and supporting emergency response and Search & Rescue.
- **European Geostationary Navigation Overlay Service (EGNOS)**: EU´s regional satellite-based augmentation system (SBAS). It provides safe critical navigation services to aviation, maritime and land-based users throughout the EU.
- **Copernicus**: Europe´s Earth Observation Programme. Through its land, marine, atmosphere, climate change, emergency management, and security services, Copernicus supports a wide range of applications including environmental protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection, and tourism.
- **Space and Situational Awareness (SSA):** EU's initiative to monitor and protect space assets from space hazards.
- **Governmental Satellite Communication (GOVSATCOM):** EU's initiative to provide national authorities with access to secure satellite communications.

In addition, the European Commission tabled in February 2022 two new Space flagship initiatives:

- **A proposal for a Regulation on a space-based secure connectivity (IRIS^2)** to ensure worldwide access to secure and cost-effective satellite communications services via a new constellation, for governmental communications and commercial use. It aims to protect critical infrastructures, support surveillance and crisis management, as well as enable high-speed broadband everywhere in Europe to best anticipate future challenges of our economy. This initiative reached at the end of 2022 a political agreement between the European Parliament and Member States.
- **A Joint Communication on an EU approach on Space Traffic Management (STM)** to further strengthen the EU's space surveillance and tracking capabilities (and set clear standards and regulation for a safe, sustainable, and secure use of space.

The EU Space Programme is implemented in close cooperation with the Member States, the European Union Agency for the Space Programme (EUSPA), the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and other stakeholders.

Further information on the EU Space Programme can be found in EU Space Programme (europa.eu).

3.2 Galileo Services

Galileo is the **EU's global satellite navigation system**, providing a highly accurate, guaranteed global positioning service under civilian control. While providing autonomous navigation and positioning services, Galileo is interoperable with other GNSS systems such as GPS, GLONASS and BeiDou.

Galileo is made up of a space segment consisting of a constellation Medium Earth Orbit (MEO) satellites broadcasting positioning and timing signals, a ground segment which controls the satellite's operation and generates the navigation information to be transmitted in the Galileo signals and a user segment constituted by the worldwide user terminals. Galileo is **operational since 15 December 2016** and continuously evolving within the Galileo First Generation while the Galileo Second Generation is under development.

The services provided by Galileo shall comprise the:

- **Galileo Open Service (OS)**, which is free of charge for users and shall provide positioning and synchronisation information intended mainly for high-volume satellite navigation applications for use by consumers. It includes the Galileo Open Service Navigation Message Authentication (OSNMA) and Service Volume capabilities.
- **High-Accuracy Service (HAS),** which is free of charge for users and shall provide, through additional data disseminated in a supplementary frequency band, high-accuracy positioning and synchronisation information intended mainly for satellite navigation applications for professional or commercial use.
- **Signal Authentication Service (SAS),** based on the encrypted codes contained in the signals, intended mainly for satellite navigation applications for professional or commercial use.
- **Public Regulated Service (PRS),** which is restricted to government-authorised users for sensitive applications which require a high level of service continuity, including for security and defence, using strong, encrypted signals.
- **Emergency Service (ES),** which is free of charge for users and shall broadcast, through emitting signals, warnings regarding natural disasters or other emergencies in particular areas.
- **Timing Service (TS),** which is free of charge for users and shall provide an accurate and robust reference time, as well as realisation of the coordinated universal time, facilitating the development of timing applications based on Galileo and the use in critical applications.

Galileo shall also contribute to the:

- **Search And Rescue** support service **(SAR)** of the COSPAS-SARSAT system by detecting distress signals transmitted by beacons and relaying messages to them via a return link.
- **Integrity-monitoring services** standardised at the European Union or international level for use by safety-of-life services, based on the signals of Galileo open service and in combination with EGNOS and other satellite navigation systems.
- **Space Weather** information via the GNSS Service Centre and early warning services via the Galileo ground-based infrastructure, intended mainly to reduce the potential risks to users of the services provided by Galileo and other GNSS related to space.

Each of the services will be further described in the next sections.

Further information on Galileo can be found in European GNSS Service Centre (gsc-europa.eu).

3.2.1 Galileo Open Service (OS)

The Galileo Open Service provides **global ranging, positioning, and timing services** for single-frequency and dual-frequency users equipped with a Galileo Open Service compatible receiver. While each Galileo satellite transmits navigation signals (also called Signal-In-Space or SIS) in three frequency bands, the Galileo Open Service is **broadcast on two** out of the three **frequency bands**.

Galileo Open Service Programme Documents include:

- **Galileo Open Service – Service Definition Document**, which describes the characteristics and performance of the Galileo Open Service provided through the Galileo Open Service Signal-In-Space.
- **Galileo Open Service – Signal In Space Interface Control Document**, which contains the publicly available information on the Galileo Signal-In-Space and specifies the interface between the Galileo Space Segment and the Galileo User Segment. It is intended for use by the Galileo user community.
- **Ionospheric Correction Algorithm for Galileo Single Frequency Users**, which describes in detail the reference algorithm to be implemented at user receivers to compute ionospheric corrections based on the broadcast coefficients in the Galileo navigation message for single-frequency users.

Galileo Open Service quarterly performance reports provide detailed information on the performance of the Galileo Open Service with respect to the Minimum Performance Level (MPL) targets specified in the Galileo OS Service Definition Document.

The Galileo Open Service **ranging and positioning accuracy exceed by far those of the other GNSS systems,** achieving a ranging accuracy better than 30 cm (95%) and a horizontal and vertical position accuracy better than 2 m and 2.5 m (in average) respectively. The **timing service accuracy** is better than 5 ns (95%). Galileo Open Service healthy signals are available more than 99% of the time for operational satellites. Typical performance can be found in the Galileo Performance Reports, which show the statistics of the typical GNSS ranging errors.

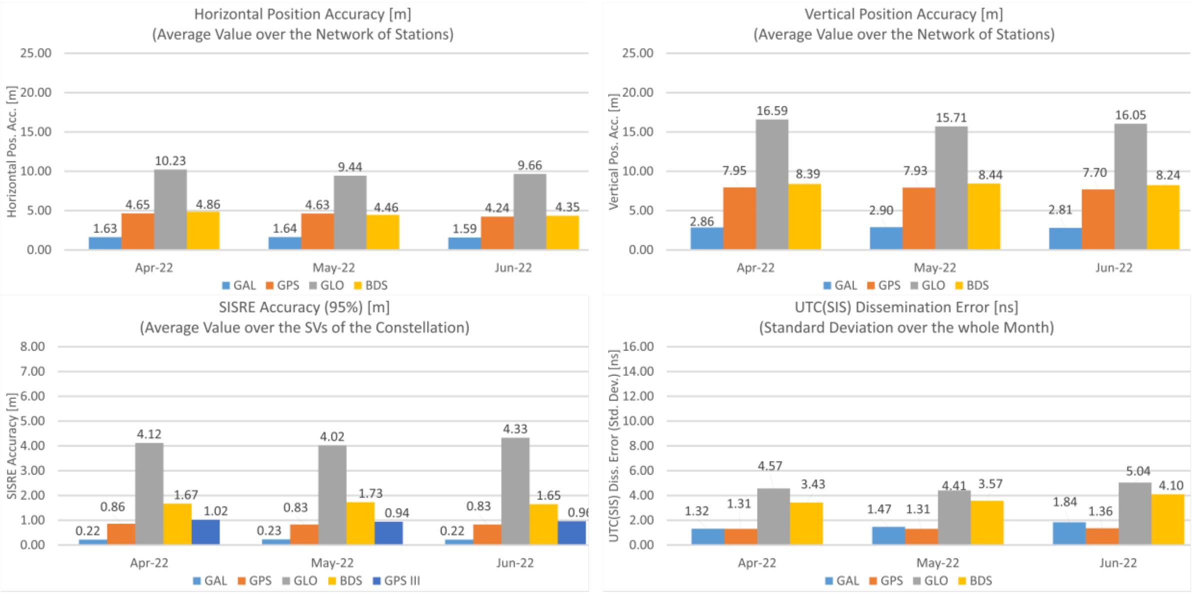

Figure 8 – Galileo Position and Timing Accuracy when compared to other GNSS (GPS, GLONASS and BeiDou)

Further information on Galileo Open Service can be found in its Service Definition Document.

3.2.1.1 Open Service Navigation Message Authentication – OSNMA

As part of a set of innovative services meant to add authentication capabilities, Galileo is introducing a unique feature called Open Service Navigation Message Authentication (OSNMA). This is meant to answer the clear need for **more robust and trustworthy GNSS solutions**. Users may benefit from this enhanced Galileo capability by means of a GNSS receiver or user terminal enabled to process the OSNMA data.

Galileo OSNMA is a **data authentication** function based on cryptographic operations, freely accessible to worldwide users and which provides receivers with the assurance that the received Galileo navigation data is coming from the system itself and has not been modified. OSNMA increases the likelihood of detecting spoofing attacks at data level, hence significantly contributing to the **security of the solution**. The OSNMA data, which are partly unpredictable, can be also exploited by receivers to provide some level of protection against signal replay attacks.

OSNMA provides the means to authenticate several sets of Galileo data through a specific message transmitted within the **I/NAV** Navigation Message broadcast on the **E1-B signal** component.

Table 2 – Galileo OSNMA performance targets

Characteristic	OSNMA
GNSS Receiver Minimal Capabilities	Single frequency E1
Object of Authentication	Nav Data (E1B I/NAV and E5b I/NAV)
Required Components	E1B
Need of Raw GNSS Signal Storage at Receiver Side	need for I/NAV data
Navigation Signals Decryption by GNSS Receiver	No
Authentication	Clock & Ephemeris Data (CED), ionospheric correction, Broadcast Group Delay (BDG), status flags and timing parameters (GPS to Galileo Time Offset – GGTO - and UTC), delayed
Time To First Authentication	One to few minutes
Authentication Availability	High, expected above 95%
Other Requirements	Time Synchronisation

OSNMA **public testing phase started in 2021**. It allows receiver manufacturers, application developers or researchers to implement and test the protocol and provide feedback to the Galileo Programme. OSNMA **service declaration** is expected **by the end of 2023**.

The Galileo Second Generation (**G2G**) will **improve the scope and robustness** of the authentication capability of OSNMA and extend it with ranging authentication.

Further information on the Galileo OSNMA can be found in OSNMA User ICD and OSNMA Receiver Guidelines.

3.2.1.2 Space Service Volume

Originally designed to offer positioning, navigation, and timing services to terrestrial users, **GNSS** has also proven its worth as a **valuable tool for in-space applications**. Real-time spacecraft navigation based on spaceborne GNSS receivers is becoming a common technique for low-Earth orbits (LEO) and geostationary orbits (GEO), allowing **satellites to self-determine their position using GNSS,** reducing dependence on ground-based stations. Deriving **Earth observation** measurements from GNSS signals is also becoming usual, adding-up to the list of established and potential uses of GNSS in outer space.

With an ever-increasing number of spacecrafts and the continuous development of GNSS spaceborne solutions, Galileo will offer a service for Space users – a **Galileo Space Service Volume (SSV)** as part of the Galileo Second Generation, which will be defined over three regions.

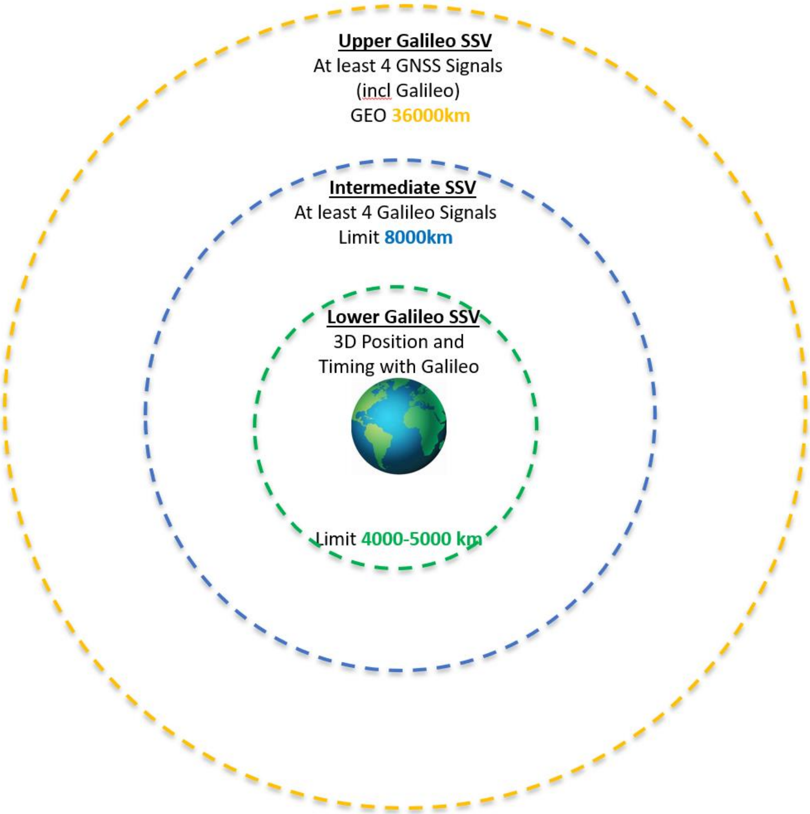

Figure 9 – Galileo Space Service Volume regions

The Galileo **Space Service Volume** will provide **service autonomously up to around 8 000 km altitude** (higher than the 3 000 km defined in the GPS SSV) thanks to the higher orbits of the Galileo satellites while for higher altitudes, a multi-constellation GNSS SSV solution will be required. This will satisfy most of the position and timing performance needs of Space users.

In addition, the international community is working on the **definition of an Interoperable GNSS Space Service Volume**, based on the outcomes of the work carried-out within the Working Group B of the United Nation International Committee on GNSS (UN ICG). As part of the ongoing activities, the Working Group is analysing the convenience of developing Standards in support of GNSS Space Users.

3.2.2 High Accuracy Service (HAS)

Galileo is the first GNSS constellation to provide a **high accuracy positioning service globally** aimed at applications that require higher performance than the one offered by the Galileo Open Service. The Galileo High Accuracy Service is based on the provision of Precise Point Positioning – **PPP** – **corrections** (orbit, clock, biases, atmospheric corrections) at a maximum rate of 448 bps per Galileo satellite connected to an uplink station, allowing the user to obtain a **horizontal positioning** error better than **20 cm (95%)** in nominal conditions of use.

The Galileo High Accuracy Service comprises two services levels:

- **Service Level 1 (SL1)** with **global coverage** and providing high accuracy corrections (orbits, clocks) and biases (code and phase) for Galileo and GPS signals.
- **Service Level 2 (SL2)** with **regional coverage** and providing **SL1 corrections plus atmospheric corrections** (at least ionospheric) and potential additional biases.

Along with the Galileo High Accuracy Service corrections via the Signal in Space (E6b), it is foreseen that **corrections** will **also** be **distributed using a terrestrial channel**, aiming to provide users (both SL1 and SL2) with an alternative or complementary input source to the Signal in Space.

The Galileo High Accuracy Service will be implemented in two phases:

- **Initial Service** declared on 24 January 2023: provision of Service Level 1 with reduced performance since based on processing of Galileo system data only.
- **Full Service** from 2026: provision of the Service Level 1 and 2 fulfilling target performance.

Table 3 – Galileo High Accuracy Service performance targets

HAS characteristic	Phase 1 (Initial Service)	Phase 2 (Full Service)
Coverage	SL1: EU	SL1: Worldwide SL2: EU
Type of Corrections	PPP – orbit, clock, biases (code and phase)	SL1: as phase 1 SL2: SL1 + atmospheric corrections
Format of Corrections	Open format similar to Compact-SSR (CSSR)	As phase 1
Supported Constellations & Frequencies	Galileo E1/E5a/E5b/E6; E5 AltBOC GPS L1/L5; L2C	As phase 1
Horizontal / Vertical Accuracy 95%	< 20 cm / < 40 cm	As phase 1
Convergence Time	< 300 s	SL1: < 300 s SL2: < 100 s
Availability	> 99%	As phase 1

The Galileo Second Generation (**G2G**) will improve the High Accuracy Service by providing orbit and clock **corrections in other bands** on top of E6 **and** by **enhancing several aspects** such as increased bit rate, faster acquisition additional GNSS constellations and faster convergence time.

Further information on Galileo High Accuracy Service can be found in the Galileo HAS SIS ICD, Galileo HAS Info note and GSC - HAS.

3.2.3 Commercial Authentication Service (CAS) / Signal Authentication Service (SAS)

The Galileo Commercial Authentication Service is based on the **full encryption of the E6C signal** and allows the **user PVT authentication** based on E6C encrypted ranging and OSNMA authenticated Navigation data. The service will be provided in a semi-assisted mode, as **ACAS** (Assisted CAS).

The ACAS concept, which provides user **autonomy between server connections** (for hours/days depending on the user), relies on OSNMA and therefore requires that the receiver is loosely synchronised to the Galileo system time.

The ranging authentication capability relies on retrieving on the server E6C replicas which were re-encrypted with an OSNMA key, then storing snapshots of transmitted E6C signal at predefined instants, and once the OSNMA key is disclosed, decrypt the E6C replicas and perform the correlation with the snapshots, obtaining a-posteriori authenticated range measurements.

The Galileo Commercial Authentication Service will be implemented in two phases with the following objectives:

- **Initial Capability** from 2024 where ACAS services will be based on Galileo capabilities already existing or under development (E6C encryption, OSNMA), plus assistance services integrated in the Galileo service facilities.
- **Full service** from 2026 with the completion of the deployment ground infrastructure.

In addition, an assessment is on-going on the feasibility of a Standalone CAS (**SCAS**), based on market analyses and ACAS adoption. This would require the storage in the receiver of a symmetric secret key and would enable real-time authentication.

For Galileo Second Generation, the performance of these authentication capabilities will be enhanced, and the name will be changed to **Signal Authentication Service** (**SAS**).

Further information on the Galileo Commercial Authentication Service can be found in the European GNSS Service Centre website.

3.2.4 Public Regulated Service (PRS)

The Galileo Public Regulated Service is an **encrypted navigation service** for governmental authorised users and sensitive applications that require high continuity. It is the most secure of the Galileo services and provides **worldwide unlimited and uninterrupted PNT capabilities** to authorised users even in crisis situations.

Access to the service is **limited to the Galileo PRS participants**, which are the Member States, the European Council, the European Commission, and the European External Action Service, as well as European Union agencies, third countries and international organisations, in so far as they have been duly authorised. Third countries and international organisations can become PRS participants subject to the conclusion of international agreements (detailed conditions of access to Galileo PRS are established under Decision 1104/2011/EU).

The **Member States have full sovereignty regarding the national users** authorised to access the Galileo Public Regulated Service and the use cases and application domains.

Only those entities authorised by the Security Accreditation Board can develop and manufacture **Galileo PRS User receivers**. Galileo PRS equipment and technology is subject to export controls.

Galileo Public Regulated Service is providing **Initial Services since December 2016**, including for demonstration purposes, support to PRS user segment technology development and user uptake.

Further information on Galileo Public Regulated Service can be found in GSC PRS and Navipedia PRS.

3.2.5 Emergency Service (ES)

The Galileo Emergency Service, also-called Emergency Warning Service, will include in the Galileo signals **alert messages to population threatened by natural disasters or other emergencies**. The Galileo receivers implemented in various devices (smartphones, smartwatch, handheld, billboards, etc.) will receive and decode these alert messages and display them on screen for immediate information.

This service provides an **additional mechanism** for the civil protection authorities to alert the population and is supporting directly the objectives set in the **United Nations' 'Sendai framework for disaster risk reduction'.**

The Galileo Emergency Service has the following **main characteristics**:

- Global coverage.
- Broadcast via the Galileo E1 frequency band (and later also via the E5 frequency band).
- Resilient to ground destruction since independent from terrestrial communication networks.
- Cover Multi-hazards (e.g., tornadoes, earthquakes, nuclear disaster, terrorist attacks).
- Reach out population in a timely manner (i.e., 2-3 minutes), whatever the size of the area.
- Provision of start time of the emergency, the expected duration and guidance to citizens.
- Only relevant population targeted due to geo-location encoded in the message.
- Interoperable solution studied in cooperation with Japan and India.

The **operational concept** of the Galileo Emergency Service is as follows (see following figures):

- The authorised national emergency centres generate an alert message and send it to the Galileo system via a dedicated secure interface.
- The Galileo system generates an Emergency Warning Message with an ellipse defining target area. The message is uploaded to two Galileo satellites and transmitted down to Earth via the Galileo Navigation Messages. The alert message will be also made available on a server, for further usage and monitoring/archiving purposes.
- The user segment, equipped with a Galileo Emergency Service compatible equipment, receives, decodes, and displays the emergency message. The message is only shown to the users located inside the area of emergency.

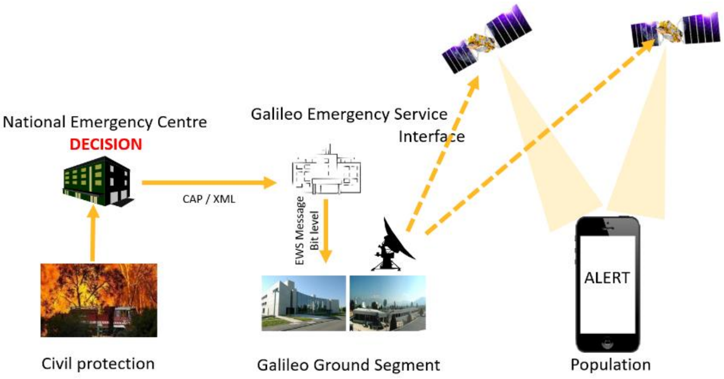

Figure 10 – Operational concept

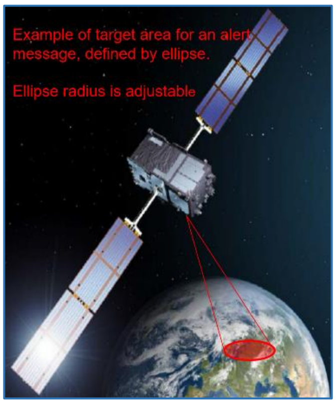

Figure 11 – Target Area as ellipse

A **public demonstration phase** is expected in **2023,** while the Galileo Emergency **Service** will be active **from the end of 2024** and evolve in the Galileo Second Generation.

3.2.6 Timing Service (TS)

Despite timing representing a small market, timing services are of **paramount importance for Critical Infrastructure** sectors such telecommunications, energy, and finance. Timing is also exploited in many other domains such as aviation, metrology, remote sensing, and atmosphere research.

The Galileo Timing Service (TS) will provide an **accurate and robust reference time**, as well as a **realisation of the coordinated universal time**, facilitating the development of timing applications based on Galileo and the use in critical applications.

The Galileo Open Service already allows the time stamping of an event with respect to the Galileo System Time and to the Coordinated Universal Time (UTC). In addition, **time sources can be synchronised** to each other (and to an absolute time reference) by using time-distribution techniques.

The Galileo Timing Service will expand the Galileo Open Service current capabilities to better respond to user needs. It will have the following **major characteristics**:

- Synchronisation with higher accuracy levels through the Galileo System Time when compared to other GNSS Systems. The current typical level of timing accuracy is better than 5 ns (95%) and that it will be maintained and even improved through the development of the Galileo second generation.
- Increased robustness and trust in the Galileo Timing Service by being the first GNSS to:
  - Benefit from the authentication of the Galileo navigation messages.
  - Provide dedicated flags for Galileo timing users.
  - Implement a dedicated monitoring with various monitoring levels.

In complement to the Galileo Timing Service, a **European standard for GNSS timing receivers** will be developed. This will be the first ever Timing receiver standard and will become a fundamental piece to ensure the end-to-end user performance of the Galileo Timing Service.

The Galileo Timing Service will be provided in the Galileo Second Generation, as of **2026**.

3.2.7 Contribution to Search And Rescue support service (SAR)

Galileo support to Search and Rescue Service (SAR) represents the **contribution of Europe to the international COSPAS-SARSAT**, a co-operative effort on humanitarian Search and Rescue activities. SAR services detect and locate emergency radio beacons activated by persons, aircraft or vessels in distress and forward this alert to authorities that initiate the rescue activities. Galileo SAR service reduces significantly the time needed to detect a distress beacon after its activation (**< 10 minutes**) and increases the localisation accuracy (uncertainty radius **< 5 km** and < 100 m in the future).

The Galileo SAR service is the biggest contributor to the COSPAS-SARSAT Medium Earth Orbit SAR system (MEOSAR) in terms of ground segment and space segment assets, with **more than 24 SAR transponders** in orbit[4] and **4 MEOLUT ground stations** that relay the distress to the SAR authorities. It is composed of two services:

- In the **Galileo Forward Link service**, the Galileo SAR transponders pick up the signals emitted from distress beacons in the 406 MHz band and broadcast this information to dedicated ground stations (MEOLUTs) in the L-band at 1544.1 MHz. These downlink signals transmitted by the Galileo SAR payloads are used by the MEOLUTs to generate the location of the beacon, which is then relayed to first responders through dedicated COSPAS-SARSAT Mission Control Centres.

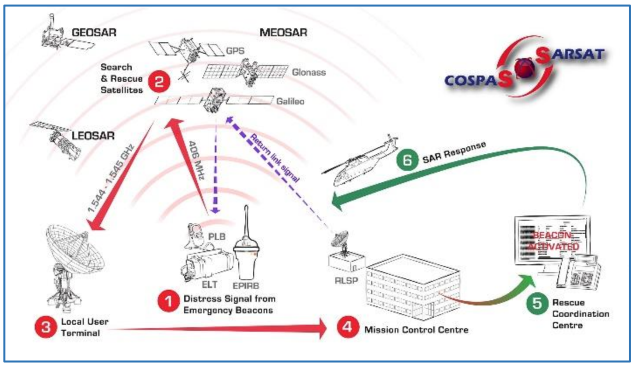

Figure 12 – Operational concept

- The **Galileo Return Link Service (RLS)** allows to send over the Galileo L1 Navigation signal an acknowledge message to the distress user indicating that the alert has been detected and localised. It allows several additional features such as the **Remote Beacon Activation** which will allow authorised users (Aircraft Operators, Maritime Rescue Control Centres) to remotely activate a distress beacon in case, for example, of aircraft disappearance or overdue vessel. This functionality for aviation applications has been standardised in the EUROCAE document ED-277.

In addition, a **Two-Way Communication** via Return Link Service is under assessment. This functionality will allow rescue operators to exchange messages via pre-coded questions and answers and send instructions (how-to-react) to the users in distress equipped with COSPAS-SARSAT beacons. Similarly, a future **Distress Position Sharing** service would allow rescue operators to share through the position of a distress user with other nearby users and enable quicker rescue operations.

The **Galileo SAR Service Definition Document** describes the characteristics and performance of the service while the Galileo SAR quarterly performance reports provide the performance of the Galileo SAR Service with respect to the Minimum Performance Level (MPL) targets specified in the Galileo SAR Service Definition Document.

Further information on can be found in the SAR-SDD, in the GSC SAR website.

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[4] In 2022, Russia has 2 SAR transponders while US will have its first operational L-Band SART starting on GPSIII block B – current US transponders do not broadcast in the COSPAS-SARSAT allocated frequency band.

3.2.8 Contribution to Safety-of-Life services

Galileo contributes to standardised **integrity monitoring services or safety-of-life services** by providing Open Service signals and dedicated information which are combined with augmentation systems:

- Satellite-Based Augmentation Systems (SBAS) such as EGNOS.
- Aircraft Based Augmentation Systems (ABAS) such as Receiver Autonomous Integrity Monitoring (RAIM) and Advanced Receiver Autonomous Integrity Monitoring (ARAIM).
- Ground Based Augmentation System (GBAS).

The use of GNSS signals and its augmentation services is a **fundamental technology in aviation** and has been standardised by the International Civil Aviation Organisation (ICAO). ICAO foresees evolutions of the current Navigation Systems, taking advantage of the Multi-Constellation environment with Dual-Frequency signals (in E1 and E5a bands).

ARAIM is the evolution to multi-constellation and multi-frequency of the current **RAIM**, which is based on GPS and on a single frequency only.

The ARAIM Concept Definition has been developed by the EU/US WG-C and later formalised at international level under the ICAO Navigation System Panel (NSP). While developing the concept, the EU/US WG-C published 3 Reports, being the last one the Milestone III Report.

The introduction of ARAIM will be done incrementally:

- First **Horizontal ARAIM (H-ARAIM)** will support en-route Navigation and will be included in the first version of DFMC MOPS.
- Then **Vertical ARAIM (V-ARAIM)** will support vertical navigation targeting LPV200 operations.

Table 4 – Main characteristics of RAIM vs V-ARAIM

	RAIM	ARAIM
Operations	Down to RNP 0.1	LPV 200
Hazard category	Major	Hazardous
Signals	L1CA	L1CA/E1-L5/E5a
Threat model	Single fault only	Multiple faults
Nominal error model	Gaussian Uses bound broadcast by GPS	Gaussian + nominal/max bias validated by independent ground monitoring
Constellations	GPS	Multi-constellation

ARAIM operations will enable vertical approaches down to CAT I / LPV-200 and hence redundancy in areas served by SBAS and will also have a **global coverage** which can support Artic navigation.

Galileo is formally supporting ARAIM thanks to the necessary commitments in the Open Service, reflected in the Galileo Programme documentation (OS SDD, SIS ICD) and in the Aviation Standards (ICAO SARPS) as needed.

3.2.9 Contribution to Space weather information

Space weather events related to solar activity and the interaction with the Earth magnetosphere, can affect both ground and space-based infrastructures, potentially resulting in **disruptions or performance degradation** of satellite services across the globe, sometimes also causing damage to equipment and systems.

GNSS can suffer from electromagnetic phenomena, in particular those happening in the ionosphere. The effects on GNSS navigation can include PNT degradation, temporary position and timing disruption or complete loss of visibility of one or more satellite signals. Considering the increasing reliance on satellite navigation, it is becoming more and more relevant to anticipate the potential degradations and inform/alert users thereof.

Today, **EGNOS** already provides a real-time ionosphere modelling for Europe including Vertical TECs (VTEC) and their bounding while **Galileo** provides a real-time world-wide ionosphere model, much more precise than the Klobuchar model provided in the GPS Navigation Message.

In addition, Galileo will provide an **integrated monitoring and prediction capability** of space weather, allowing to:

- Quantify, predict, and forecast potential impacts of end-user GNSS performance by means of monitoring and forecast:
    - Solar and geomagnetic indices, such as F10.7, R12, Kp, Ap, Dst, as parameters characterising solar events and expected flow of particles towards the Earth.
    - Ionosphere activity parameters, such as Total Electron Content and its derivatives, as well as scintillation events.
    - GNSS performance at user level, such as positioning and timing errors, and loss of lock probability.
- Alert GNSS users in due time of upcoming severe events that may degrade or disrupt GNSS services and so allow a timely reaction to hazard and the activation of mitigation strategies.

This service will process **vast amount of external data** that will in turn feed the monitoring and forecast algorithms. Relevant categories of sensors include geodetic networks (e.g., IGS, EUREF), solar and heliosphere missions, space-based sensors for radio occultation data methods, other ground-based sensors, or network (e.g., ionosondes), and internal Galileo/EGNOS system infrastructure data (e.g., Galileo Sensor Stations).

Several general-purpose space weather monitoring platforms exist around the world, providing bulletins for a variety of space users requiring knowledge of space weather in advance of their operations: human spaceflight, launchers, space surveillance, etc. This Galileo service is deployed as a **Galileo-only platform delivering prediction of performance for its GNSS users**.

The Galileo Programme is currently introducing this capability as a web-based platform into the Galileo Service Centre portal.

Initial declaration of service is planned in **2024**, and regular evolutions are foreseen in the roadmap to cater for the improvement of prediction algorithms or for new methods of collecting data.

3.2.10 Roadmap for Galileo services

Figure 13 provides the overview of the European Commission objectives for the various Galileo services in the period 2023-2025.

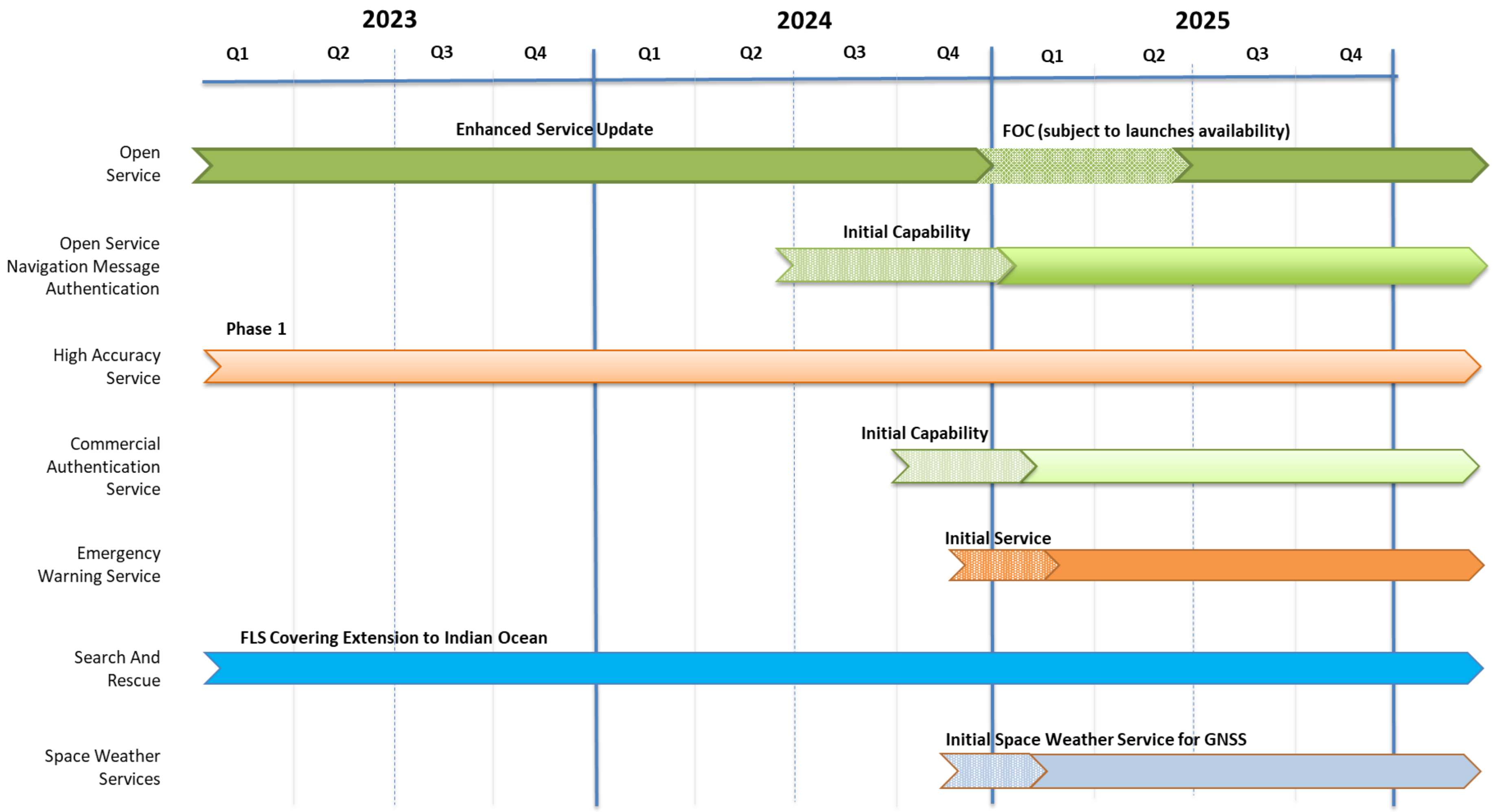

Figure 13 – Galileo services roadmap

3.3 EGNOS Services

EGNOS (European Geostationary Navigation Overlay Service) is the **European Satellite-Based Augmentation Service (SBAS)** that complements the GPS (and Galileo in the future) satellite navigation services.

EGNOS is made up of a space segment (geostationary satellites), ground segment (reference stations, master stations and uplink stations), a user Segment (user receivers processing the SBAS signals) and a support Segment (to support the provision of the SBAS services).

EGNOS reference stations are mainly geographically distributed across Europe and receive GNSS signals which they forward to the master stations. Since the locations of the reference stations are accurately known, the master stations can accurately calculate wide-area corrections. Those corrections are sent to dedicated stations for uplink to the EGNOS satellites which broadcast them to GNSS receivers throughout the SBAS coverage area.

The services provided by EGNOS shall comprise:

- **EGNOS Open Service (OS)**, which shall be free of direct user charges and shall provide positioning and synchronisation information intended mainly for high-volume satellite navigation applications for use by consumers.
- **EGNOS Data Access Service (EDAS),** which shall be free of direct user charges and shall provide positioning and synchronisation information intended mainly for satellite navigation applications for professional or commercial use, offering improved performance and data with greater added value than those obtained through the EGNOS Open Service.
- **Safety-of-Life Service (SoL)**, which shall be free of direct user charges and shall provide positioning and time synchronisation information with a high level of continuity, availability and accuracy, including an integrity message alerting users to any failure in, or out-of-tolerance signals emitted by, Galileo and other GNSSs which EGNOS augments in the coverage area, intended mainly for users for whom safety is essential, in particular in the sector of civil aviation for the purpose of air navigation services, in accordance with ICAO standards, or other transport sectors.

The **EGNOS Service Definition Documents** (SDDs) for OS, EDAS and SoL describe the characteristics and performance of the EGNOS services.

The **EGNOS Monthly Performance Reports** provide detailed information on the performance of the EGNOS OS, EDAS and SoL services with respect to the Minimum Performance Level (MPL) targets specified in their respective Service Definition Documents.

The current EGNOS services (so-called EGNOS V2) provide augmentation to the GPS L1 signal.

The EGNOS Second Generation (so-called EGNOS V3) will provide augmentation to GPS and Galileo L1 and L5 signals. The **technical and operational specifications of EGNOS V3** are established through a Commission Implementing Decision.

Further information on each of the services are provided in the next sections and also in the EGNOS Service Provider website and in their Service Definition Documents.

3.3.1 EGNOS Open Service (OS)

The EGNOS Open Service, available since **1 October 2009,** provides **positioning and timing services** for single-frequency users equipped with a SBAS compatible receiver.

The main objective of the EGNOS OS is to **improve the achievable GNSS positioning accuracy** by *augmenting* the ranging accuracy of the GNSS signals. The accuracy augmentation is possible since EGNOS correct various GNSS ranging error sources: the satellite clocks or orbits and the ionospheric effects. Moreover, EGNOS can also detect distortions affecting the signals transmitted by GNSS and prevent users from tracking unhealthy or misleading signals that could lead to inaccurate positioning.

Typical EGNOS Open Service **performances** for the EU territories include horizontal and vertical accuracies better than 3 m and 4 m (95%) respectively and timing accuracies better than 20 ns (3 sigma) for more than 99% of the time.

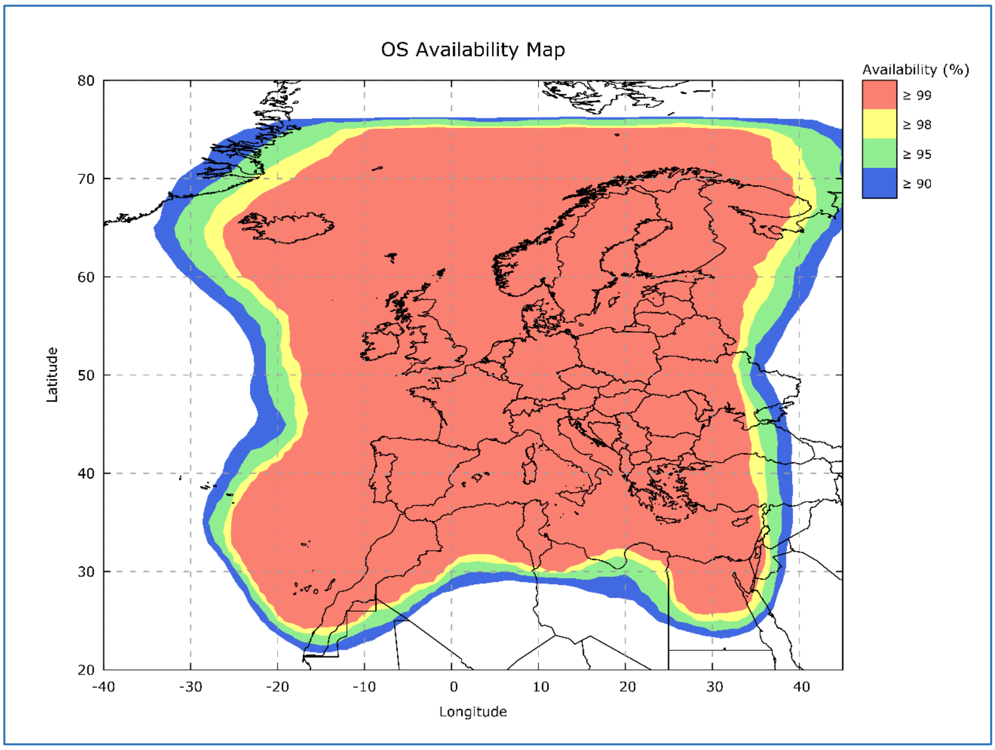

Figure 14 – EGNOS Open Service Availability (source: EGNOS Open Service SDD)

EGNOS Open Service is used for **non-safety critical purposes** (i.e., the absence or incorrect EGNOS Open Service information cannot cause any direct or indirect personal damage, including bodily injuries or death).

The main EGNOS Open Service **users** are precision agriculture, transport applications such as maritime, rail or road and in general any user community interested in obtaining better positioning accuracy.

3.3.2 EGNOS Safety of Life Service (SoL)

The EGNOS Safety-of-life service (SoL) provides the most stringent level of signal-in-space performance to all Safety of Life user communities which require **enhanced and guaranteed performance and integrity warning information**.

It is tailored to **safety-critical transport applications,** and it is provided to the aviation community today and in the future will be provided to the maritime and other communities.

3.3.2.1 EGNOS Aviation SoL

Available since **2 March 2011**, the main objective of the EGNOS SoL service is to support civil aviation operations down to Localiser Performance with Vertical Guidance (LPV) minima (also called approach operations with vertical guidance).

Two **EGNOS SoL Service levels** enable the following SBAS-based operations in compliance with ICAO SARPs Annex 10 Volume I:

- Non-Precision Approach (NPA) operations and other flight operations supporting PBN navigation specifications other than RNP APCH, not only for approaches but also for other phases of flight.
- Approach operations with Vertical Guidance (APV-I) supporting RNP APCH PBN navigation specification down to LPV minima as low as 250 ft.
- Category I precision approach with a Vertical Alert Limit (VAL) equal to 35 m and supporting RNP APCH PBN navigation specification down to LPV minima as low as 200 ft.

The operational use of the EGNOS SoL Service may require specific authorisation by the relevant civil aviation authorities.

The EGNOS SoL Service is accessible to any user equipped **with an EGNOS certified receiver**, in compliance with RTCA SBAS Minimum Operational Performance Standards (MOPS) DO-229[5] and located within the appropriate EGNOS SoL Service area corresponding to the phase of flight in which the EGNOS SoL Service is used (as referred to in EGNOS SoL SDD).

The EGNOS SoL signal also covers territories outside the EU. In this case, authorising and safety oversight of the use of EGNOS in civil aviation is the sole responsibility of the respective third country. The **EU supports the operational use of EGNOS based procedures** in third countries with an equivalent level of safety to the Single European Sky provided there is an agreement between the EU and the third country on the use of EGNOS SoL[6].

Typical EGNOS SoL **performance** includes the availability of the NPA service better than 99.9% for the European Airspace and better than 99% for APV-I and LPV-200 services (except Azores and partially some parts of Canary, Cyprus, and North of Scandinavia).

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[5] RTCA MOPS DO 229 (Revisions C, D Change 1 or E)

[6] At the beginning of 2023, there exist EGNOS based operations in the following non-EU states: Norway, Switzerland, Bailiwick of Guernsey, Bailiwick of Jersey, Iceland, Serbia, and Montenegro.

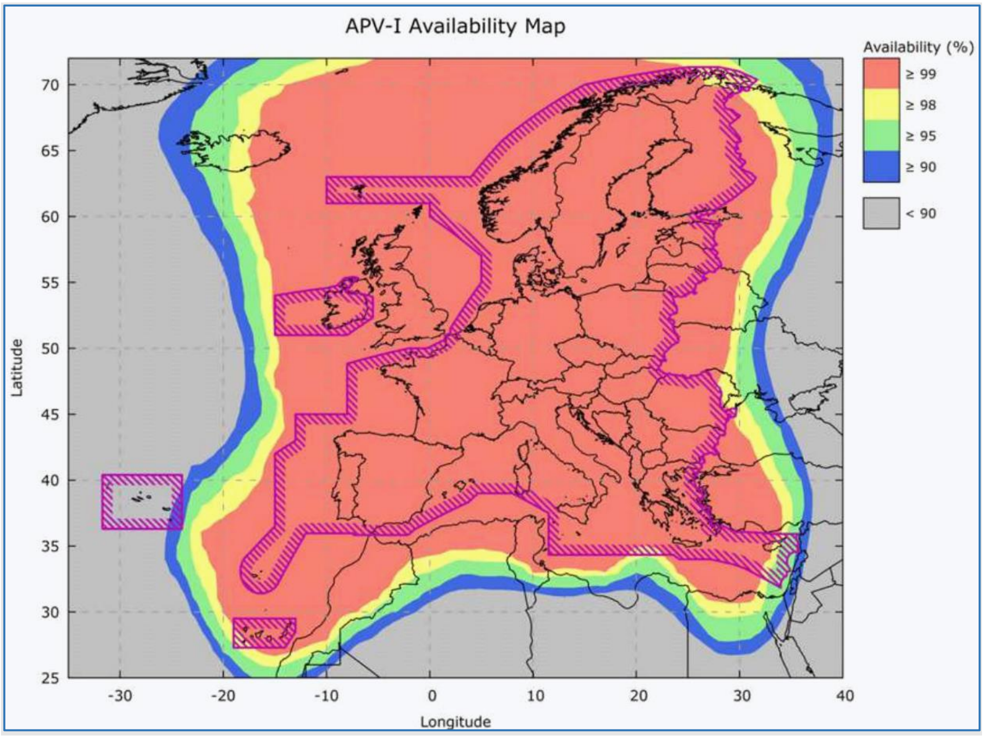

Figure 15 – EGNOS SoL Service Availability (source: EGNOS Safety of Life SDD)

EGNOS V3 (i.e., the next EGNOS generation) will provide improved services according to the following implementation approach:

- **EGNOS v3.1**, in service before 2030, aims to provide **full compliance to ICAO requirements in all the EU territories** when using GPS L1 signals.
- **EGNOS v3.2**, in service around 2030, aims to:
  - Provide DFMC services (dual frequency L1/L5, multi-constellation GPS/Galileo) with increased availability 99.9% for LPV-200 service level and a new service level targeting VAL = 10 m which may enable approval of additional operational capabilities.
  - Extend GPS L1 Legacy services to the European Neighbourhood Policy South[7] and East[8] Territories.

In addition, **authentication of the SBAS messages** is currently under inclusion in the DFMC SBAS Standard and will then add resilience to the DFMC SBAS services.

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[7] Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestine, Tunisia.

[8] Armenia, Azerbaijan, Belarus, Georgia, Moldova, and Ukraine.

3.3.2.2 EGNOS Maritime SoL

The provision of EGNOS services for the maritime users is implemented in three phases:

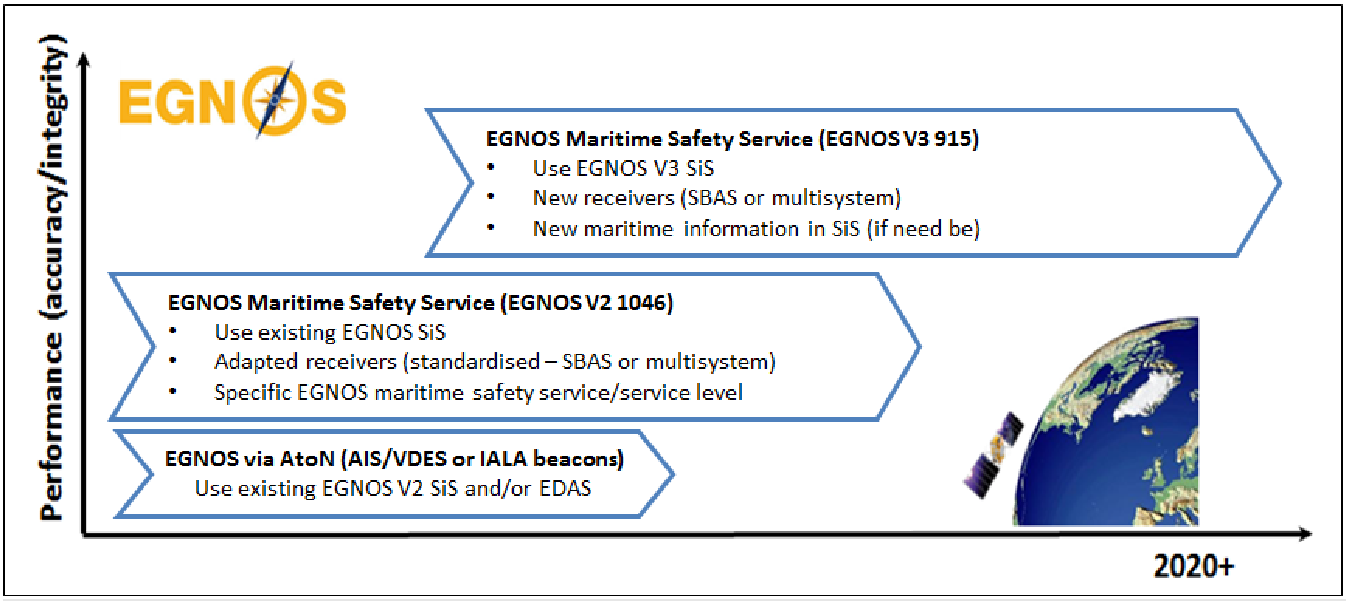


Figure 16 – Phases of implementation of EGNOS Maritime SoL

- **Phase 1: EGNOS corrections transmitted via existing Aids to Navigation (AtoN)**

  The current EGNOS SoL L1 service is used as a source for the differential corrections transmitted via the existing IALA beacons and AIS stations (AtoN) according to the IALA Guidelines G1129 on the retransmission of SBAS corrections using MF radiobeacon and AIS.

- **Phase 2: EGNOS L1 maritime service + dedicated L1 receivers**

  The current EGNOS SoL L1 service will be tailored for maritime users by providing the following **additional information:**

  1. Signal in Space commitments on range (orbits + clock) and ionospheric errors
  2. Integrity Alerts (system alerts, satellite alerts, ionosphere alerts)
  3. Maritime Safety Information to inform about planned/unplanned outages

  In addition, an **IEC test standard for SBAS in shipborne receiver** (IEC 61108-7) is under development which will allow obtaining of the receiver type certificate for the processing of this EGNOS maritime L1 service.

  This Service will be used by shipborne receivers to compute a navigation solution in line with the operational requirements included in the **IMO Resolution A.1046** for maritime navigation in ocean waters, harbour entrances, harbour approaches and coastal waters.

Table 5 – IMO Resolution A.1046 Operational requirements

	Ocean Waters	Harbour entrance, harbour approach and coastal waters
Accuracy (95%)	100 m	10 m
System integrity (Time to Alarm)	As soon as practicable by Maritime Safety Information	Within 10 s
Signal availability	99.8%	99.8%
Continuity	N/A	99.97% (over 15 minutes)

The declaration of this EGNOS maritime service is targeted by the **end of 2023**.

- **Phase 3: EGNOS DFMC maritime service + dedicated new multi-system shipborne radionavigation receivers (MSR)**

  The future EGNOS DFMC service will allow for **improved navigation** as per IMO Resolution A.915(22) and A.1046(27) in harbour entrances, harbour approaches and coastal waters when processed by tailored multi-system shipborne radionavigation receivers.

3.3.2.3 EGNOS Railway Service for train localisation

The introduction of EGNOS Services covering railway **safety-related applications** is **expected to increase safety, increase** railway network capacity, whilst decreasing operational costs.

The inclusion of EGNOS in European Rail Traffic Management System (ERTMS) and the definition of this EGNSS rail service for train localisation is currently under study.

3.3.3 EGNOS Data Access Service (EDAS)

EDAS is the **single point of ground-based access for EGNOS data,** including that generated by the EGNOS ground infrastructure, mainly Ranging and Integrity Monitoring Stations (RIMS) and Navigation Land Earth Stations (NLES).

EDAS services are **accessible through the Internet** regardless of whether the EGNOS GEO is in view. This is especially important in urban canyons, mountain terrains or other areas with limited visibility of the GEO satellites.

EDAS is **accessible to registered users** within the EGNOS Participating countries (Member States, Norway, Switzerland, and Iceland) and to other users upon registration and authorisation by the European Commission.

In addition, existing Maritime, and Inland Waterways transmission infrastructure (IALA beacons and/or AIS base stations) can rely on the **retransmission of DGPS corrections based on EDAS**.

EDAS is available free of charge since **26 July 2012** and can only be used for non-safety critical purposes.

3.4 EU PNT policies and recommended actions

This section will focus on the EU's main policies and actions related to PNT and will include:

1. A **summary**, per market segment, **of the major EU initiatives relevant to PNT**, with a highlight on the role of the European GNSS services.
2. **Recommendations**, including for regulation or standardisation to:
    - Facilitate the use of Galileo and EGNOS in the relevant market segments.
    - Increase the resilience of PNT services, notably for Critical Infrastructure.

This section also addresses the recommendation 4-c of the **Special Report 07/2021** of the European Court of Auditors. The time schedules for each relevant market segment, where regulation or standardisation can facilitate the use of Galileo are detailed in APPENDIX C: Regulations and Standards. Future versions of the ERNP will reflect the evolution in the use of Galileo in different market segments.

Before discussing the EU PNT policies per market segment, Figure 17 illustrates how PNT systems are typically used for the various market segments:

- Starting from the **inner circle**, the services from the **global and regional GNSS** systems are being extensively used today in all market segments and can be considered as the backbone for all PNT services. The reason behind is the relatively low cost, outstanding performance, and ease of use of GNSS receivers.
- The second circle shows the services from the **augmentation GNSS** systems which also serve all market segments and provide improved performance for added-value services (e.g., integrity for safety-of-life applications or high-accuracy in PPP).
- The outer circle shows how **conventional PNT** systems are used mainly in the aviation and maritime domains, while **emerging technologies** have the potential to serve all market segments including those environments where the use of GNSS services is more challenging (e.g., indoors).

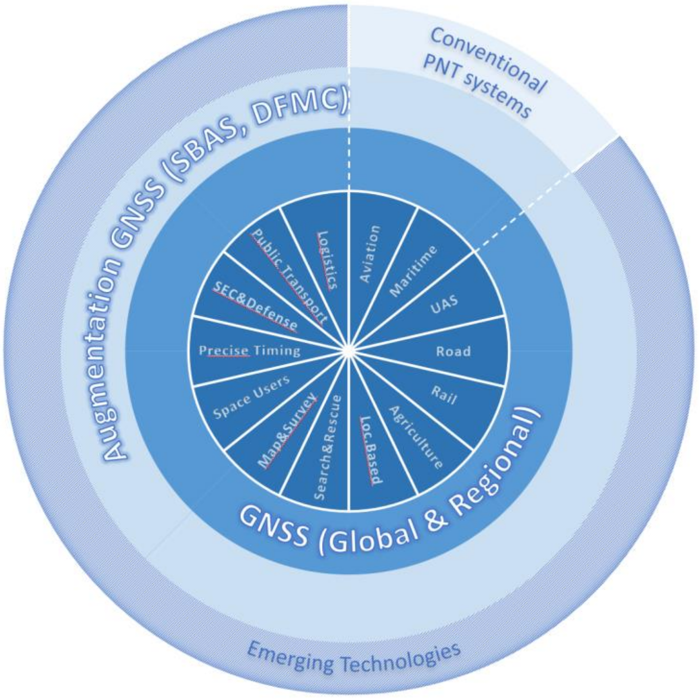


Figure 17 – Overview of technologies per domain

3.4.1 Resilience of European Critical Infrastructures

Ensuring the **resilience of entities that use critical infrastructure to deliver essential services** remains high on the agenda of the European Union and its Member States. The EU Security Union Strategy for 2020-2025 and the Counter-Terrorism Agenda for the EU, both stressed the importance of ensuring the resilience of critical infrastructure in the face of physical and digital risks. The Covid-19 pandemic demonstrated major complex threats to the services on which the lives of European citizens and the good functioning of the internal market depend. Critical infrastructures resilience is highlighted in key political declarations, such as the EU leaders' Versailles declaration.

The European Commission supports Member States to ensure resilience on various levels:

- The Critical Entities Resilience Directive (EU) 2022/2557 (CER Directive) which establishes obligations to identify critical entities in different sectors, in order to enhance their resilience, ensuring that services which are essential for the maintenance of vital societal functions or economic activities are provided in an unobstructed manner in the internal market.

  The Directive will strengthen the resilience to a range of threats **ensuring that critical entities can prevent, resist, absorb and recover from disruptive incidents**, no matter if they are caused by natural hazards, terrorist attacks, insider threats, or sabotage, as well as public health emergencies like the recent COVID-19 pandemic. The Directive reflects the increasingly complex operational reality, the shift of perspective from 'protection' to 'resilience' in academia, industry, and policy making. The CER Directive does not cover cyber security risks.

  Against an ever more complex risk landscape, the Directive has a wider sectoral scope which will allow Member States and critical entities to better address interdependencies and potential cascading effects of an incident. **Eleven sectors are covered**: energy, transport, banking, financial market infrastructures, health, drinking water, wastewater, digital infrastructure, public administration, space and production, processing, and distribution of food.

  PNT services and their resilience are relevant for many of the sectors covered by the Directive, notably for transport, energy, telecommunications, and finance and hence should be assessed as part of the **risk assessments** to be carried out by critical entities and **resilience-enhancing measures** implemented when required. Since the CER Directive will also cover the ground segments of space infrastructure operated by Member States or private operators, it will also increase the resilience of the entities that provide PNT to other sectors of the economy.

  Finally, the Directive lays the ground for **closer cooperation at EU-level** and serves as reference point also for legislative and regulatory activities on critical infrastructure outside of the EU.
- The Directive (EU) 2022/2555 (NIS 2 Directive) which establishes measures for a high common level of cybersecurity across the EU for the same entities identified under the CER directive. It will boost the overall level of cybersecurity in the EU by promoting a culture of security across sectors and ensuring the Member States' preparedness and cooperation (e.g., requiring a Computer Security Incident Response Team (CSIRT) and creating a Cooperation Group to support and facilitate strategic cooperation and the exchange of information among Member States).
- In October 2022, the European Commission adopted a proposal for a Council Recommendation to strengthen the resilience of EU critical infrastructure. The priority is given to the key sectors of energy, digital infrastructure, transport, and space.
- The Commission Delegated Regulation (EU) 2022/30, which imposes requirements on cybersecurity, privacy and protection from fraud to certain categories of radio equipment, including those used under critical infrastructure, as a condition for its placing on the EU market. The evolution of this legal act will constitute the Cyber Resilience Act.

3.4.2 European Green Deal

Europe has set out to address the **global challenge of climate change and environmental degradation** and will play an instrumental role in reversing the damages protecting, preserving and restoring biodiversity and ecosystems, mitigating the impact of climate change that human practices have induced whilst supporting the planet's recovery. Europe's commitment has been made evident through several agreements, initiatives, policies, and regulations over the years. The game-changing sustainable growth strategy known as the European Green Deal (EGD) and its initiatives aim to achieve climate neutrality by 2050 in a just and inclusive manner, encouraging a low-carbon and climate resilient economy. The Green Deal helps advancing towards a well-being economy that gives back to the planet more than it takes and accelerates the transition to a non-toxic circular economy, where growth is regenerative, resources are used efficiently and sustainably.

The European Greed Deal calls for capacities, tools, and services to monitor anthropogenic carbon emissions but also to monitor, analyse, predict, and mitigate the impacts of human activities on soil, air, water quality. The utilisation of **Earth Observation and meteorological data**, together with in-situ data (e.g., ground sensors, etc.) and other non-satellite-based data (e.g., mobile data, statistics, etc.), offers a unique capability to monitor on a global, and yet precise enough scale, the state, and changes of the environment, informing policies and further mitigation and adaptation actions.

GNSS radio occultation provides in situ water vapour profiles and is used to **enhance meteorological forecasts** and GNSS observations allow to estimate geodetic properties of the Earth (magnetic field, atmosphere) that **supports climate modelling.** GNSS also provide precise orbit determination of environmental LEO satellites which monitor the Earth climate change.

The EU Space Programme is a pillar in the space-based transformations towards a healthier planet also thanks to the **advanced PNT data** provided by Galileo and EGNOS. It generates environmental benefits with a positive effect on Europe's Green Deal objectives and activities, for example:

- In the **aviation and maritime sector** GNSS enables efficient travel routing leading to the **reduction** of a fuel use and the associated **Green House Gas emissions**, for example thanks to the less time spent for incoming planes when circling airports waiting for a runway.

  In addition, accurate monitoring of the aircraft position, as well as of weather conditions and occurrence of ice-supersaturated areas would reduce the generation of **persistent contrails and the associated non-CO_2 effects**.

- In the **agriculture sector** GNSS enables automatic steering of agriculture machines and brings reduced soil compaction improving soil health and its capacity to store carbon.
- In the **rail sector** GNSS-enabled driver advisory systems optimise train driving and reduce the consumption of traction energy and thus Green House Gas emissions.
- In the **road sector** GNSS enables shorter and more efficient journeys which result in lowering the amount of time a vehicle engine is engaged and consequently lowers the carbon impact of each journey.
- In the **power distribution sector** GNSS enables accurate timing and synchronisation of the power transmission infrastructure. This is fundamental for the proliferation of smart grids and for the maintenance of accurate voltage frequency, needed due to the increased use of renewable energy for the green transition.
- In the **monitoring offshore infrastructure** (e.g., wind turbines or oil platforms) GNSS enables more efficient drones' operation than the traditional means which dramatically reduces Green House Gas emissions.

3.4.3 Manned Aviation

PNT (notably GNSS and its augmentations SBAS, ABAS and GBAS) **play a key role in aviation** for Communications, Navigation and Surveillance (CNS) systems and applications which support Air Traffic Management (ATM) and increase airport capacity and environmental and economic efficiency (e.g., lower noise impact, more efficient route, fuel and emissions savings) while guaranteeing safety:

- **In Communications,** a **trustful time reference**, as the one based on GNSS, is key for applications such as the synchronisation of ground networks and the CPDLC (Controller Pilot Data Link Communications) enabling ATC communications via data link.
- In **Surveillance**, the full surveillance system, from the sensors to ATC, makes use of a **single time reference**, ensuring that ATC decisions are taken based on reliable surveillance information (as a drawback, GNSS becomes a single mode of failure, rising the need for alternative Timing services). The benefits of the GNSS performance are recognised through ADS-B integrating GNSS information. For example, the US mandate on ADS-B de facto requires the use of SBAS to guarantee the feasibility of operations. Finally, ADS-B based on GNSS positioning may allow the rationalisation of SSR infrastructure.
- In **Navigation**, GNSS is essential to implement Performance Based Navigation (PBN). Among the navigation operations, RNP Approaches down to LPV (Localiser Performance with Vertical guidance) minima are the most essential function provided by SBAS technology, the so called **LPV approaches** (i.e., 3D approaches which provide lateral and vertical guidance similarly to ILS CAT I approaches but with no on-site radio-navigation ground infrastructure). If the minima of the approach operation is below the cloud ceiling, the operation is feasible, **minimising the disruptions** (i.e., cancellations, delays, or diversions to other airports) **and improving safety, efficiency, and accessibility**. Minima down to 250 ft and 200 ft can be obtained at non-precision and precision approach runways respectively, and in both cases it is possible to fly the final approach segment down to 100 ft or even touchdown without visual contact with the runway environment when **combining the use of SBAS with aircraft equipped with EFVS** (Enhanced Flight Vision System) provided that the EFVS on board has the proper characteristics and that there is a Special Approval by the National Competent Authority.

It is worth mentioning that GNSS does not only add value on the ground systems, but it is extensively used also by **on board systems** and applications in the aircraft, in particular for timing purposes.

In addition, **other benefits of using GNSS** are further described in the Aviation User Needs and Requirements report such as SBAS based approaches at Non-Instrument runways for General Aviation environments (normally VFR small aerodromes), rotorcraft operations often in non-optimal conditions for Search and Rescue (SAR) or Helicopter Emergency Medical Services (HEMS) operations and the use of geometric altitude based on SBAS for the development of improved ground warning systems such as Enhanced Ground Proximity Warning System (EGPWS) over the classical Terrain Avoidance and Warning System (TAWS) and the monitoring of baro-altitudes.

In the future, the inclusion of **Galileo and EGNOS DFMC will bring additional benefits** to aviation such as improved performance (e.g., improved availability and continuity), larger SBAS service areas, lower protection levels meaning more advanced operations, capability to support CAT III operations based on GBAS in all latitudes, increased robustness against RFI or mitigation to ionosphere vulnerabilities or support to future applications such as 4D Navigation through GNSS Timing.

To facilitate the use of GNSS for the European air traffic management, some major initiatives exist. The **European ATM Master Plan defines the roadmap for the use of EGNOS and Galileo, in combination with GPS, for different phases of flight** (as part of the CNS systems). Its CNS roadmap includes milestones for the operational use of systems augmenting GPS and Galileo: EGNOS V3 (DFMC SBAS), Advanced RAIM and GBAS.

The Commission Implementing Regulation (EU) 2018/1048 (the 'PBN IR' Regulation) mandates the gradual implementation of **Performance Based Navigation** (PBN) routes and approach procedures to enhance airspace design hence supporting safer, greener, and more efficient aircraft operations and at the same time improving cost efficiency. It requires from 2030 that all SID & STAR are based only on PBN, with GNSS as the main mean of navigation, and makes SBAS the main means of navigation for CAT I operations. In addition, it requires the **implementation of PBN approach procedures including EGNOS procedures** (LPV procedures) in all European IREs (Instrumental Runway Ends) by 2020 (IREs without precision approach) and 2024 (IREs with precision approach).

In addition and with the goal to enable the **rationalisation of the conventional navigation infrastructure** and also ensuring a minimum level of service with an acceptable level of safety in case of contingency (e.g., GNSS outage), the PBN IR expressly excludes the use of conventional navigation procedures as from 6 June of 2030, except in the event of PBN contingencies, i.e., situations where, for unexpected reasons beyond the control of ATM/ANS service providers, GNSS or other methods used for performance-based navigation are no longer available. For these exceptional cases, the PBN Regulation requests to retain a Minimum Operational Network (MON) of conventional navigation aids (e.g., ILS, VOR, DME) to ensure that navigation services can still be provided without compromising safety and security in case of contingency.

Therefore, from 6 June 2030, GNSS will be the nominal means of navigation in the European airspace for all phases of flight down to and including CAT I, complemented by GBAS and ILS CAT II/III landing systems, where necessary (Transition to PBN Operations).

In addition to the regulatory actions like the PBN Regulation, the European Union is facilitating the adoption of PNT and European GNSS in aviation policies by:

- **Supporting, including funding, the implementation and compliance to the PBN Regulation** through different actions oriented to ease both the equipage of the European fleet with GNSS enabled receivers and the implementation by the Air Navigation Service Providers of GNSS based procedures.
- **Broadening the scope of EGNSS usage** for rotorcraft operations, SBAS-based approaches at non-instrument runways, and developing tools supporting the implementation of EGNOS.
- **Funding programmes** supporting R&D on GNSS applications such as the SESAR project.
- Working on the inclusion of **Galileo and EGNOS Dual Frequency Multi-Constellation (DFMC) in aviation** signal-in-space **standards** ICAO Annex 10 Volume I and EUROCAE receiver standards (for SBAS, A-RAIM and GBAS augmentations).

Moreover, there are ongoing activities in Europe (e.g., SESAR, EUROCAE, EUROCONTROL) to define **Complementary PNT technologies** which **could provide secure and resilient PNT**, offering an **effective backup in the event of GNSS** disruption and therefore ensuring continued operations. In the short term, this focuses on improving DME infrastructure and service provision, which will likely support RNP 1). In the long term, a suitable mix of complementary PNT should provide assured PNT, safeguarding against both safety and security PNT threats, while optimising the radio spectrum use of these systems, in line with ICAO Assembly Resolution A41-8C.

3.4.4 Unmanned Aviation

The Unmanned Aircraft System (UAS or drones) market has been quickly increasing in the recent years. **ICAO** has established the Remotely Piloted Aircraft Systems Panel (RPASP) to develop the required **standards for international flights** and the Unmanned Aircraft Systems Advisory Group (UAS-AG) to advise the ICAO Secretariat in developing guidance material. ICAO is also setting up an Advanced Air Mobility Study Group to provide similar guidance to support the development of advanced and urban air mobility. PNT will be a key enabler for many of the UAS applications similarly to manned aviation (e.g., PNT support to CNS applications).

In Europe, Regulation (EU) 2018/1139 (the *EASA Basic Regulation*) extended the scope of competences of EASA to all unmanned aircraft, irrespective of their weight and size, and introduced a risk-based, operations-centric approach to the safety regulation of aviation, in particular for drones. Subsequent Regulations (EU) 2019/947 and 2019/945 set out **the framework for the safe operation of civil drones in the European skies**, distinguishing three categories for the UAS operations depending on the associated operational risk: '**Open**' category (for low-risk operations), '**Specific**' category (for medium-risk operations) and '**Certified**' category (for higher risk operations including the transport of people or dangerous goods).

For the Certified category, those (certified) unmanned aircraft flying according to Instrument Flight Rules will be subject to the same airspace usage requirements and operating procedures as manned aircraft and these are being reviewed to ensure that all the particularities of the drones are properly covered. Much of the previous section 3.4.3 on manned aviation would therefore equally apply to those unmanned aircraft in terms of PNT. This is the category with the most demanding PVT performances especially for Beyond Visual Line of Sight (BVLOS) operations.

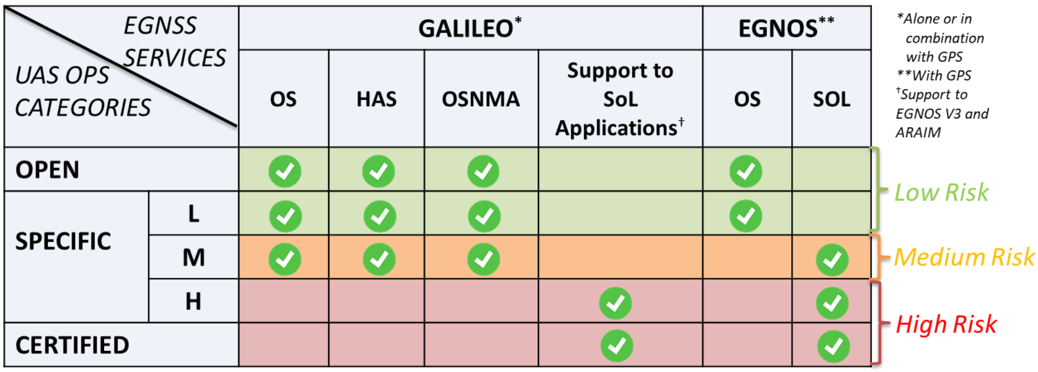
On the other hand, drones flying in the Open and Specific categories are currently not subject to specific navigation performance requirements. It is the responsibility of the UAS operator to ensure that externally provided services, which are necessary for the safety of the UAS operations such as GNSS services, reach a level of performance that is adequate for the operation and are kept for its full duration. However, in the Specific category, the applicant needs to define the risk area when conducting the operation, which includes the operational volume composed of the flight geography and the contingency volume. **To determine the operational volume the applicant should consider the position keeping capabilities of the UAS in 4D space (latitude, longitude, height, and time)** and hence the accuracy of the navigation solution should be considered and addressed in this determination, and **depending on the operation (SAIL level), the integrity may also play a key role in ensuring that the GNSS PNT solution is trustable for the intended operation as an input to the drone's navigation system**.

In this sense major steps have been taken by the European Commission and EASA to further support the drone industry with the publication of clear regulations laying the foundation for current and future innovative operations. The adoption of the first regulatory framework for **U-space** (Commission Implementing Regulations (EU) 2021/664, 2021/665 and 2021/666) sets out provisions for UAS operators, U-Space Service providers (USSP), providers of Common Information Services (CIS) and impacted ANSPs, establishing some U-space mandatory services to be provided wherever a U-space airspace is designated. Member States are responsible to determine the performance requirements in a designated U-space airspace, based on an airspace risk assessment before the U-space designation.

There are currently no harmonised U-space airspace usage requirements in terms of navigation capabilities and performances but it is envisaged that **GNSS can play a role in improving the U-space**

services since services such as the Network Identification, Geo-awareness, Flight Authorisation and Traffic Information can benefit from the use of GNSS, also in support the implementation of the **Urban Air Mobility (UAM) concept**.

Despite GNSS already supporting UAS operations and contributing to U-space services and Urban Air Mobility, the European Commission is working on further facilitating the use of EGNSS services for drone operations according to an internal **Roadmap for the use of EGNSS Service in drones** which will support the emerging drone market with the development of adequate EGNSS services. First, the roadmap considers the following allocation of EGNSS services to drone operations:



EGNSS SERVICES / *UAS OPS CATEGORIES*		GALILEO*				EGNOS**		
		OS	HAS	OSNMA	Support to SoL Applications†	OS	SOL	
OPEN		✓	✓	✓		✓		*Low Risk*
SPECIFIC	**L**	✓	✓	✓		✓		
	M	✓	✓	✓			✓	*Medium Risk*
	H				✓		✓	*High Risk*
CERTIFIED					✓		✓	

**Alone or in combination with GPS*
***With GPS*
†Support to EGNOS V3 and ARAIM

Figure 18 – EGNSS services allocation to drone operation categories

Since UAS operations comprise an immense range of use cases and operational environments, a stepwise methodology is followed which addresses first low-risk operations (which have almost reached today an acceptable level of maturity), then medium-risk operations (which are demanding in terms of requirements but are about to bloom due to an improved regulatory and standardisation support) and finally the higher risk operations (which support the most demanding future applications like for example Air Taxis within the UAM concept):

- For low-risk operations, EGNSS information and support to UAS Users (e.g., websites, helpdesk) will be improved.
- For medium-risk operations, an EGNSS service provision model based on the existing or planned EGNSS services, including also dedicated SDD commitments if needed, and an EGNSS navigation operational/integrity concept will be developed.
- For high-risk operations, dedicated EGNSS services for drones will be created, with the aim to declare dedicated SDD commitments.

Alongside a support for EGNSS standardisation will be provided, mainly through EUROCAE which is already proposing a variety of supporting documentation via its group WG-105. In particular, the following GNSS initiatives are ongoing:

- ED-301 '**Guidelines for the Use of Multi-GNSS Solutions for UAS Specific Category – Low Risk Operations SAIL I and II**' covering specific aspects of the use of GNSS for low-risk operations and published in 2022.
- Development of the '**Guidelines for the use of multi-GNSS solutions for UAS: Medium Risk**' to extend the use of GNSS by UAS operators in the frame of the Specific Category to medium-risk operations, for publication in 2024.

Finally, the European Commission funds a number of projects under Horizon 2020 and Horizon Europe programmes to study navigation performance of unmanned aircraft operations (e.g., REALITY or EGNSS4RPAS), providing valuable inputs to standardisation and regulatory initiatives.

3.4.5 Maritime and inland waterways navigation

IMO (International Maritime Organization) sets out the basic Required Navigation Performance parameters for the World Wide Radio Navigation Systems (WWRNS) in IMO Resolution A.1046(27). IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) defines the appropriate standards, recommendations and guidance material for maritime authorities considering the established requirements and maritime regulations, referenced in the IMO's Safety of Life at Sea (SOLAS) convention. Since maritime is a global industry, those standards, recommendations, and guidelines are key. **Galileo is recognised as a component of the WWRNS since 2016,** while IMO stated in June 2017 that **SBAS** is not in the scope of IMO Resolution A.1046(27) and hence it does not require IMO recognition to be used in maritime.

IMO resolution A.915(22) provides a **list of maritime applications**, regulated or not, **requiring the knowledge of the craft position or velocity for general navigation or any other purpose**. This resolution, which might require update in the future, is the internationally agreed reference summarising the positioning needs of the maritime users, in particular **IMO defines the maritime requirements for GNSS**, defining general, operational, institutional, and transitional requirements.

Waterborne transport takes place in different environments or phases of navigation:

- **Ocean navigation**: beyond the continental shelf and more than 50 nautical miles from land.
- **Coastal navigation**: above the continental shelf or within 50 nautical miles from shore.
- **Harbour approach and entrance, and inland waterways**: normally takes place in restricted waters, where ships must navigate through well-defined channels.

Waterborne navigation requirements for general navigation depend on the phase of navigation (further information in EUSPA maritime and inland waterways user needs report).

The IMO started to develop at the Maritime Safety Committee (MSC) in 2006 the **e-Navigation concept** as 'the harmonised collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment'. This concept is based on robust PNT services offering sufficient redundancy. Resilient PNT is one of the seven pillars of the IMO e-Navigation architecture. The e-Navigation concept is expected to spread the use of multi-constellation GNSS receivers and ensure resilience using alternative systems.

For the **Maritime Navigation**, Directive 2002/59/EC Annex III (as amended) is establishing a Community vessel traffic monitoring and information system, with Automatic Identification System **(AIS) data collected by satellite** as one of the interfaces of the central SafeSeaNet system, hence as **a source of data for the electronic messages including information such as the ship's position**. It is an important element for vessel traffic monitoring and thus to help enhancing the safety and efficiency of maritime traffic.

With regard to **Security**, IMO issued high level Guidelines on maritime cyber risk management (MSC-FAL.1/Circ.3) complemented with further recommendation from shipping associations, International Association of Classification Societies (IACS) and International Association of Ports and Harbours (IAPH). The guidelines on cyber security on board ships provided by the shipping associations, underscores that […] *cyber incidents can arise as the result of loss of or manipulation of external sensor data, critical for the operation of a ship. This includes but is not limited to Global Navigation Satellite Systems* (GNSS) […] *A cyber incident can extend to service denial or manipulation and, therefore, may affect all systems associated with navigation*. **Authentication and integrity of accuracy of the vessel position is needed** to support alerting the bridge of a situation of risk.

The EGNSS programmes are working in different initiatives to provide additional information for both integrity and authentication to be used in maritime (see 3.3.2.2 for the various phases):

- **EGNOS corrections use** in RTCM format **via MF-radio beacons and AIS VDL Message 17** is already enabled and IALA Guidelines G-1129 explain how to implement this retransmission.
- With respect to **integrity**, developing a first **EGNOS maritime service that together with RAIM** will enable more accurate positioning including alerts to the bridge. IALA Guidelines G1152 provide coastal Maritime Authorities with information on how SBAS will be used as a maritime service. A new shipborne receiver test standard is under preparation within IEC for SBAS receivers (IEC 61108-7) and is expected to be published in 2023.
- With respect to **authentication**, two projects funded under fundamental elements GSA/GRANT/02/2019 are implementing Galileo Open Service Navigation Message Authentication (OS NMA) for shipborne receivers.

Related to these initiatives, there is a need to **update certain standards and regulations**:

- IMO Res. MSC233 (82) adoption of the performance standards for shipborne Galileo Receiver Equipment: IMO NCSR is currently discussing a new approach to simplify these performance standards. IEC 61108-3 on Maritime navigation and radiocommunication equipment and systems will then include in the update specific recommendations for shipborne GALILEO receiver equipment, normally in 2023.
- A new work item will be requested in IMO to develop performance standards for **DFMC SBAS + ARAIM.** The work could be finalised in 2025, and consequently a new IEC test standard for DFMC SBAS should be developed with the objective to finalise it 2 years later.
- Commission Implementing Regulation (EU) 2022/1157 on design, construction and performance requirements and testing standards for marine equipment: to include new and updated performance and test standards for shipborne receivers, both for Galileo and DFMC SBAS + ARAIM. It should happen in the next yearly update after the availability of standards.

In terms of resilient PNT services, International Association of Lighthouse Authorities (IALA) with a key contribution of several Member States is working in a **back-up system for coastal and harbour areas called R-MODE** (or Ranging Mode) using signals from Medium Frequency (MF) Radio beacon stations and AIS/VDES stations (AIS – Automatic Identification System / VDES - VHF Data Exchange System). R-MODE Baltic2 project, co-funded by the European Union under Interreg Baltic Sea Region initiative, set-up a test bed in the Baltic Sea (see Appendix A, section 5.3.5 for more information on R-MODE). IALA Guidelines G1158 explain that **GNSS timing can be used** at shore level as one of the sources of timing to provide the synchronisation of the VDES signals required **for R-MODE**. This requires a reassurance that the GNSS signal, as received by the stations, is not spoofed (e.g., by using encrypted GNSS signals and verifying the GNSS integrity in the stations).

EU-funded research and innovation on civil maritime security has also exploited PNT and GNSS services for developing capabilities for security of maritime assets and individuals against natural or international threats, as well as the capabilities of Coast Guards and for civilian tasks of Navies.

Navigation in Inland Waterways **requires position accuracy, including the vertical domain**, used to calculate clearance of bridges, locks etc. and to monitor traffic situation. To increase the performance of GNSS, IALA DGPS stations were established to some extent also to cover the inland waterways. In addition to this, distribution of DGPS data through AIS message 17 is done in many areas with the help of Inland AIS base stations, available to vessels that are equipped with an Inland AIS transponder (which is compatible with the maritime AIS transponder).

In comparison with maritime navigation, inland navigation faces more **difficulties related to blocking of satellite signals** due to land shadowing, mountains, or obstructions from man-made objects such as bridges and locks. Unfortunately, in locations where highest position accuracy is required, also GNSS signal blocking is likely to occur (e.g., when a ship enters a lock). In terms of integrity, accuracy and reliability, the inland navigation users would therefore benefit from **multi-constellation navigation**, because more satellites are available.

Inland navigation users could benefit from the **High Accuracy Service** from Galileo and future dedicated **EGNOS services** for maritime use if the positioning equipment on board of inland vessels is installed properly. However, higher levels of automated inland navigation will require **additional near-field sensors** such as LIDAR and Radar sensors on top of the GNSS sensors. **Multiple antennas processing** could be also exploited to increase navigation robustness and safety.

Directive 2005/44/EC (RIS Directive) on harmonised river information services on inland waterways contains a recommendation for the use of satellite positioning technologies. Commission Implementing Regulation (EU) 2019/838 on technical specifications for vessel tracking and tracing systems contains **detailed requirements and technical specifications** for vessel tracking and tracing systems in accordance with the provisions in the RIS Directive, respecting the following principles:

- The definition of the requirements concerning systems and of standard messages as well as procedures so that they can be provided in an automated way.
- The differentiation between systems suited to requirements of tactical traffic information and systems suited to requirements of strategic traffic information, both regarding positioning accuracy and required update rate.
- The description of the relevant technical systems for vessel tracking and tracing such as Inland AIS (inland automatic identification system).
- Compatibility of data formats with the maritime AIS system.

Directive 2005/44/EC (RIS Directive) is currently being revised, with a view to adoption in 2023. The revision will consider the work of the European Committee for Standards for Inland Navigation (CESNI), which has adopted the first set of RIS Standards in April 2021 (European Standard for River Information Services, ES-RIS 2021/1). ES-RIS 2021 is a reproduction of the currently applicable technical specifications contained in the Implementing Regulations (EU) under the RIS Directive. Future evolutions of the technical specifications, including the ones on vessel tracking and tracing systems, will be covered by the two-yearly revisions of the ES-RIS, and set into force through secondary legislation under the revised RIS Directive. **Specific provisions on PNT and GNSS may also be covered by the ES-RIS in the future**.

In addition, the Inland AIS test standard mandate all the IEC standards included in the series 61108 for the internal GNSS receiver. Today those includes Galileo (part 3) and enables the use of EGNOS once part 7 is published (expected by mid-2023). The use of EGNOS corrections transmitted in RTCM format via VDL Message 17 is already enabled.

Finally, inland waterways transport is evolving and benefiting from emerging technologies that lead to a safer, digital and more sustainable sector. Autonomous vessel operations will create new business opportunities (also for Maritime Navigation), as well as new challenges, supporting the digitalisation and sustainability challenges of the EU. The European Commission intends to launch in 2023 a **preparatory action on EU Space Data for autonomous vessels in Inland waterways** with a duration of 3 years to assess how EU Space Data from Galileo, EGNOS and Copernicus can be key enablers of this transformation, by facilitating reliable and robust positioning information and harmonised images of the fairways and environment, needed for safe and green autonomous operations.

3.4.6 Road transport

The **success of satellite positioning in vehicle application platforms and portable navigation devices** thanks to the accurate position and advanced navigation they deliver has been reinforced lately by the appearance of user friendly navigation apps and maps on smartphones as described in the EUSPA road user needs report.

The **dominant place of GNSS road applications** in the market is confirmed by public authorities' decisions and the advent of connected cars, which, combined with permanent short-range communication between vehicles, other road users and infrastructure (vehicle to everything – V2X communications), offer an almost unlimited series of applications which will improve both road safety and traffic efficiency. Moreover, GNSS coupled with other on-board sensors and 3D mapping will play a key role in **autonomous vehicles** due to the very demanding performance requirements in terms of positioning accuracy, availability and robustness required.

The **smart tachograph**, introduced by Regulation (EU) No 165/2014, is an evolution of the digital tachograph, which notably includes a connection to a GNSS receiver, a remote early detection communication facility and an interface with intelligent transport systems. The use of tachographs connected to **GNSS** is an **appropriate and cost-efficient** means of automatically recording the position of a vehicle at certain points during the daily working period to support officers during controls. The **technical specifications** of the smart tachograph were laid down in Commission Implementing Regulation (EU) 2016/799, and smart tachographs have been installed in newly registered vehicles since 2019.

The technical specifications were updated in Commission Implementing Regulation (EU) 2021/1228 to cover the registration of starting and ending positions of the working days of drivers of commercial vehicles, and also border crossings and loading and unloading operations. GNSS and border-crossing geofencing allow enforcement authorities to control more efficiently international transport operations of road undertakings against EU market and social rules. This **second version** of the smart tachograph is also expected to **use the Galileo OSNMA service,** once it is declared operational. This tachograph will start being rolled out in newly registered vehicles in August 2023. All vehicles engaged in international transport operations and in the scope of the Regulation (EU) No 165/2014 will be retrofitted with a second version smart tachograph by August 2025 at the latest.

Regarding **Electronic Tolling, GNSS for Road User Charging**, which consists of charging a user (i.e., vehicle) based on its reported position, is regulated under Directive (EU) 2019/520 on the interoperability of electronic road toll systems. The Directive allows **satellite-based tolling** for heavy-duty and light-duty vehicles, which permits the removal of physical toll stations in highways, eliminating also queues and saving time for the final user, while granting users' privacy through data anonymisation. From October 2021, all new electronic toll systems brought into service using satellite positioning shall be compatible with EGNOS and Galileo. In addition, from 2028 all new electronic toll systems for passenger cars shall be compatible with GNSS.

As regards **Intelligent Transport Systems (ITS)**, Directive 2010/40/EU on the framework for the deployment of Intelligent Transport Systems in the field of road transport states that for ITS applications and services, for which accurate and guaranteed timing and positioning services are required, satellite-based infrastructures or any technology providing an equivalent level of precisions should be used, such as those provided by EGNOS and Galileo. Several Delegated Regulations adopted within this framework, such as Commission Delegated Regulation (EU) 2015/962 with regard to the provision of EU-wide real-time traffic information services, organise the access to and exchange of data generated thanks to accurate positioning, including in-vehicle generated data.

The Commission proposal (COM (2021) 813) for the revision of Directive 2010/40/EU proposes to ensure the compatibility of ITS applications and services, which rely on timing or positioning, with at least the navigation services provided by EGNOS and Galileo, including OSNMA.

In 2020, two **relevant PNT standards** were released for ITS secure communications (CEN/ISO TS 21176) and vulnerable road users (ETSI TS 103 300-1, ETSI TS 103 300-2, ETSI TS 103 300-3). DATEX II is the data exchange standard for ITS stations exchanging traffic information between public authorities and service operators: traffic incidents, road works, etc. Since 2021, DATEX II v.3.2 includes a location data model requiring the registration of GNSS authentication.

Regarding **eCall**, Regulation (EU) 2015/758 lays down the type-approval requirements for the deployment of the eCall in-vehicle system based on the 112 service. The provision of accurate and reliable positioning information is an essential element of the effective operation of the 112-based eCall in-vehicle system. According to this Regulation, manufacturers of eCall shall ensure that the **receivers** in the 112-based eCall in-vehicle systems are **compatible** with the positioning services provided by the **Galileo and the EGNOS** systems. The Commission Delegated Regulation (EU) 2017/79 specifies testing methods and performance requirements for the type approval of GNSS.

In 2018, UN Regulation 144 entered into force establishing a harmonised type approval mechanism of eCall systems, devices or components to be valid in more than 50 countries, including Japan, Korea and Russia. Compatibility with GPS, GLONASS, Galileo and all existing SBAS is required.

In 2021, the European Commission started the works to update the current eCall specifications, both for vehicles and public safety answering points, to adapt the current legal framework to the evolution of the telecommunications networks towards packet switched networks.

For **Safety Automotive Systems** and In the frame of the new General Safety Regulation (EU) 2019/2144 for automotive vehicles, the Commission Delegated Regulation (EU) 2021/1958 on Intelligent Speed Adaptation (ISA) systems employing a combination of a camera system, GNSS and digital maps, require that where such a system is enabled with positioning capabilities, it shall be **compatible at least with Galileo and EGNOS.**

In 2021, UN Regulation 155 entered into force establishing uniform provisions concerning the cyber security management in autonomous vehicles. GNSS spoofing is considered a threat and the use of authenticated messages is required as mitigation.

The CEN/CENELEC EN 16803 standard established the GNSS test procedures and methodologies for the establishment and assessment of performances in highly demanding road applications, such as autonomous vehicles. The publication of a compatible ISO standard is still needed.

Finally, over the next years, the **digitalisation of enforcement practices** can likely offer more possibilities for the use of EGNSS, and lead to more efficient controls of vehicles and drivers. Indeed, enforcement of rules in road transport is key to ensure road safety and a well-functioning market, be it driving and rest times, weights, and dimensions of vehicles, posting of drivers, possession and compliance with transport authorisations, licences and permits, etc. For example, precise and reliable location information could contribute to the management of priority goods combination with electronic freight transport information (eFTI) in customs and border controls.

Related to road, the follow **standards** would facilitate the introduction of EGNSS services:

- Update 3GPP standard for DFMC GNSS signal dissemination through Mobile Network.
- Test Standard for GNSS + HAS through RTCM SC134.

3.4.7 Rail transport

The **European strategy for railways** aims to make the rail network open and interoperable, which includes replacing national train control systems with the **European Rail Traffic Management System / European Train Control System (ERTMS/ETCS)**, a standardised system developed specifically for the needs of European railways. This system does not use GNSS in its current form, as its core architecture has been designed in 1989/90. Different initiatives have been launched to include GNSS in ETCS, due to its potential to reduce trackside infrastructure by eliminating **Eurobalises** used as position reference markers. This would not only lower the cost of signalling, but also increase availability, reduce engineering and maintenance requirements and its exposure to theft, vandalism etc.

Additional new functionalities are also being investigated for ERTMS/ETCS which could rely heavily on GNSS, such as **train integrity monitoring**, a function within the ERTMS Level 3 system which thanks to the absolute positioning of trains would enable to reduce the separation of the trains, to optimise the traffic and to have positive effects on the environment.

The **main technical challenges** for exploiting GNSS on railway lines lie in the environment, which differs significantly from the aviation and maritime applications. The major differences are a limited and continuously changing satellite visibility, signal attenuation, electromagnetic interference, and significant multipath. In some locations, such as in urban and mountainous areas, these effects can all appear simultaneously. Further information can be found in the EUSPA rail user needs report.

Today, GNSS systems in the railway domain are predominantly used for **non-safety related applications**. Passenger information systems are the main applications, with asset management gaining importance. In the coming years, safety relevant applications, signalling and train control, based on GNSS will be increasingly developed, to complement traditional technologies. Within **safety critical applications**, EUSPA has developed a roadmap for EGNSS adoption in Rail, approved by the main rail and space stakeholders, which summarises the main activities towards EGNSS enabled ERTMS and allows elementary orientation in the activities to achieve this goal.

In 2022, the European Parliament resolution on railway safety and signalling assessing the state of play of the ERTMS deployment pointed out the need to ensure synergies between ERTMS and EGNSS as soon as possible. This is well reflected by the rail sector, which is for instance developing a train localisation onboard unit prototype (Horizon 2020 CLUG project).

The European Commission continues to also investigate the possibilities to use or evolve EGNSS services for rail safety critical applications. At present, two mission studies are on-going and aim to clarify the parameters of a rail specific EGNSS service that could satisfy the user requirements for rail signalling and ERTMS (EGNSS-R, IMPRESS).

The **Technical Specifications on Interoperability (TSI)** define the technical and operational standards which must be met by each subsystem or part of subsystem to meet the essential requirements and ensure the interoperability of the railway system of the European Union. In particular, **the inclusion of GNSS in the Control Command and Signalling TSI is also a prerequisite to enable a wide-scale GNSS adoption for fail-safe train localisation in European Union**. The last modification of this document was adopted in June 2019 and the next release is foreseen during 2023. Further, a maintenance release of the TSI is foreseen in 2026, with an updated version containing new functionalities in 2028/2029.

3.4.8 Agriculture

The projected growth of the world's population to 9.7 billion by 2050, coupled with a higher caloric intake of increasingly wealthy people and the ensuing increase of food demand, renders the intensification of food production imperative as described in the EUSPA agriculture user needs report. There is a need for a comprehensive global food security strategy where **information technology-enabled solutions** play a key role. **With GNSS holding a predominant position**, other technologies such as GIS (Geographic Information System), remote sensing through satellites or UAS (Unmanned Aircraft System), optical sensors for nitrogen content and canopy condition, machine vision systems, gamma-radiometric soil sensors, etc. have been deployed across a wide range of applications. The utilisation of the various enabling technologies and the combination of the different types of data they generate, has given rise to **Precision Agriculture (PA)**, which has demonstrably contributed to increasing yield and productivity while controlling costs and reducing the environmental impact of agricultural activities.

The market uptake of **GNSS-enabled Precision Agriculture** applications will increase along the need for increased food production. Accuracy will remain the most fundamental GNSS parameter for farmers. Reliability, availability, authenticity, and coverage will also have relevance for specific applications. **SBAS-based solutions**, improving the accuracy, integrity, and availability of the basic GNSS signals, are becoming increasingly available in precision agriculture applications, frequently being the preferred option for farmers entering the precision agriculture market. Available over continental scales, free of subscription fees or additional investment costs, SBAS-based solutions are widespread amongst farmers requiring accuracy to sub-metre level. **High accuracy solutions (sub-decimetre)** are needed for automation and are provided by RTK / Network RTK services and real Time PPP services, either commercial or institutional as the Galileo High Accuracy service.

The integration of GNSS positioning in **Farm Management Information Systems (FMIS)** together with the use of additional information coming from various sensors, including Earth Observation, is due to revolutionise precision farming and further driving its uptake. FMIS is a system for collecting, processing, storing, and providing data enabling informed decision-making and management strategy elaboration for farmers. **GNSS links this data to specific geographical coordinates**.

Despite the varying successes and uptake rates of the various technology-driven solutions for agriculture, mainstreaming and extending their adoption require **several technological, economic, and awareness-related challenges to be addressed**. Recently the dedicated Focus Group on Mainstreaming Precision Farming set up by the European Innovation Partnership on Agriculture, has placed on top of their recommendation list the need for 'Farmers and cooperatives to play a major role in innovation and in research on decision support systems and technical solutions to current problems'.

Several initiatives facilitate the adoption of EGNSS in the European agriculture sector.

EGNSS4CAP is a **mobile phone application** for Android and iOS that **digitises procedures for farmers** in the European Union to satisfy their reporting requirements under the current and post-2020 Common Agricultural Policy (CAP) reform.

New rules adopted by the European Commission for the current and upcoming CAP allow a range of modern **satellite-based technologies** to be **used** when administering and controlling **area-based payments**. For example, automatic monitoring procedures employing data and signals from both the Copernicus and Galileo programmes can be used to reduce the number of on-the-spot checks (OTSC). These procedures are part of the Checks by Monitoring (CbM) mechanism and are applied in a certain number of Member States on a voluntary basis.

For the **new CAP**, the Area Monitoring System (AMS) will be introduced. With that mechanism, all Member States will need to **monitor 100% of area-based payments**. The use of these technologies is a part of the European Commission's ongoing commitment to modernise and simplify the Integrated Administration and Control System (IACS) processes within CAP.

The EGNSS4CAP application will use EGNSS differentiators to enable farmers to provide geotagged photos and LPIS (Land Parcel Identification System) updates that both support and complement a Copernicus Sentinel-based monitoring approach for CAP.

The tool is Open Source, available for free and can be integrated by any Android or iOS developer. Mass market devices such as smartphones and tablets will be able to run the application and use GNSS to provide location and timing of the photo ensuring required accuracy and authentication for reporting to the paying agencies.

The **Farm Sustainability Tool (FaST)** is a digital service platform making available capabilities for agriculture, environment and sustainability to EU farmers, Member State Paying Agencies, farm advisors and developers of digital solutions. FaST will support farmers in their administrative decision-making processes, for farm profitability and environmental sustainability.

EGNSS will be an integral part of FaST as it will permit farmers to combine earth observation data with real-time positioning, as well as communicate geotagged information with the Member State authorities.

Although not considered as a primary source of information for the **Land Parcel Identification System (LPIS),** data collected on site using **GNSS**, **provides valuable contribution** for the LPIS upkeep. Most of the field information using GNSS used for the LPIS, is gathered during the classical on-the-spot checks of the farmer declarations. Moreover, field inspectors are required to report any non-correct reference parcels and the EFA layer. Some Member States are also conducting occasionally more systematic field surveying using GNSS.

The **New IACS Vision in Action (NIVA)** modernise IACS with digital solutions and e-tools, by creating reliable methodologies and harmonised data sets for monitoring agricultural performance while reducing administrative burden for farmers, paying agencies and other stakeholders.

The **UC4a 'Geotagged Photos'** use case of the NIVA project consists in designing and developing an application for mobile devices to facilitate a farmer and/or advisor to upload a geotagged photograph as supporting evidence to scheme applications. This project will exploit novel features of GNSS preventing location spoofing (e.g., authentication within Galileo signal). The App will demonstrate the ways to receive notifications from the supporting system and the ability to notify and guide farmers to successfully locate, line up, frame and capture images for the requested points of interest.

The end user will benefit by having more engagement options with the paying agency. The farmers may reduce on-the-spot inspections if they upload the photographic evidence of activity or clarify the query. The Administration will have an electronic record of the response and a comprehensive profile of agricultural activity in the parcel.

In eco-schemes concerning **precision farming** EGNSS could help farmers to improve nutrients management plans, reduce inputs (fertilisers, water, plant protection products) and improve irrigation efficiency or the monitoring of the use of pesticides by precisely recording the location where the pesticides were spread.

3.4.9 Location-Based Services

The most used navigation device is our mobile phone where PNT is mostly used for Location Based Service (LBS) applications. In a context of global urbanisation and smart city, **GNSS-enabled LBS addresses some of the most immediate economic and societal concerns** such as improvement of work productivity, ease of movement, tracking of people, resources' management and effective services to facilitate consumer interactions (EUSPA Location Based Service user needs report).

GNSS-enabled solutions cover a myriad of applications, including navigation, mapping, GIS (Geographical Information System), geo-marketing and advertising, safety and emergency, sports, games, health, tracking, augmented reality, social networking, infotainment. Several of these applications require stringent horizontal and vertical accuracy levels and authentication of the position (e.g., location-based billing to prevent fraud).

Standardisation activities related to LBS can be divided in **signalling, performance** requirements for positioning including GNSS and A-GNSS (Assisted GNSS), and **testing** procedures. The main standardisation bodies are the 3rd Generation Partnership Project (3GPP), the Open Mobile Alliance (OMA), ETSI TC SES, and CEN-CENELEC.

According to the Commission Delegated Regulation (EU) 2019/320 from 17 March 2022 all **smartphones placed in the European single market** need to offer the option to send handset- derived location information using Galileo signals, in addition to other GNSS, to the closest Public Safety Answering Point (PSAP) **emergency service**. This is to enhance the 112 emergency calls location for faster response times and consequently saving more lives (EUSPA EO and GNSS Market Report 2022 LBS). A large majority of the smartphones already complies with the requirements, which are assessed by notified bodies through conformity assessment procedures, using European Commission provided Guidelines. This functionality is activated on a country-by-country basis depending on the technical and operational readiness of the **Advanced Mobile Location (AML)**.

Two standards for 4G and 5G enabled smartphones, released by 3GPP in 2020 and 2021 (3GPP TS 36.171 version 16.1.0 Release 16 and 3GPP TS 38.171 version 16.2.0 Release 16) *Requirements for support of Assisted Global Navigation Satellite System (A*-GNSS) foresee a 'constellation agnostic' approach (i.e., the system having the satellite with highest signal level, shall be selected by the device manufacturer). This is an important safety step moving from a 'GPS centric approach', irrespectively of the time to first fix provided by other constellations.

Following the **availability of pseudoranges on Android** operating system, the Raw Measurements Task Force aims to bridge the knowledge gap between raw measurement users and industries. In addition, **EUSPA/JRC testing campaigns** are running to evaluate the performance and functionality features specifically aimed at smartphones and other mass market devices.

Finally, the **5G PNT Navigation Task Force** contributes to 3GPP works on PNT and promotes the **inclusion of EGNSS into the 5G PNT ecosystem** to ensure that the technical specifications produced by 3GPP account also for the possibility to **complement EGNSS with 5G**, where GNSS coverage is not available (e.g., indoor) but also for improved positioning accuracy when in nominal conditions. Furthermore, 5G positioning architecture and protocols have been adjusted over the last years to support the delivery of assistance data needed for high-accuracy GNSS techniques (e.g., RTK, PPP, etc.) in both unicast and broadcast with the first products and services starting to emerge both in Europe and US.

3.4.10 Search and Rescue

The objective of Global Search and Rescue (SAR) operations is to quickly locate and help people in distress. Although not all Search and Rescue beacons are GNSS-enabled, there is an increasing trend towards GNSS uptake amongst these beacons.

The COSPAS-SARSAT Programme is an international satellite-based search and rescue distress alert detection system. Currently, the **Galileo SAR service contributes** to this system by swiftly relaying radio beacon distress signals to the relevant SAR crews, using dedicated payloads on-board Galileo satellites and three ground stations deployed across Europe (refer to section 3.2.7 for further information). The SAR service requires SAR enabled receivers (beacons).

The availability of the Galileo SAR service benefits all those sectors in which due to the nature of their operations the lives of people is at stake, notably maritime and aviation.

For **maritime**, the IMO established in 1988 the Global Maritime Distress and Safety System (GMDSS), with the intention to always allow vessels send and receive maritime safety information. It reached operational status by 1997.

Ships need to be equipped with Emergency Position Indicating Radio Beacons (EPIRBs) and Personal Locator Beacons (PLBs) which transmit, once activated, the necessary information to emergency authorities. The AIS-SART (Search and Rescue Transmitter) and AIS-MOB (Man Overboard) beacons not only transmit the position of the person in distress, but also share this location through the Automatic Identification System (AIS) with nearby vessels, by pinpointing an AIS distress signal onto the nearby vessels Electronic Chart Display Information System (ECDIS).

In **aviation**, following the tragedies of Air France 447 and Malaysia Airlines 370 and given the time taken to locate the aircraft, ICAO established the Global Aeronautical Distress and Safety System (GADSS) which ensures that aircraft are tracked and that their latest known GNSS derived position is always recorded, maintaining an up-to-date record of aircraft progress. Under the current aircraft tracking standards and recommended practices (SARPs), aircraft under normal flight conditions need to be tracked every 15 minutes. The latest update of ICAO Annex 6 requires autonomous position reporting every minute when the aircraft is in distress. The standard for the distress tracking element of GADSS will be applicable on 1 January 2025 to aeroplanes with a first individual Certificate of Airworthiness (CofA) on or after 1 January 2024.

Aircrafts need to be equipped with Emergency Locator Transmitters (ELTs) or Personal Location Beacons (PLB) that help Search and Rescue operations in the event of an incident. In line with requirements in ICAO Annex 10 (and standards set in ICAO Annex 6) as well as the implementation of the GADSS, many ELTs make use of GNSS to report their position when triggered.

Finally, SAR services are also extensively used on **land** where climbers and hikers are advised to equip themselves with a PLB in case they find themselves in distress.

More information about Galileo SAR is available at the EUSPA webpage. EUSPA EO and GNSS Market Report 2022 contains information on the SAR related market , and the EUSPA GNSS User Technology Report provides an overview of the existing technology.

3.4.11 Mapping and Surveying

The mapping and surveying market in general and its use of GNSS, are expected to show significant growth in the coming years especially in regions of the world where there are no alternative legacy systems or dense geodetic ground networks. Significant growth is also expected in regions with intense construction activity, where the importance of cadastral surveys will also increase as a function of the increasing GDP and population. In this context, GNSS-enabled surveying addresses some of the most immediate economic and societal concerns such as increased urbanisation, increased demand for hydrocarbons and modernised transportation needs as described in the EUSPA surveying user needs report.

GNSS-enabled solutions cover a wide range of applications including cadastral surveying (delineation of property boundaries), construction surveying (precise setting out of the buildings and infrastructure), mapping (charts that contain points of interest and are typically integrated in Geographic Information Systems), mine surveying and marine (offshore and hydrographic) surveying.

However, the role of the traditional GNSS surveying is undergoing a rapid transformation thanks to the integration of **emerging applications**, such as optical, multispectral or LiDAR (Light Detection and Ranging), terrestrial laser scanning, UAS (Unmanned Aircraft System), IMU (Inertial Measurement Unit), SLAM (Simultaneous Localisation and Mapping), AR (Augmented Reality), mobile and crowdsourced mapping. In addition, these emerging geomatics applications are mainly focusing the implementation of solutions directly in the cloud.

Thanks to digitalisation, **Building Information Model (BIM)** and **Geographic Information Systems (GIS)** are now integrated into a single holistic environment to produce digital twins. The process of accurate 3D modelling – common for both – is leveraged by **high-precision GNSS location data**. When stored and processed in the cloud, the GNSS, GIS and BIM information enable stakeholders in the whole construction industry to remotely manage data everywhere and produce better building/infrastructure designs with long-term savings.

Another example is urban planning. SLAM technology, with its laser/IMU/camera integration, and portable laser scanners have opened a huge field for detailed realistic modelling inside buildings. When combined with GNSS receivers, these systems are providing seamless indoor-outdoor transition.

As many new methods and tools arise, so does the **need for well-defined requirements and standards**. Within mobile mapping systems, a set of standards would frame the fusion of GNSS with LiDAR, optical cameras, inertial, laser and odometer instruments. Other key areas requiring stringent requirements and standards are seamless indoor-outdoor positioning and PPP-RTK. The recent advancement of augmented reality applications that rely on GNSS accuracy and availability would also benefit from standards.

For mapping and surveying's stringent accuracy requirements (down to cm or mm-level) augmentation services such as **Real Time Kinematic RTK**, **Precise Point Positioning PPP** and the recently emerged PPP-RTK is of paramount importance. Both RTK and PPP multi-GNSS corrections are supported in the standard Radio Technical Commission for Maritime Services (RTCM) protocol, either for a single reference station or network (NTRIP) or PPP.

PPP-RTK implementation within the RTCM is not available yet. As a result, there has been a strong push for the standardisation of PPP-RTK corrections via new messages within the RTCM protocol while, in the meantime, various industry stakeholders and scientific initiatives proposed other protocols or standards (e.g., IGS, Sapcorda, 3GPP, etc.).

To overcome the challenges regarding the lack of availability, quality, organisation, interoperability, accessibility, and sharing of **spatial information**, common to many sectors and various levels of public authority in the Europe, the EU adopted the INSPIRE directive (The Infrastructure for Spatial Information in the European Community). INSPIRE will enhance the **sharing of environmental spatial information** among public sector organisations and better facilitate public access to environmental information across Europe. Mapping and surveying, which utilise geo-data collection services and tools, including those EGNSS-based, are directly linked to INSPIRE.

On this basis, it is essential to ensure the ability to combine spatial data and services from different sources (data interoperability) across the EU in a consistent way without additional efforts of humans or machines. The data interoperability in INSPIRE is assured, amongst others, by **mandating the use of a common coordinate system**, the **European Terrestrial Reference System 1989 (ETRS89)**. This ensures that geospatial data, derived from EGNSS, is fully compatible and integrated into end user applications, leading to accelerating the use of EGNSS.

Machine Control is important and growing part of the survey market. As reported by the **EUSPA Report on User Needs and Requirements Mapping and Surveying**, the most important target markets are **construction** and **mining** sector (e.g., control and semi-automatic guidance of vehicles in earth-moving machines or mining equipment) where centimetre-level accuracy is necessary to increase productivity and lower the cost. Recently dry **port operations** become a new market where unlike the other two segments where machine control is implemented by the vehicle manufacturers, port operations are implemented by the crane producers integrating hardware with the logistics and port management software. Its main advantages consist of managing vessel load, logistics of loading, increased operational speed and safety. This, combined with use of GNSS and different PNT systems creates a unique European Expertise.

The **Machine Directive (2006/42/EG)**, which sets requirements for machines, safety components, lifting accessories (such as chains and ropes) and other related products, is the widely used by EU manufacturers to ensure a common safety level in the machinery placed on the market and to maintain Intellectual Property Rights (IPRs) within EU.

3.4.12 Precise Timing and Synchronisation (finance, power grids, communication)

Electricity transmission, telecom networks operation, timestamping of financial transactions, air traffic management systems, transportation systems, satellite platforms, water and wastewater systems, scientific applications (astronomy, particle physic, geophysics, metrology), digital TV broadcast, LTE small cells networks – femto, pico and microcells -, Internet of Things (IoT) are only a few examples of the **myriad of applications relying on GNSS for timing and synchronisation purposes** (further information can be found in the GSC time and synchronisation user needs report and the GSC GNSS User Technology Report).

Although relatively unknown to the public, the **timing and synchronisation capability offered by satellite navigation** systems has become **essential for critical infrastructures**. The **robustness and resilience in the timing and synchronisation services are key** to avoid serious disruptions of the critical infrastructure's operation. Moreover, since infrastructures in Europe are highly interwoven, the resilience increase of the network cannot be achieved by a Member State acting alone.

Galileo, used as primary source of timing information or as a redundancy solution, will **contribute** to a **more resilient GNSS timing service** by improving both the timing service availability (bringing another independent constellation) and providing several added values such as authentication, which increases the resilience against spoofing.

EGNOS offers time information obtained from GEO satellites or via the terrestrial EDAS service, allowing users to access data online in real time and through two different channels.

In the EU, a major step was the formal creation of a stand-alone **Galileo Timing Service** as part of the mission of the Galileo Second Generation, which leverages on the intrinsic timing capabilities of Galileo as a GNSS System and brings in additional features to better fulfil the specific needs of the timing and synchronisation users:

- **High Availability** of the Timing Service as a whole.
- **Improved Accuracy** for all timing parameters.
- **Dedicated requirements** for the Galileo System Time (GST), making it a very performing reference for synchronisation applications.
- **Galileo Timing Service Monitoring function**, that will significantly reinforce the Timing Service robustness and the confidence in the timing solutions obtained through Galileo. Thanks to the monitoring function, users will be informed through specific flags of faults that might impact the timing service levels' compliance. This particularly relevant for Critical Infrastructure applications.

The Galileo Timing Service concept also includes the development of a **Standard for Galileo Timing receivers.** This Standard will ensure the correct contribution of the user receiver as a fundamental piece for the end-to-end performance. It will also include the implementation of local barriers, such as T-RAIM (Timing RAIM), to further improve the overall robustness. The development of this Standard, the first ever GNSS timing receiver standard, is formally ongoing within CEN-CENELEC.

Finally, Precise Timing is also provided by non-GNSS technologies which further enhance or act as back-up of the GNSS-based timing services, such as longwave systems (Appendix A, section 5.2.7) and emerging technologies (Appendix A, section 5.3). The provision of Alternative Timing is already commercially available in the European Union, as confirmed by a 2022 study conducted by the European Commission. Mature Alternative Timing services exist in the market which **distribute** precise time over long-distances while the EU has a unique distributed network of National Metrology Institutes (NMIs) that can be used to **generate** precise time synchronised to UTC(k).

3.4.13 Space users

The **GNSS market for space is evolving extremely fast** over the last decade, resulting in a deep paradigm shift in the space industry. Characterised by the opening-up of the sector to non-governmental and more business-oriented actors, a disruptive commercially driven approach to space has emerged, which coupled with important technological advances, lead to, and increase number of satellites and space services. While entering the third millennium, about 800 satellites were actively orbiting the Earth. Twenty years later, this number now exceeds 3 000 and is expected to quadruple over the next decade. Highlighting the democratisation of space in our society and the convergence of the sector with the ever more digitalised human activities, the development of new satellite mega constellations systems on Low Earth Orbits (LEO) is a marker of this new era.

With satellites manufactured in batch, launches occurring almost every day, equipment being mass produced and processes being industrialised, the space environment is progressively considered as a commodity and **spaceborne GNSS receivers are increasingly common** and relevant for space users, from LEO altitudes (i.e., 300 km) up to Moon Transfer Orbit (MTO).

Spaceborne GNSS receivers are **not fundamentally different from classical GNSS receivers**. They perform the same operations and provide the same PVT services, but they must address **specific constraints of the space environment** (e.g., high dynamics, reduced signal power and visibility, solar radiation). Depending on the mission expected from the spacecraft, the role of the embedded GNSS receiver varies. While they can be used as a guidance and navigation control subsystem (i.e., for precise orbit determination, attitude determination or synchronisation purposes), they can also be used as one of the payloads directly serving the mission objectives (e.g., radio occultation measurements).

The **benefits of GNSS-based solutions aboard spacecraft** range from the reduction of spacecraft's dependence on ground-based stations to improved navigation performances. The security of space infrastructures has also become a driver for spaceborne developments, as the threat of offensive counterspace capabilities is growing. In order to facilitate the development for space users of GNSS solutions that would benefit of the combined use of existing global and regional navigation systems, the International Committee on Global Navigation Satellite Systems (ICG) has issued The Interoperable GNSS Space Service Volume to reap the benefits of the existing global and regional navigation systems when used together to provide improved capacities.

In the EU, the main initiative to facilitate the use of Galileo by space users is the formal definition of a **Galileo Space Service Volume** as part of the mission **for the Galileo Second Generation** (see 3.2.1.2 for further information). This will ensure that all the required activities are implemented, to allow Galileo commitments on the level of performance that space users can achieve when using Galileo signals in space. It is important to recall that **Galileo signals are the most suitable for space users** amongst the GNSS systems thanks to the higher altitudes of the Galileo satellites and to the authentication capabilities offered by the Galileo Open Service Navigation Message Authentication.

Finally, the **validation** of the performance **of precise orbit determination from Galileo signals** in a typical configuration of low-cost receiver is on-going in the frame of Horizon 2020 In-Orbit Demonstration/Validation (IOD/IOV).

More information can be found in the EUSPA space user needs report.

3.4.14 Security and Defence

Security and military operations rely heavily on space-based data and space-enabled capabilities, including dual-use ones, to provide secure, reliable, and highly performant services in an evolving threat environment. The Strategic Compass for Security and Defence identified space as a strategic domain and called for an EU Space Strategy for Security and Defence, published in March 2023.

The **EU Security Research and Innovation Programme** and the Research and Development (R&D) actions of the Cluster 3 'Civil Security for Society' of Horizon Europe, and its precursors in Horizon 2020, FP7 and Preparatory Action for Security Research (PASR) which has funded over 700 projects since 2004, promote cooperation and include the development and exploitation of PNT / GNSS for security practitioners such as law enforcement, border management, maritime security, protection of critical infrastructures and disaster resilience. **Horizon Europe Cluster 3's security projects mandate the use of EU Space Programme whenever developing relevant PNT capabilities.**

The R&D actions of the **European Defence Fund (EDF)**, and its precursors the European Defence Industrial Development Programme (EDIDP) and the Preparatory Action on Defence Research (PADR), include the development of Galileo and other PNT technologies for military users. The EDF promotes cooperation among companies and research actors of all sizes and geographic origin in the EU, for the sake of state-of-the-art and interoperable defence technology and equipment. It also aims to improve PNT performances and resilience to achieve the goal of 'uninterrupted PNT access worldwide'.

From the many awarded projects, the following R&D actions are of relevance for PNT services:

- **GEODE - Galileo for EU defence**, EDIDP 2019 - will prototype, test, and qualify multiple Galileo PRS enabled PNT solutions for defence specific requirements and applications (7 PRS Security Modules, 9 PRS receivers, 4 GPS/Galileo PRS compatible Controlled Radiation Pattern Antennas) and a European PNT test & Qualification Facility. PRS infrastructure will also be developed to ensure the availability of the security assets required for operational testing of the receivers. Military operational field-testing will be organised on Naval and Land platforms, RPAS, Timing and Synchronisation system in multiple Member States.
- **QUANTAQUEST - Quantum Secure Communication and Navigation for European Defence**, PADR 2019 - will contribute to the applicability of quantum technologies in the military field and to the strategic autonomy of Europe. Navigation and timing will be achieved through a fully autonomous sensor based on cold atom chip and photonic integrated circuit that provide the required performance and portability. Secure communication will be improved by a new modulation scheme to implement Quantum Key Distribution. Field operation compatibility will be ensured with a free space approach. Quantum interface will be implemented as the opening gate to a quantum network of sensors.
- **NAVGUARD (Advanced Galileo PRS resilience for EU Defence**, EDF 2021) will strengthen the Galileo PRS resilience through new ground and space-based systems. It will develop a European NAVWAR capability relying on GNSS spectrum surveillance based on ground and space-based systems to detect illegitimate activities in GNSS frequency bands and geo locate their sources. The project will also design, prototype, and test an Information management subsystem together with a user interface to establish a situational awareness picture. Five different PRS mobile receivers will contribute to the overall NAVWAR capability together with an in-orbit demonstration of a PRS space-based augmentation system.
- AI-ARC (Artificial Intelligence based Virtual Control Room for the Arctic) and FOLDOUT (Through-foliage detection, including in the outermost regions of the EU will develop and exploit PNT capabilities for maritime security and civil surveillance.

3.4.15 Multimodal travel user needs

GNSS is used by transport operators and on-demand service providers in various ways, starting from more efficient fleet management to accurate passenger information. **GNSS-based solutions can also allow for a further development of sustainable types of transport** by serving as a base for shared mobility, such as shared vehicles or free-floating bikes.

While the current use of GNSS in Public Transport is relatively limited in comparison to other sectors, an increasing number of public transport operators are using of Galileo-based applications in their day-to-day operations. This **growing trend to use GNSS-based solutions** is not limited to public transport, but also reflected in the ever-growing Mobility-as-a-Service solutions, as described in the EUSPA public transport user needs report. The use of GNSS is relevant for providing information to passengers on real-time locations of vehicles (public transport and on-demand) and delays in the schedule as requested by Commission Delegated Regulation (EU) 2017/1926 on multimodal travel information services (MMTIS).

Two main categories cover the increase of GNSS-based services:

- **Smart mobility**: efficient public transport requires increased performance for GNSS-based solutions. Within this context, multi-constellation multi-frequencies receivers will be able to improve the positioning in urban environment to meet the most demanding applications like collision avoidance, lane keeping, and automatic braking which will require authentication, integrity, and robustness. In addition, the increasing combination of several transport modes for the same journey requires real-time information on vehicles location and delays.
- **Safety critical applications** such as emergency breaking for trams or door control for trains may be enabled thanks to EGNSS signals and specific services (Galileo OS NMA, Galileo HAS).

3.4.16 Freight transport and logistics

The digital transformation of the freight transport and logistics sector, including the implementation of the Regulation on electronic freight transport information (EU 2020/1056) and the work of the Digital Transport and Logistics Forum focusing on the paperless transport and corridor freight information system, opens a possibility to develop a range of **new services for multimodal transport and logistics, including PNT technologies.**

Examples of the use of GNSS in this sector are:

- The **real-time tracking of containers** within the multimodal logistics chain and between logistics modes and actors is enabled by the real-time access to PNT information. This also allows to deploy real-time remote diagnostics monitoring systems.
- The use of PNT data connecting the **transport of dangerous goods** to the emergency services in case of accidents, providing the real-time location of the vehicle carrying dangerous goods and the exact content of its cargo.
- The improvement of **freight management services** by transportation stakeholders like rail service providers to become increasingly assets centred. Railway operators and infrastructure managers benefit from digitalisation because it improves **asset management** and maintenance, thereby reducing the operational costs. Those are recognised by the European Commission as a sustainable, smart, and safe means of freight transport with GNSS receivers used to track rolling stock (more than 50 000 freight wagons of multiple EU railway undertakings are already equipped with GNSS-based telematic solutions).

Further information can be found in the EUSPA EO and GNSS Market Report 2022.

3.5 EU Cooperation on Satellite Navigation

The EU cooperate with several countries and international organisations on satellite navigation. This cooperation ranges from non-EU countries' participation in the EU Space Programme components to cooperation based on GNSS Cooperation Agreements.

In terms of participation to components of the EU Space Programme:

- **Norway** participates to Galileo, EGNOS and Copernicus via the mechanisms of the European Economic Area (EEA).
- **Iceland** participates to EGNOS and Copernicus via the European Economic Area (EEA).
- **Switzerland** participates to Galileo and EGNOS based on GNSS Cooperation Agreement signed in 2013.

In addition, the following **GNSS Cooperation Agreements** on GNSS exist:

- EU - **Norway** signed in 2009 covering security, export control and the protection of radio spectrum as well as of the Galileo and EGNOS stations on territory under Norwegian control.
- EU – **ASECNA** (Agency for Aerial Navigation Safety in Africa), signed on 2016, on the development of satellite navigation and the provision of associated services in the ASECNA's area of competence for the benefit of civil aviation. Under this Agreement the EU supports ASECNA in the development of a Satellite Based Augmentation System.
- The EU also concluded GNSS Cooperation Agreements with **South Korea** and **Morocco** covering spectrum protection, standards, trade, scientific and technical cooperation.

The European Union and its Member States have **privileged cooperation with the United States** in the field of satellite navigation since 2004, when the parties signed an agreement on the promotion, provision and use of Galileo and GPS satellite-based navigation systems and related applications. The cooperation aims to ensure that GPS and Galileo and Space-Based Augmentation Systems are interoperable at user level for the benefit of civil users. The cooperation also aims to maintain fair trade in the global satellite navigation market. The EU - US agreement was extended in 2022 by means of Council Decision (EU) 2022/1089.

The GPS-Galileo Agreement includes three working groups for cooperation:

- **WG-A Radio frequency compatibility and interoperability**: among other things, this WG ensures that Galileo and GPS are compatible at radio frequency level, in part through ITU Coordination, as well as aiming to make the respective civil signals interoperable as far as possible at system and receiver level. WG-A also helps to coordinate EU and US actions in other regulatory forums for the benefit of GNSS.
- **WG-B Trade and civil applications**: this WG aims to ensure that there are no regulatory barriers created by either side that would hamper the use of GPS or Galileo and their applications in respective markets.
- **WG-C Design and development of the next generation of systems**: this WG works on three streams of activities through three dedicated subgroups on:
    - Evolutions Sub-Group: it focuses the following areas:
        - R&D actions for the use of ARAIM in aviation and other domains and contribution to the preparation of ARAIM Standards for aviation.
        - Coordination of long-term R&D actions for GPS/WAAS and Galileo/EGNOS.
        - Coordination on next generation SBAS definition for user communities other than aviation.

  - Service provision Sub-Group: it focuses on aspects that are strategic for the provision of navigation services and exchanges on GNSS service provision aspects, status, and plans both for EGNOS/Galileo and WAAS/GPS.
  - Resiliency Sub-Group (RESSG): it focuses on the key topic of resilience of the GNSS systems against various types of threats. As part of this group, frameworks and standards used by ICAO and other bodies are developed. The purpose of RESSG is therefore to make GPS, Galileo, their augmentations, and their applications more resilient in the presence of harmful interference. The long-term objective is to develop solutions and propose recommendations that can be incorporated in future receivers, systems, and services.

The EU participates in the International Committee on Global Navigation Satellite Systems (ICG), established in 2005 through the U.N. Office of Outer Space Affairs. The ICG promotes cooperation on civil PNT and worldwide applications of satellite navigation technology. The ICG encourages coordination among GNSS providers, regional systems, and augmentations, to foster greater compatibility, interoperability, and transparency, and to promote the introduction and utilisation of these services and their future enhancements, including in developing countries.

The EU also works with Member States and other GNSS provider nations via the International Telecommunication Union (ITU) to ensure that radio spectrum, used for Galileo and other GNSS, is available and protected from interference, and that global rules governing radio use do not impact GNSS. This activity primarily takes place in ITU working parties (mainly ITU-R WP 4C) as well as at World Radiocommunication Conferences (WRCs), that take place every four years.

Finally, the EU works also on international satellite navigation issues through other multilateral bodies, including:

- International Civil Aviation Organization (ICAO)
- International Maritime Organization (IMO)

4 VISION for the EU PNT

The previous sections described the PNT ecosystem in the European Union, discussed the importance of Galileo and EGNOS across all markets and how new services are constantly introduced. They also highlighted limitations and possible threats to PNT services, as well as emerging PNT technologies, that address some of those concerns.

This section describes the (medium-term) vision for the EU PNT ecosystem. It is built considering the major trends of new constellations and signals, improvements in hardware and processing algorithms, increasing radio frequency interference and global connectivity.

From the **market segments** point of view, the tendency shown in the 2020 GNSS User Technology Report is mostly valid, where PNT services will be combined at user level in a sensor fusion approach to obtain the required performance:

- **Mass market** will use low-cost hardware but will demand more and more high-accuracy PNT services (cm-level), especially Galileo High Accuracy free service for intelligent transport systems, fusing GNSS services, augmented by PPP, sensor data and 5G. The use of multi-constellation, dual-frequency will be generalised.
- **Professional** will require multi-constellation, multi-frequency (e.g., triple) high-accuracy services fully integrated into a connected and automated workflow management. AI will be generalised and will revolutionise this market segment.
- **Safety-of-life and liability-critical**, traditionally constrained by regulations and standards, will adopt new technologies at a much slower pace. While important work is on-going to develop standardised multi-constellation, dual-frequency solutions, the real challenges will be to standardise resilient solutions, resistant to RFI. In addition, integrity to high-accuracy services will continue to be pursued for aviation (manned and unmanned) and autonomous vehicles and vessels.
- **Timing** importance will increase exponentially, being time synchronisation and distribution solutions vital for **critical infrastructure**, telecom, energy, finance, or transport sectors. Resilient timing will become a must and multi-frequency, multi-constellation, Timing-RAIM, interference monitoring and alternative-PNT services will be combined to complement GNSS.

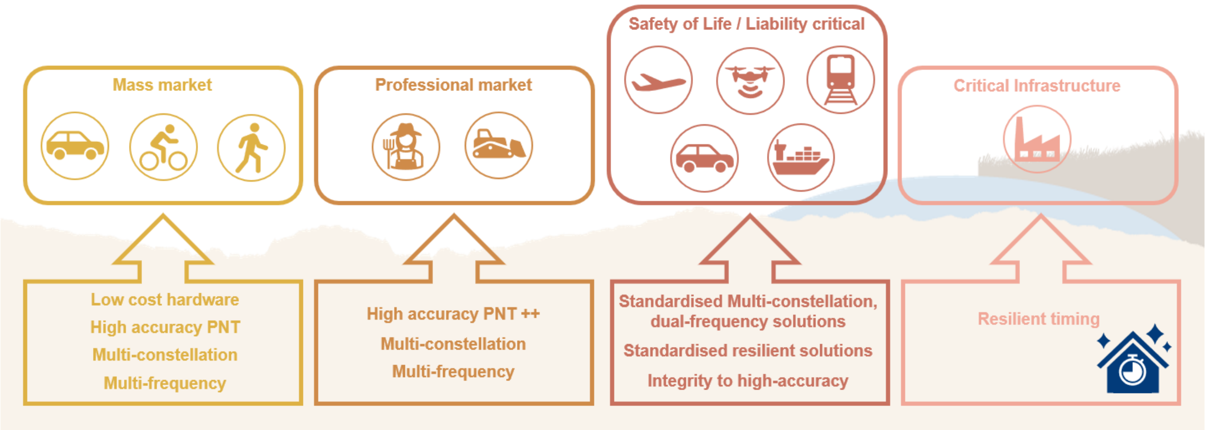


Figure 19 - Market Segments vision for the EU PNT

From the **PNT systems' architecture** point of view, the EU PNT ecosystem will become a System of PNT systems, with a combination of GNSS, conventional and emerging PNT services, all synchronised to UTC(k):

1. The **European GNSS** (Galileo and EGNOS) **together with GPS** will remain the **backbone of the PNT services in the EU**. The European GNSS services will be strengthened and improved with new services (high-accuracy, authentication, etc.), improved infrastructure (Galileo Second Generation, EGNOS Second Generation) and dedicated monitoring capability. The European Commission will continue pursuing the uptake of Galileo and EGNOS services with new Regulations, Standards, and the funding of projects for innovative applications.

   GNSS high-accuracy services such as the Galileo High Accuracy service, RTK or PPP will be **widely adopted** for high-precision applications.

   EGNSS-only solutions may also be required for specific applications and markets.

   Finally, the EU new proposed secure space connectivity IRIS^2 Satellite Constellation could also act as a platform for complementary PNT services, in addition to its primary communication mission.

2. **Emerging PNT** services, which can provide Alternative-PNT services, independent from GNSS, will **continue to develop** and more of them will achieve maturity and become commercially available, addressing the needs of the specific markets (e.g., indoors), or acting as a backup of GNSS services notably for the time provision to critical infrastructures. The EU recommends developing cross-sectorial Alternative-PNT solutions.

   On **timing**, the EU has the mature technology to provide highly accurate timing services independent from GNSS. The network of National Metrology Institutes (NMIs) will play a fundamental role in the time generation, while European companies offer commercial solutions for time distribution. The EU should work to fully develop the timing ecosystem and ensure cost-effective and resilient time provision to relevant users (e.g., critical infrastructures).

   On **position / navigation**, the market offers some commercial solutions independent from GNSS, however there are today no mature solutions from EU companies. The EU will work to support the implementation of the CER and NIS2 Directives (see section 3.4.1) and **improve** the **resilience** of the European economy and society. The EU should also consider the development of EU solutions to cover use cases requiring a strategic autonomy.

3. **Conventional PNT** systems, despite their disadvantages (e.g., cost, old signal, and hardware design) will remain in use for strongly regulated markets such as aviation and maritime and rationalisation plans will only be slowly implemented (also due to long lifetime of the equipment), while for non-regulated markets they are likely to disappear. However, some systems (such as the longwave time and frequency distributions) may maintain their importance as they offer good resilience to RFI although with limited performance (e.g., microsecond accuracy).

As a conclusion, due to the integral role of PNT in the well-functioning of the EU economy and society **RESILIENT PNT is paramount**. Underpinned by GNSS, PNT services need to be diverse and incorporate a holistic mix of technologies, terrestrial and space-based, since no single technology, even GNSS, will deliver sufficient resilience for critical users of PNT information. Resilient PNT will also require an efficient monitoring system, including for GNSS RFI and the necessary coordination procedures between GNSS providers, RFI agencies and governments:

The **EU PNT ecosystem** should become a **System of PNT systems** to achieve resilient PNT.

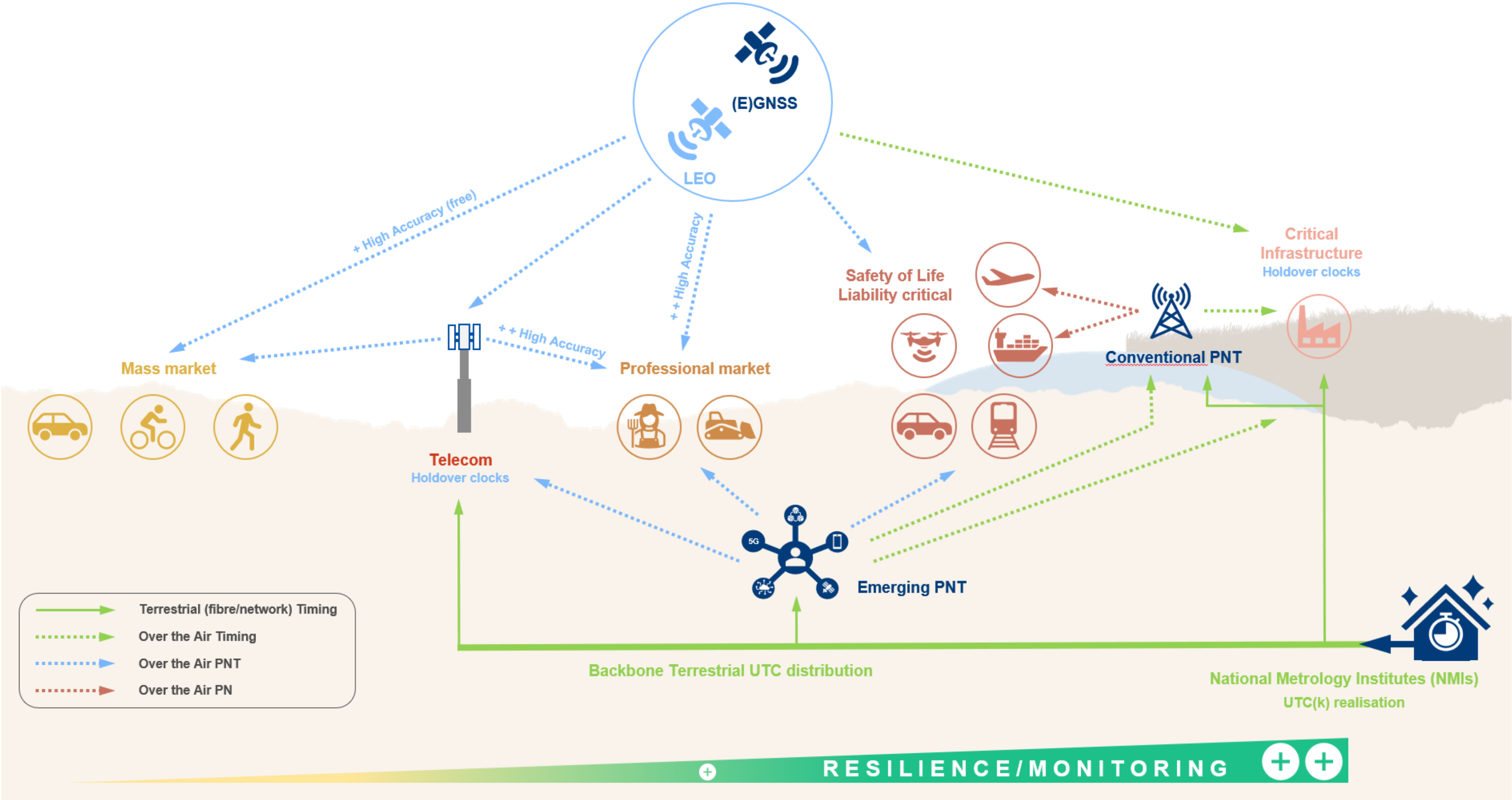


Figure 20 - Vision for the EU PNT

5 APPENDIX A: PNT Systems

5.1 Global Navigation Satellite Systems (GNSS)

Global Navigation Satellite System (GNSS) refers to **constellations of satellites which transmit signals from space and provide positioning and timing services to GNSS receivers**.

GNSS include systems with a global coverage such as Europe's Galileo, the USA's NAVSTAR Global Positioning System (GPS), Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and China's BeiDou Navigation Satellite System **and regional systems** such as the Indian Navigation with Indian Constellation (NavIC), also known as Regional Navigation Satellite System (IRNSS), or the Japanese QZSS which have a coverage in India's region and Asia-Oceania region respectively. The main characteristics of these GNSS systems are shown in *Table 6*.

Table 6 – GNSS constellations (Credit: GNSS User Technology Report)

GNSS constellations				
Parameter	**Galileo**	**GPS**	**BeiDou**	**GLONASS**
Orbital Period (MEO)	14 h 04 min	11 h 58 min	12 h 37 min	11 h 15 min
Orbital Height (MEO)	23 222 km	22 200 km	21 528 km	19 100 km
Inclination (MEO)	56°	55°	55°	64,8°
Number of Orbital Planes (MEO)	3	6	3	3
Reference frame	GTFR	WGS-84	CGCS 2000	PZ-90
Reference time	Galileo System Time (GST)	GPS Time (GPST)	BeiDou Time (BDT)	GLONASS Time (GLONASST)

The systems are designed to be **compatible and interoperable**, using signals which are transmitted on the frequencies bands E5/L5, L2, E6 and E1/L1 as shown in *Figure 21*.

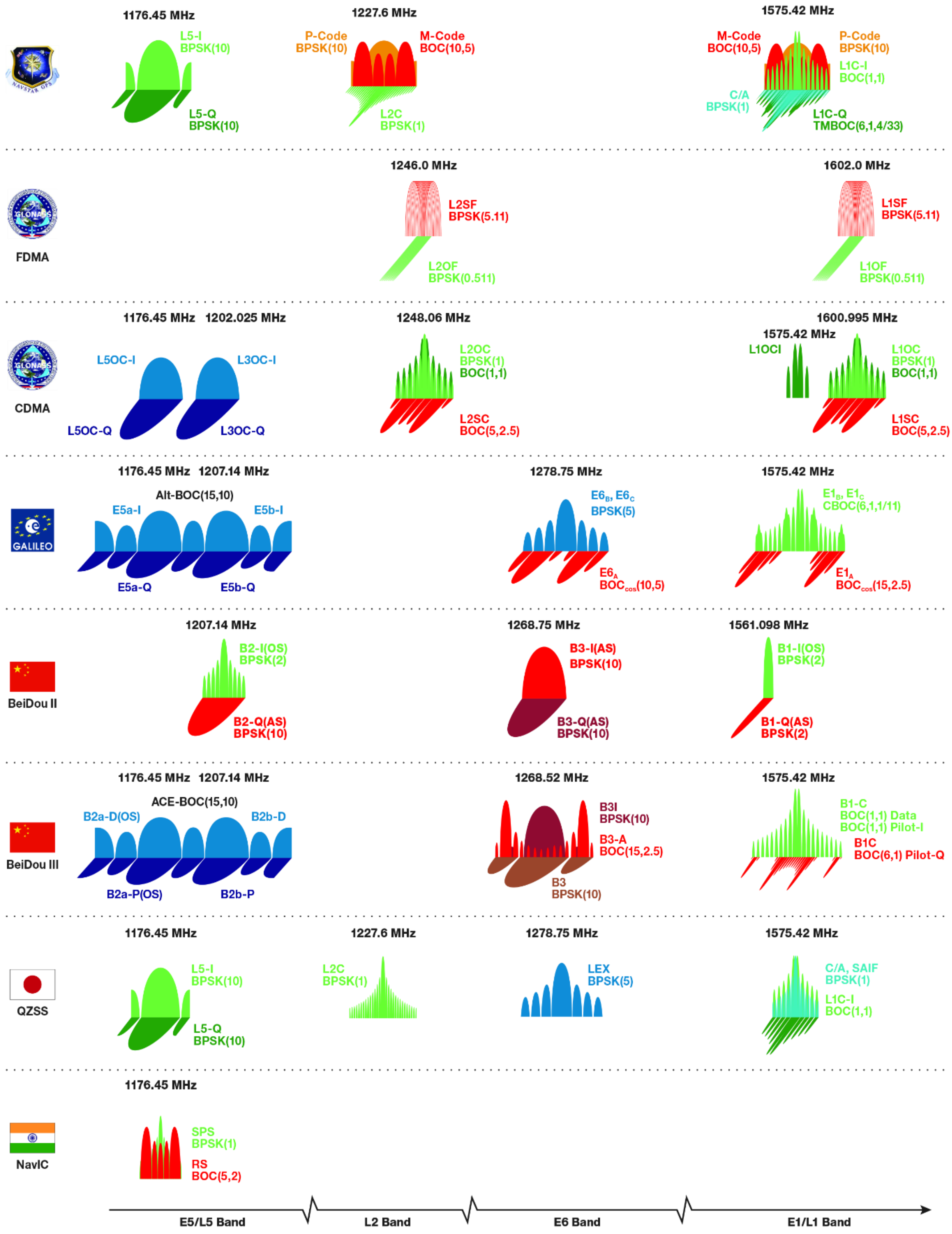


Figure 21 – GNSS frequencies (Credit: Navipedia)

The typical position accuracy of GNSS systems is in the order of metres, with Galileo providing the best performance as can be seen in *Figure 22* for the GNSS with global coverage in Q2 2022 and in Figure 23 for the ranging accuracy in June 2022 (GAL – Galileo, GLO – GLONASS, BDS - BeiDou).

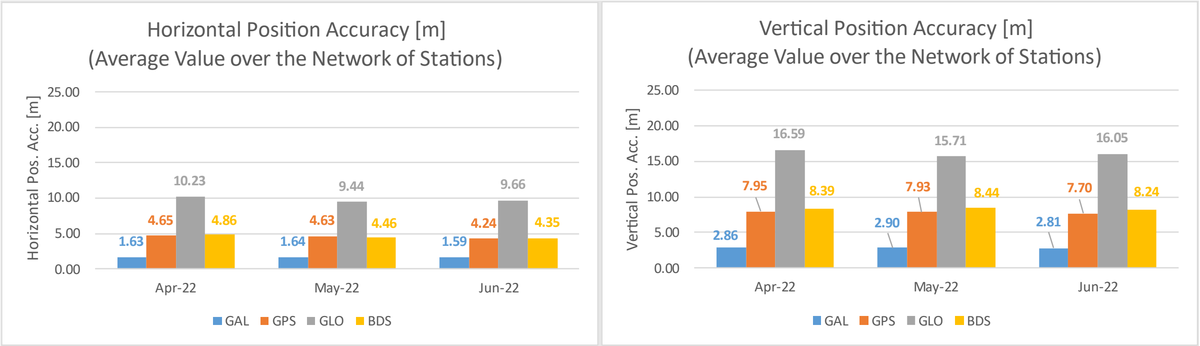


Figure 22 – GNSS horizontal and vertical accuracy performance (Credit: EUSPA)

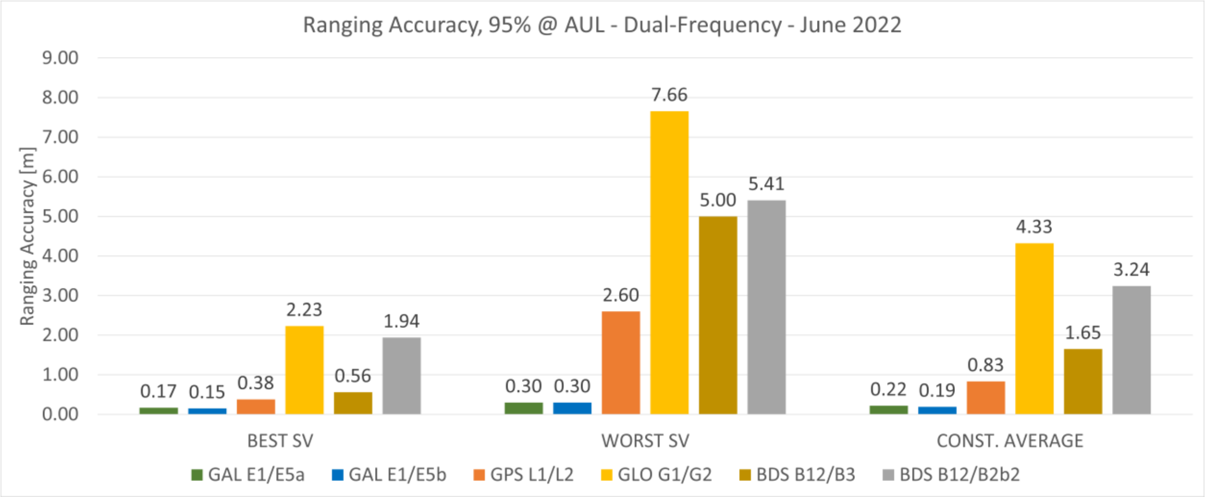


Figure 23 – GNSS ranging accuracy 95% for Galileo, GPS, GLONASS and BeiDou Dual Frequency users

5.1.1 Satellite Navigation Systems – Global coverage

5.1.1.1 Galileo

Galileo is the European global navigation satellite system under **civilian control** providing since **December 2016** a global and highly accurate positioning service and a distress localisation service in the European region for Search and Rescue (SAR) purposes. It is interoperable with the other global satellite navigation systems.

Galileo consists of a Space Segment, a Ground Segment, and a User Segment.

A constellation of satellites in medium Earth orbit forms the **Galileo Space Segment**. The baseline Galileo constellation configuration is defined as a 24/3/1 Walker constellation: 24 nominal Medium Earth Orbit satellites are arranged in 3 orbital planes, with their ascending nodes uniformly distributed at intervals of 120°, inclined at 56° with respect to the Equator. Each orbital plane includes 8 satellites uniformly distributed within the plane, at intervals of 45° of argument of latitude. The angular shift between satellites in two adjacent planes is 15°. The constellation is complemented by spare satellites that can be repositioned to any given nominal slot within each orbit plane depending on maintenance or service evolution needs.

The **Galileo Ground Segment** includes the following infrastructure core infrastructure:

- Two **Galileo Control Centres (GCC)** located in Oberpfaffenhofen (Germany) and Fucino (Italy), with 'control' functions supported by a *Ground Control Segment (GCS)* and 'mission' functions supported by a dedicated *Ground Mission Segment (GMS)* at each site:
    - The Ground Control Segment (GCS) handles spacecraft housekeeping and constellation maintenance by means of the globally distributed network of Telemetry, Tracking & Control (TT&C) stations. This includes control and monitoring of the satellites and payload, planning and automation functions that allow safe and correct operations to take place, and the support of payload related operations.
    - The Ground Mission Segment (GMS) determines the navigation and timing data part of the navigation messages by means of the network of Galileo Sensor Stations (GSS) and the GMS communicates with the Galileo satellites through the network of Galileo Uplink Stations (ULS).
- A worldwide network of **Galileo Sensor Stations (GSS)**, which collects and forwards Galileo SIS measurements and data to the GCCs in real time.
- A worldwide network of **Galileo Uplink Stations (ULS)**, which distributes and uplinks the mission data to the Galileo constellation.
- A worldwide network of **Telemetry, Tracking & Control stations (TT&C stations)**, which collects, and forwards telemetry data generated by the Galileo satellites, and distributes and uplinks the control commands required to maintain the Galileo satellites and constellation in nominal operational conditions.

An overview of the Galileo Ground Segment is provided in the Figure 24 where only the Galileo Ground Segment functionality related to the Open Service (OS) is included.

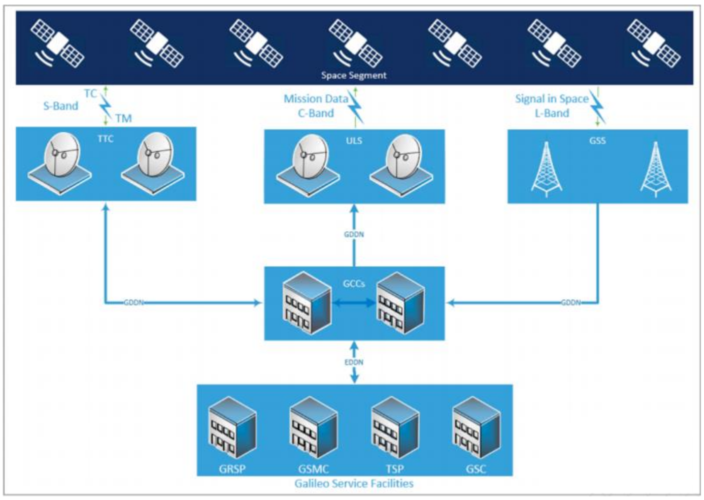


Figure 24 – High level scheme of the Galileo Ground Segment Architecture

The **Galileo Service Facilities** are elements located outside the perimeter of the Galileo core infrastructure that support the provision of Galileo services.

The service facilities contributing to the provision of the Galileo OS are:

- The European GNSS Service Centre (GSC): GSC is the interface between the Galileo OS user community and the Galileo system.
- The Geodetic Reference Service Provider (GRSP): This entity supports the GCC in realising the Galileo Terrestrial Reference Frame (GTRF), consistently with the international Terrestrial Reference Frame (ITRF).
- The Time Service Provider (TSP): This entity supports the GCC in the realisation of the Galileo System Time (GST) and its alignment to the Coordinated Universal Time (UTC).
- The Galileo Security Monitoring Centre (GSMC): This facility is in charge of monitoring the system security.
- The SAR/Galileo Data Service Provider (SGDSP): this entity in charge of the coordination of the operations related to the SAR/Galileo service.
- The Galileo Reference Centre (GRC): this entity is responsible for monitoring and assessment of the performance of the Galileo services, and it is completely independent from the Galileo core infrastructure and its operations.

For the Galileo SAR service, additional infrastructure is required both on board the satellites and on ground:

- The **SAR/Galileo Space Segment** is composed of Galileo satellites with Search and Rescue Repeaters (SARR). The Galileo SAR Repeaters are bent pipe type transparent transponders and comprise the SAR Transponder and SAR receiving and transmitting antennas.
- The **SAR/Galileo Ground Segment** consists of three MEO Local User Terminals (MEOLUT) located in Maspalomas (Spain), Larnaca (Cyprus) and Spitzbergen (Norway), providing beacon identification and location information and five Reference Beacons (REFBE) located in Maspalomas (Spain), Larnaca (Cyprus), Spitsbergen (Norway), Toulouse (France) and Santa Maria (Portugal). A fourth MEOLUT will be deployed in Reunion Island (France) in 2023.

The following figure provides an overview of the location of the various Galileo sites.

Figure 25 – Galileo sites and Ground Stations (Credit: GSC)

The **Galileo user segment** is composed of all the compatible receivers and devices which collect the Galileo signals, determine pseudoranges (and other observables), and solve the navigation equations in order to obtain their coordinates and provide accurate time synchronisation.

5.1.1.1.1 Galileo Services

Galileo services are described in section 3.2.

5.1.1.1.2 Main characteristics

Table 7 and Figure 26 show the principal characteristics of Galileo signals.

Table 7 – Principal characteristics of Galileo signals

E1		
Signal	E1 OS	E1 PRS
Frequency (MHz)	1575.42	1575.42
Access Technique	CDMA	CDMA
Modulation	CBOC (6,1,1/11)	BOC$_{cos}$ (15,2.5)
Minimum received power [dBW]	-157	
E6		
Signal	E6 CS	E6 PRS
Frequency (MHz)	1278.75	1278.75
Access Technique	CDMA	CDMA
Modulation	BPSK (5)	BOC$_{cos}$ (10,5)
Minimum received power [dBW]	-155	
E5		
Signal	E5a	E5b
Frequency (MHz)	1176.45	1207.14
Access Technique	CDMA	CDMA
Modulation	AltBOC (15,10)	AltBOC (15,10)
Minimum received power [dBW]	-155	

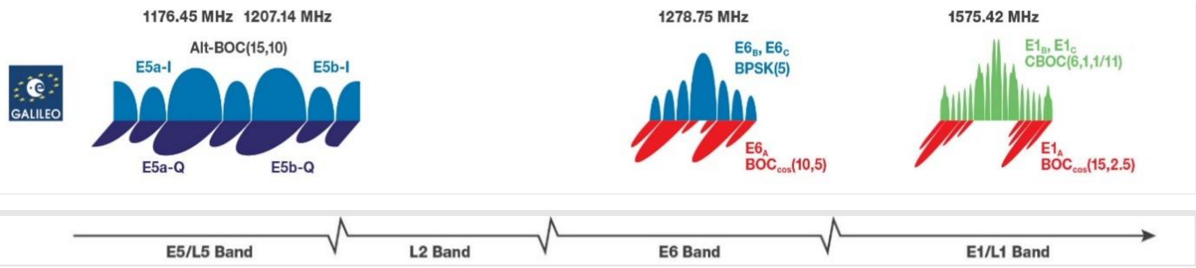


Figure 26 – Galileo signals (Credit: Navipedia)

5.1.1.1.3 Performance

The Galileo OS Service Definition Document defines the Minimum Performance Levels (MPLs) of the Galileo Open Service. Table 8 shows the typical performance for the full deployed Galileo system.

Table 8 – Galileo Service Performance when fully deployed.

	Galileo Open Service (positioning & timing)	
	Single Frequency (SF)	**Dual Frequency (DF)**
Coverage	**Global**	
Accuracy (95%)	Horizontal: 15 m	Horizontal: 4 m
	Vertical: 35 m	Vertical: 8 m
Availability	99.5%	99.5%
Timing Accuracy with regards to UTC/TAI	30 ns	Timing Accuracy with regards to UTC/TAI

Further information on OS service performance or other services such as SAR can be found in OS SDD and SAR SDD.

5.1.1.1.4 Status and modernisation plans

At the end of 2022, the **status of the Galileo Space Segment** is as follows:

- 28 First Generation satellites had been launched with 26 operational satellites for Search and Rescue and 24 operational satellites for Navigation (1 from spare slot).
- 10 First Generation satellites had been produced and are ready for launch:
    - 4 satellites will enable full operational capability by populating all the nominal slots + 1 spare per plane for robustness purposes.
    - 6 additional satellites will allow maintaining the constellation until the arrival of the Second Generation satellites.

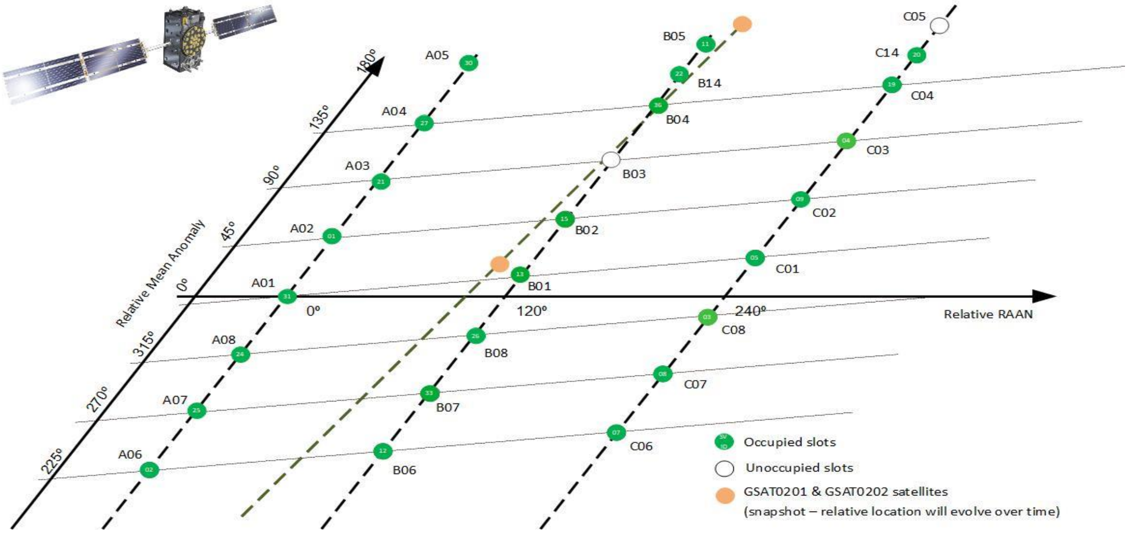


Figure 27 – Galileo Space Segment (status at the end of 2022)

The services provided by the first generation of Galileo will be enhanced by the new generation of Galileo (so-called **Galileo Second Generation - G2G**) together with the provision of new services. These services are explicitly identified in the current EU Space Regulation and have been described in section 3.2. The following figure shows the various service improvements that G2G will bring:

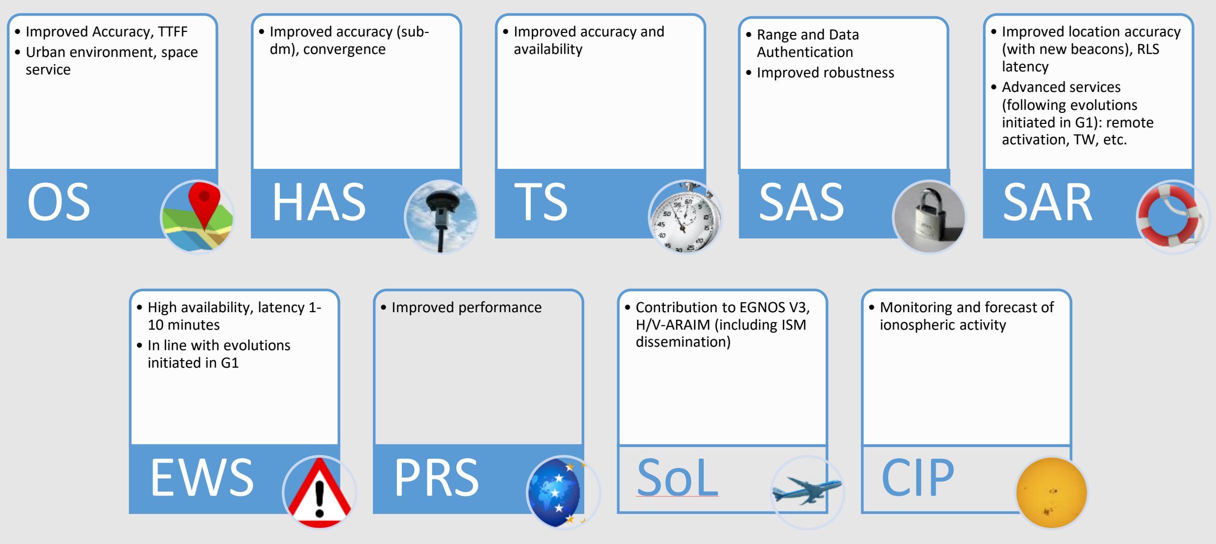


Figure 28 – Galileo Second Generation service improvements

The **Mission** requirements for G2G have been already established and also are formalised through the **Commission Implementing Decision C(2020)8968.**

These new and improved services will be achieved thanks to new generation satellites and ground segment with improved capabilities.

New on-board technologies will include **electric propulsion** to propel the satellites from the orbit in which they will be launched to the final operational orbits, allowing two satellites to be launched at once despite their increased mass. **Inter-satellite links** between the satellites will reduce the dependency on contacts from ground installations. The satellites will also feature **more powerful signals**, a **more flexible payload** including a new navigation antenna, **more precise onboard atomic clocks,** and **extended lifetime**.

The **ground segment will be enhanced** overall, from hardware to software and communication links. Algorithms will be evolved, and additional monitoring will be implemented, leading to improved performance and robustness of the already provided services. Additional functionalities will be added enabling the control of the new capabilities in the satellites as well as the provision of the new services.

Further information on the Galileo Programme can be found in the Galileo Programme Documents.

5.1.1.2 GPS

The Global Positioning System, GPS, is a positioning, navigation and timing system owned by the government of the United States (US) and operated by the US Air Forces. It is a dual use system, which provides service to civil and military users. The GPS consists of a space segment, a control segment, and a user segment. It works transmitting several radiofrequency signals containing precise timing and location information from a constellation of satellites. Combining the information received from at least four satellites, the user gets an estimation of its position and time. **GPS initial operational capability started in 1993**. It provides continuous, global coverage, under all weather conditions.

A constellation of satellites in medium Earth orbit form **GPS Space Segment**. A minimum of 24 satellites are needed to provide global coverage, although the actual number of satellites in orbit tends to be larger than that, increasing the performance of the system. The satellites are in six equally spaced orbital planes, inclined 55°, at an altitude of 20 200 km. With this constellation configuration, every point in the surface of the Earth always sees at least four GPS satellites, which is necessary to get the positioning information.

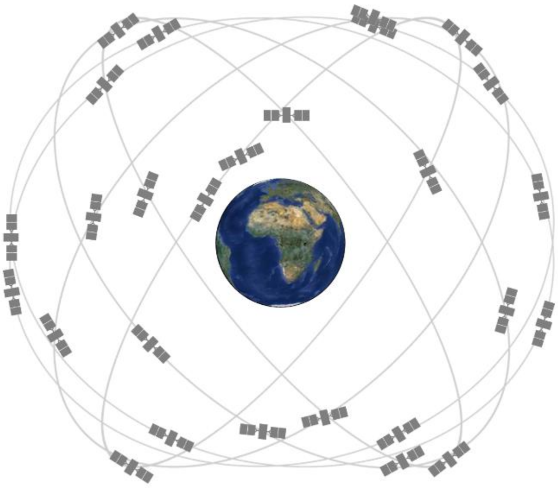
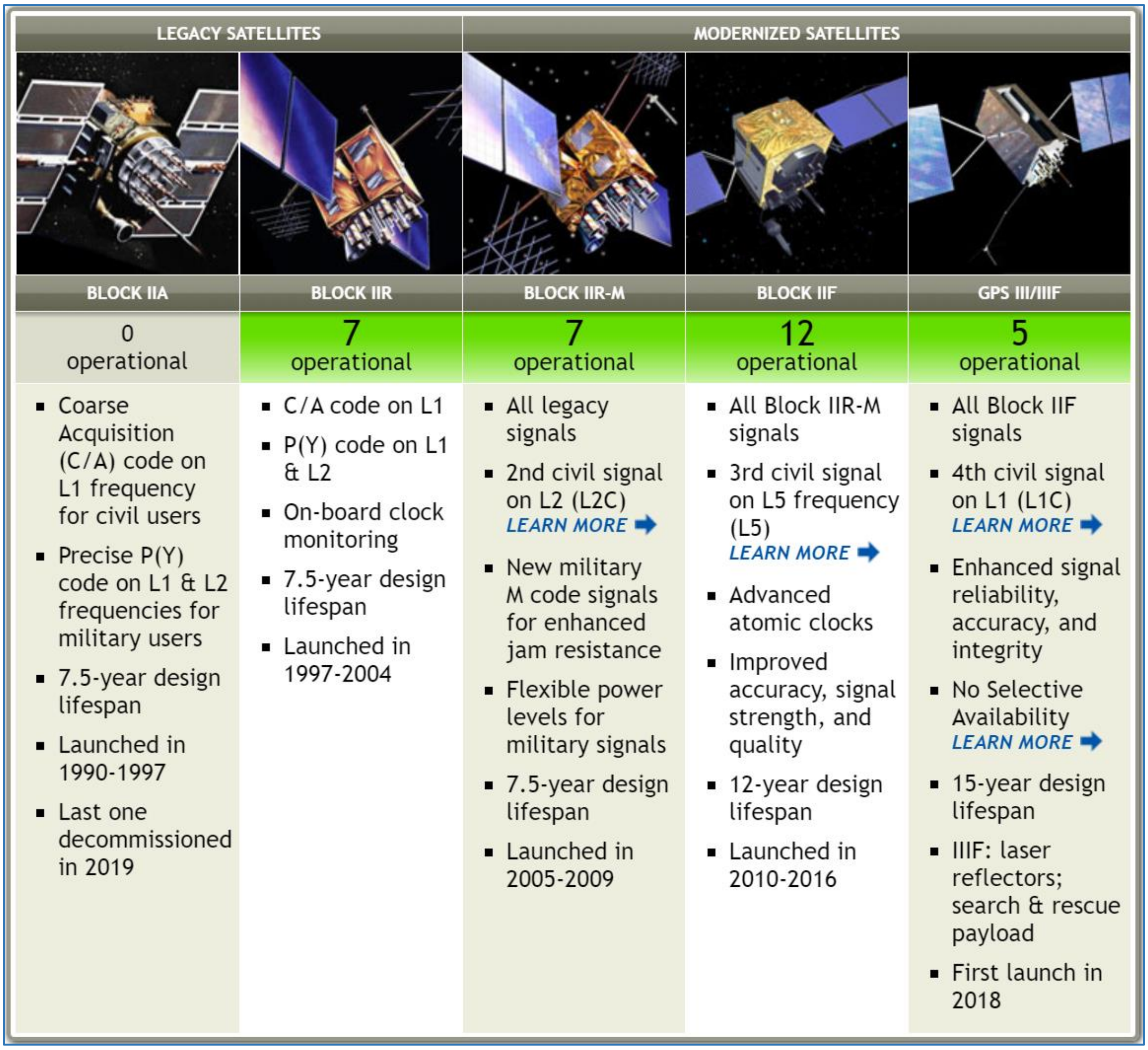


Figure 29 – GPS constellation (Credit: http://www.gps.gov)

Since the first launch in 1978, the US has been continuously improving the characteristics of GPS satellites. Each generation, or block, of satellites transmits more signals, with improved codes, in more frequencies with respect to the previous one. Modernised satellites include also better components and characteristics: improved atomic clocks, increased power, increased expected lifetime, etc. The result is a better performance and accuracy for both the civil and military users. This evolution process will continue in the future.

The GPS constellation is a mix of old and new satellites. The following table summarises the features of the current and future generations of GPS satellites, including Block IIA (2nd generation, 'Advanced'), Block IIR ('Replenishment'), Block IIR-M ('Modernised'), Block IIF ('Follow-on'), GPS III, and GPS IIIF ('Follow-on').



LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	7 operational	7 operational	12 operational	5 operational
▪ Coarse Acquisition (C/A) code on L1 frequency for civil users ▪ Precise P(Y) code on L1 & L2 frequencies for military users ▪ 7.5-year design lifespan ▪ Launched in 1990-1997 ▪ Last one decommissioned in 2019	▪ C/A code on L1 ▪ P(Y) code on L1 & L2 ▪ On-board clock monitoring ▪ 7.5-year design lifespan ▪ Launched in 1997-2004	▪ All legacy signals ▪ 2nd civil signal on L2 (L2C) *LEARN MORE* ➡ ▪ New military M code signals for enhanced jam resistance ▪ Flexible power levels for military signals ▪ 7.5-year design lifespan ▪ Launched in 2005-2009	▪ All Block IIR-M signals ▪ 3rd civil signal on L5 frequency (L5) *LEARN MORE* ➡ ▪ Advanced atomic clocks ▪ Improved accuracy, signal strength, and quality ▪ 12-year design lifespan ▪ Launched in 2010-2016	▪ All Block IIF signals ▪ 4th civil signal on L1 (L1C) *LEARN MORE* ➡ ▪ Enhanced signal reliability, accuracy, and integrity ▪ No Selective Availability *LEARN MORE* ➡ ▪ 15-year design lifespan ▪ IIIF: laser reflectors; search & rescue payload ▪ First launch in 2018

Figure 30 – Evolution of GPS satellites (Credit: http://www.gps.gov)

As of June 26, 2022, there were a total of 31 operational satellites in the GPS constellation, not including the decommissioned, on-orbit spares.

The **Control Segment** consists of a worldwide network of ground facilities that track, control and command GPS satellites. The control segment monitors the health status of the satellites, resolves any possible anomaly, controls the orbits of the satellites, and adjusts them, if necessary, adjusts the on-board clocks, and, in general, performs any task needed to keep the system working properly. It is composed of a Master Control Station (Schriever Air Force Base, Colorado), an alternate Master Control Station (Vanderberg Air Force Base, California), 16 Monitor Stations (worldwide) and 11 command and control antennas. GPS control segment is connected to the Air Force Satellite Control Network to increase tracking and command flexibility and robustness.

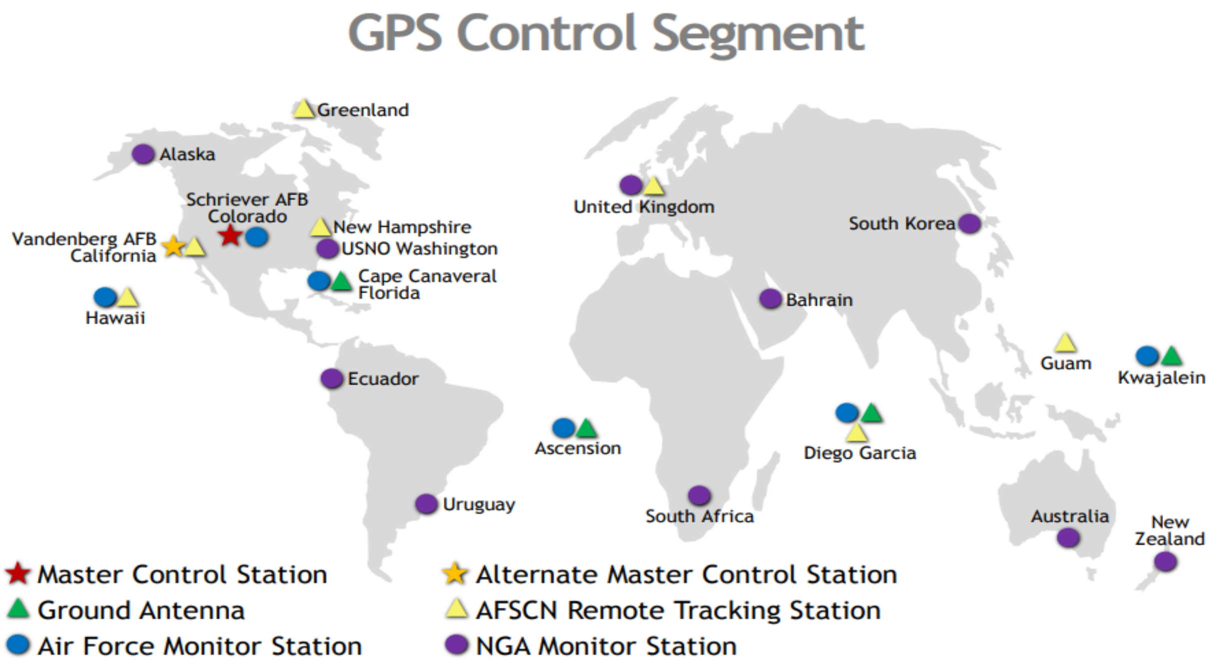


Figure 31 – GPS Control Segment (Credit: http://www.gps.gov)

The **User Segment** consists of the receivers used to receive and decode GPS signals. A receiver gives to the user its three-dimensional location information plus a very precise timing signal.

5.1.1.2.1 GPS Services

There are two types of GPS Positioning Services:

- The **GPS Standard Positioning Service (GPS SPS)** free of direct user fees, for civil, commercial, and scientific use. It is policy of the US to keep the GPS SPS free of fees. To access the GPS SPS service, users only need to have an adequate GPS receiver.
- The **GPS Precision Positioning Service (GPS PPS)** restricted to the US Government, the US armed forces and its selected allies.

5.1.1.2.2 Main characteristics

The terrestrial **service volume** of the GPS constellation comprises from the surface of the Earth up to an altitude of 3 000 km.

Table 9 and Figure 32 show the principal characteristics of **GPS signals**.

Table 9 – Principal characteristics of GPS signals

	L1			
Signal	C/A	L1C	P(Y)	M
Frequency (MHz)	1575.42	1575.42	1575.42	1575.42
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (1)	TMBOC (6,1,1/11)	BPSK (10)	BOCsin (10,5)
Minimum received power [dBW]	-158.5	-157	-161.5	N.A.

L2			
Signal	L2 C	P(Y)	M
Frequency (MHz)	1227.6	1227.6	1227.6
Access Technique	CDMA	CDMA	CDMA
Modulation	BPSK (1)	BPSK (10)	BOCsin (10,5)
Minimum received power [dBW]	-161.5	-160	N.A.
L5			
Signal	L5		
Frequency (MHz)	1176.45		
Access Technique	CDMA		
Modulation	BPSK (10)		
Minimum received power [dBW]	-157.9		

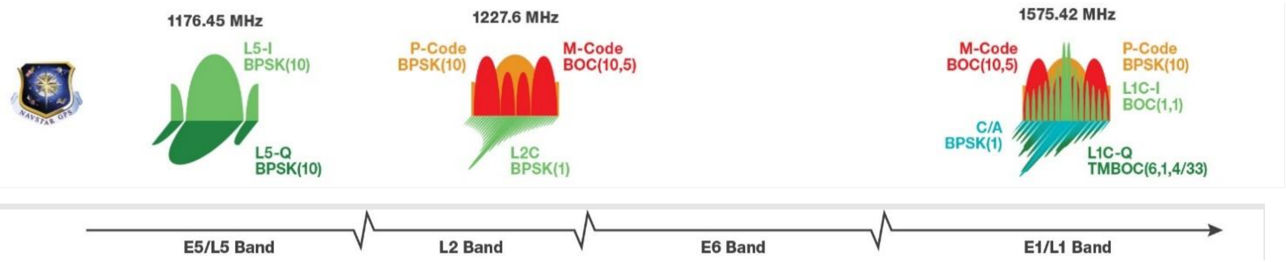


Figure 32 – GPS signals (Credit: Navipedia)

The error in position and time users will experience depends on the characteristics of the signals transmitted by GPS satellites, their propagation, and the performance of the receiver employed. Table 10 shows the **GPS SPS position and time accuracy standards** for representative user conditions.

Table 10 – GPS SPS position and time accuracy standards

Global Average Position Domain Accuracy: **Horizontal error (95%) ≤ 9 m** **Vertical error (95%) ≤ 15 m**	Standard based on a measurement interval of 24 hours averaged over all points in the service volume
Worst Site Position Domain Accuracy: **Horizontal error (95%) ≤ 17 m** **Vertical error (95%) ≤ 37 m**	Standard based on a measurement interval of 24 hours for any point in the service volume.
Time Transfer Domain Accuracy: **Time transfer error (95%) ≤ 40 ns (SIS only)**	Standard based on a measurement interval of 24 hours averaged over all points in the service volume

Table 11 shows **GPS SPS specifications for availability, integrity, and continuity**.

Table 11 – GPS SPS specifications

Availability	99%
Integrity	≥ 1 – $1x10^{-5}$ / h
Continuity	≥ 0.9998 / h

To exploit GPS signals, users just need to have a compatible receiver, meaning that GPS can serve to an unlimited number of users at the same time.

5.1.1.2.3 Performance

The U.S. government is committed to providing GPS to the civilian community at the performance levels specified in the GPS Standard Positioning Service (SPS) Performance Standard (PS).

A 2020 GPS SPS Performance Analysis, commissioned by the Space Force, concludes that, 'All the SPS PS assertions examined in this report were met in 2020.' The assertions evaluated include those of accuracy, integrity, continuity, and availability of the GPS signal-in-space (SIS) along with the assertions on accuracy of positioning and time transfer.

5.1.1.2.4 Status and modernisation plans

The GPS modernisation programme is an ongoing, multibillion dollar effort to upgrade the features and overall performance of the Global Positioning System. The upgraded features include new civilian and military GPS signals.

The **Space Segment** modernisation is shown in Figure 30.

The **Control Segment** modernisation comprises upgrades necessary to command and control the newer GPS satellites and to enhance cybersecurity. The on-going upgrades are:

- OCX: Next Generation Operational Control System.
- Cops: GPS III Contingency Operations.
- MCEU: M-Code Early Use.

A major focus of the GPS modernisation programme is the addition of **new navigation signals** to the satellite constellation. The government is in the process of fielding three new signals designed for civilian use: L2C, L5, and L1C. The legacy civil signal, called L1 C/A or C/A at L1, will continue broadcasting, for a total of four civil GPS signals. Users must upgrade their equipment to benefit from the new signals. The new civil signals are phasing in incrementally as the Air Force launches new GPS satellites to replace older ones. Most of the new signals will be of limited use until they are broadcast from 18 to 24 satellites.

The GPS modernisation programme is adding new civilian signals to the GPS constellation. The new signals use a modernised civil navigation (CNAV) message format that is more flexible than the legacy navigation (LNAV) message on the original civil signal (C/A code). CNAV also offers modern features such as forward error correction. CNAV is fully defined in the Interface Specifications for the GPS L2C, L5, and L1C signals.

5.1.1.3 BeiDou

BeiDou is a global navigation satellite system owned and developed by China’s authorities. It is a dual-use system, which will satisfy the needs of both civil and governmental users, including military.

The **Space Segment** of BeiDou, shown in Figure 33, is designed to be formed by 5 GEO satellites, three inclined geostationary satellites (ISGO) and 27 MEO satellites. The GEO satellites are at 58.75°E, 80.0°E, 110.5°E, 140.0°E and 160.0°E. The IGSO satellites are evenly distributed in an orbit with an altitude of 36 000 km, an inclination of 55° and an intersection point at 118.0°E. The MEO satellites are evenly distributed in circular orbits on three orbital planes, with an altitude of 21 500 km and an inclination of 55°.

The **Ground Segment** of BeiDou consists of a control station, upload stations and a network of monitoring stations. The monitoring stations check the quality of the navigation signals and the status of the satellites and send this information to the control centre. The control centre processes this information, it generates the new navigation message, and the commands needed to keep the satellites working correctly. The upload stations transmit this information to the satellites.

Figure 33 – BeiDou constellation

5.1.1.3.1 BeiDou Services

BeiDou will have two types of services:

- **BeiDou civil service** whose access is free and unlimited, and it is policy of the Chinese authorities to keep it like that. To access BeiDou civil service, users only need to have an adequate BeiDou receiver.
- **BeiDou restricted service** which is limited to Chinese authorities.

5.1.1.3.2 Main characteristics

BeiDou has global coverage over the surface of the Earth, under all weather conditions, providing positioning, navigation, and timing Figure 33 and Figure 34 show the principal characteristics of BeiDou signals.

Table 12 – Principal characteristics of BeiDou signals

B1				
Signal	B1-I(OS)	B1-Q(AS)	B1-C	B1
Frequency (MHz)	1561.098	1561.098	1575.42	1575.42
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (2)	BPSK (2)	MBOC (6,1,1/11)	BOC (14,2)
B3				

Signal	B3-I(AS)	B3-Q(AS)	B3-A(AS)	B3(AS)
Frequency (MHz)	1268.52	1268.52	1268.52	1268.52
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (10)	BPSK (10)	BOC (15,2.5)	BPSK (10)
B2				
Signal	B2-I(OS)	B2-Q(AS)	B2a	B2b
Frequency (MHz)	1207.14	1207.14	1176.46	1207.14
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (2)	BPSK (10)	AltBOC (15,10)	AltBOC (15,10)

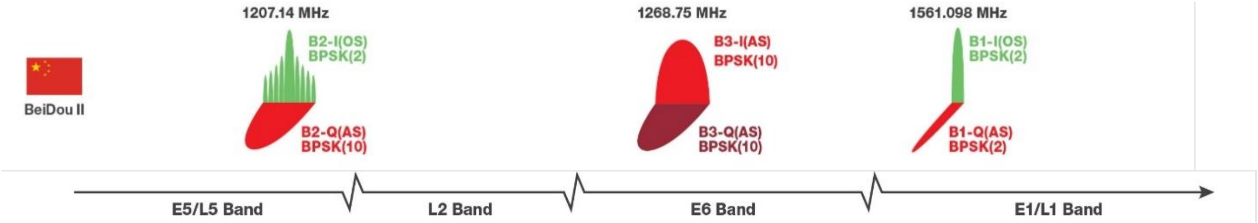


Figure 34 – BeiDou signals (Credit: Navipedia)

5.1.1.3.3 Performance

China Satellite Navigation Office published in 2013 the 'BeiDou Navigation Satellite System Open Service Performance Standard'. Table 13 reproduces the values for position, velocity, and timing accuracy.

Table 13 – BeiDou performance

Horizontal accuracy (95%)	≤ 10 m	Statistical position/velocity/time error for any point in the service volume over any 24-hour interval.
Vertical accuracy (95%)	≤ 10 m	
Velocity accuracy (95%)	≤ 0.2 m/s	
Time accuracy (95%)	≤ 50 ns	
Position availability	≥ 0.95	Any point in the service volume over any 24-hour interval

To exploit BeiDou signals, users need to have a compatible receiver and BeiDou can serve an unlimited number of users at the same time.

5.1.1.3.4 Status and modernisation plans

The full constellation of BeiDou 3 consists of 24 MEO, 3 IGSO and 3 GEO satellites and it was completed in 2020. As of January 2022, 44 satellites of the constellation are operational: 7 in GEO, 10 in 55° in IGSO and 27 in MEO. Furthermore, 5 satellites (2 in MEO, 1 in GEO and 2 in IGSO) are undergoing testing or commissioning.

5.1.1.4 GLONASS

GLONASS is a satellite-based radionavigation system owned and operated by Russia. It is a dual use system, providing service to civil and military users.

GLONASS consists of a space segment, a control segment, and a user segment. A minimum of 24 satellites are needed to provide global coverage. The satellites are located in three orbital planes inclined 63.8° at an altitude of 19 140 km. This configuration guarantees global coverage on the Earth's surface, and it is adapted to the high latitudes of Russia.

GLONASS achieved **Full Operational Capability** (24 functioning satellites) **in 1996** but in 2002 the constellation dropped to as few as seven satellites, with only six available during maintenance operations. A full constellation of 24 satellites was again achieved on 8 Dec 2011 and has been subsequently more or less maintained (see 5.1.1.4.4 for the status of the constellation).

The control segment of GLONASS consists of a network of monitoring stations, uplink and downlink communication antennas, laser tracking stations and a system control centre. The control segment monitors the status and the performance of the satellites, resolves any potential anomaly it might appear (GLONASS system documents).

5.1.1.4.1 GLONASS Services

GLONASS has two types of services:

- **GLONASS civil service** whose access is free and unlimited, and it is policy of Russia to keep it like that. To access GLONASS civil service, users only need to have an adequate GLONASS receiver.
- **GLONASS restricted service** which is limited to Russian government and armed forces.

5.1.1.4.2 Main characteristics

GLONASS has global coverage over the surface of the Earth, under all weather conditions, providing positioning, navigation, and timing. Table 14 and Figure 35 show the principal characteristics of GLONASS signals.

Table 14 – Principal characteristics of GLONASS signals

L1				
Signal	C/A	P	L1 OC	L1 OCM
Frequency (MHz)	1598.0625 to 1605.375	1598.0625 to 1605.375	1600.995	1600.995
Access Technique	FDMA	FDMA	CDMA	CDMA
Modulation	BPSK (0.511)	BPSK (5.11)	BPSK (1)	BOC (5,2.5)
Minimum received power [dBW]	-161	N.A.		
L2				
Signal	C/A	P	L2 OC	L2 OCM
Frequency (MHz)	1242.9375 to 1248.625	1242.9375 to 1248.625	1248.06	1248.06
Access Technique	FDMA	FDMA	CDMA	CDMA
Modulation	BPSK (0.511)	BPSK (5.11)	BPSK (1)	BOC (5,2.5)
Minimum received power [dBW]	-167	N.A.		

L3	
Signal	L3 OC
Frequency (MHz)	1202.025
Access Technique	CDMA
Modulation	QPSK (10)
L5	
Signal	L5 OC
Frequency (MHz)	1176.45
Access Technique	CDMA
Modulation	QPSK (10)

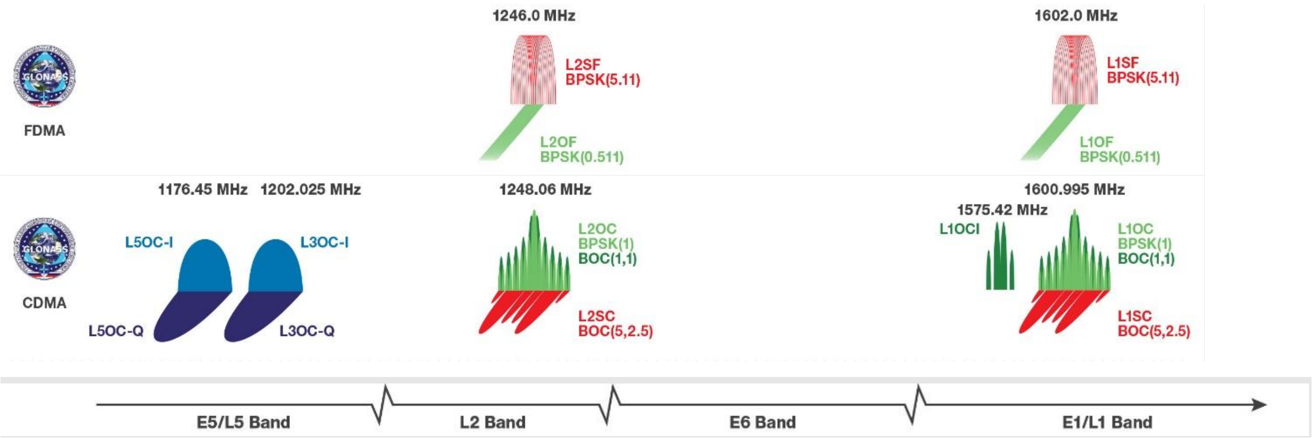


Figure 35 – GLONASS signals (Credit: Navipedia)

5.1.1.4.3 Performance

GLONASS publishes the constellation system and user performance on the GLONASS official website. The Signal-in-Space User Accuracy (SIS UA) and the Signal-in-Space Ranging Error (SISRE) in August 2022 are displayed in Figure 36 and Figure 37.

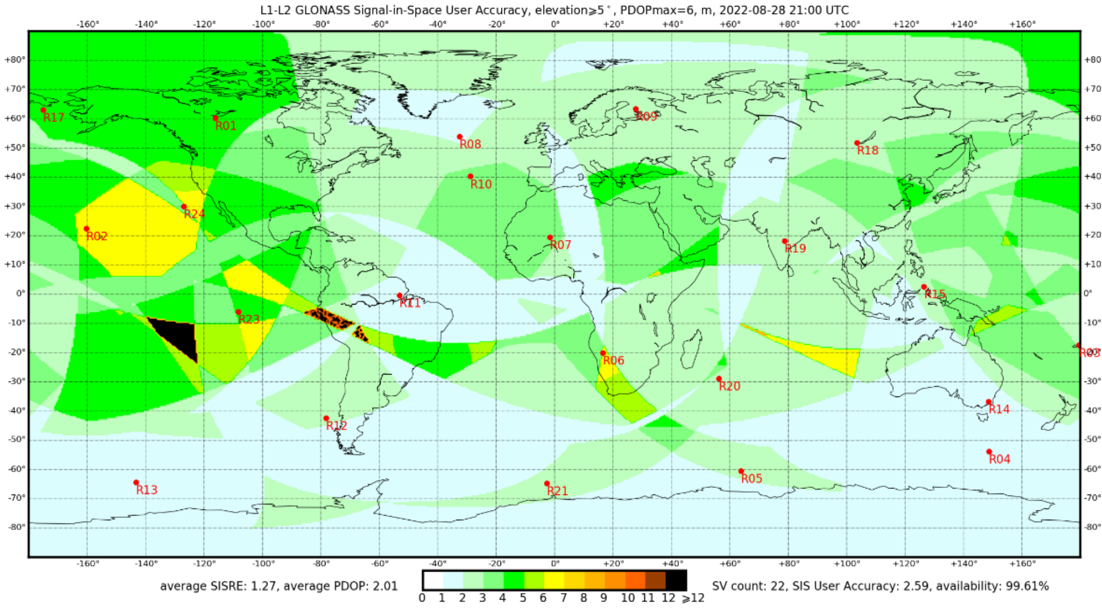


Figure 36 – GLONASS Signal-in-Space User Accuracy (SIS UA) performance

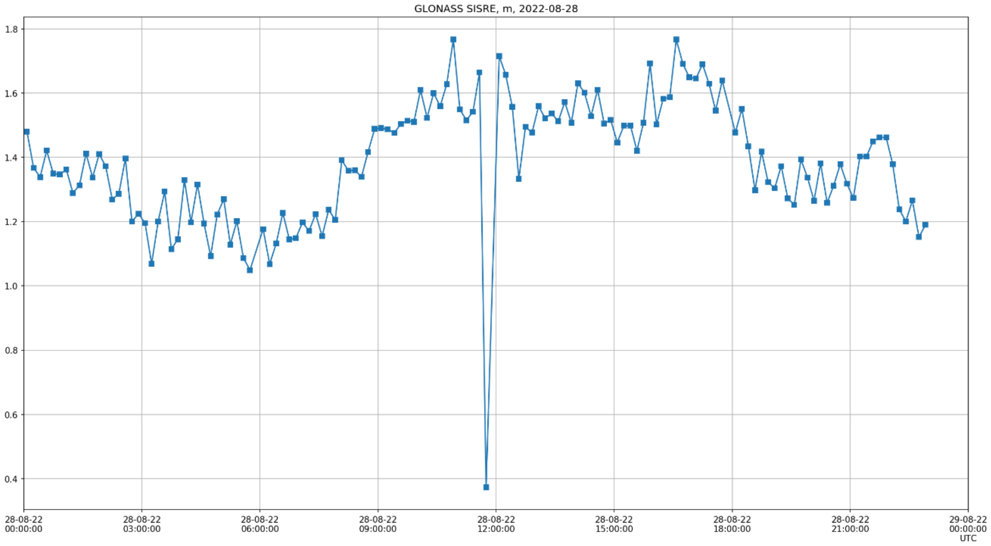


Figure 37 – GLONASS the Signal-in-Space Ranging Error (SISRE) performance

To exploit GLONASS signals, users need to have a compatible receiver and GLONASS can serve an unlimited number of users at the same time.

5.1.1.4.4 Status and modernisation plans

On May 2022, there were 22 operational GLONASS satellites in orbit and 3 in maintenance phase. All satellites belong to the GLONASS-M block, except two that belong to the GLONASS-K block. From 2019, Russia plans to replenish the constellation with the modernised GLONASS-K1 and GLONASS-K2 satellites. L1 and L2 FDMA have reached Full Operational Capability. L3 CDMA is expected to reach FOC in 2022, L2 CDMA in 2025 and L1 CDMA around 2030 (GLONASS official system documents).

More information on the system status and its modernisation is available on the GLONASS website.

5.1.2 Satellite Navigation Systems – Regional coverage

5.1.2.1 QZSS

The Quasi-Zenith Satellite System (QZSS) also known as Michibiki is a regional based satellite augmentation system developed by the **Japan** to enhance the performance of GPS users in the Asia-Oceania regions. The system is composed of four operational satellites and one spare satellite with coverage focused on Japan. The **first four satellites** were available in January 2018 and were **operational in November 2018**.

QZSS uses one geostationary satellite and three satellites in Tundra-type highly inclined, slightly elliptical, geosynchronous orbits. Each orbit is 120° apart from the other two. Because of this inclination, they are not geostationary; they do not remain in the same place in the sky. Instead, their ground traces are asymmetrical patterns (analemmas), designed to ensure that one is always almost directly overhead (elevation 60° or more) over Japan. Further information can be found in QZSS website.

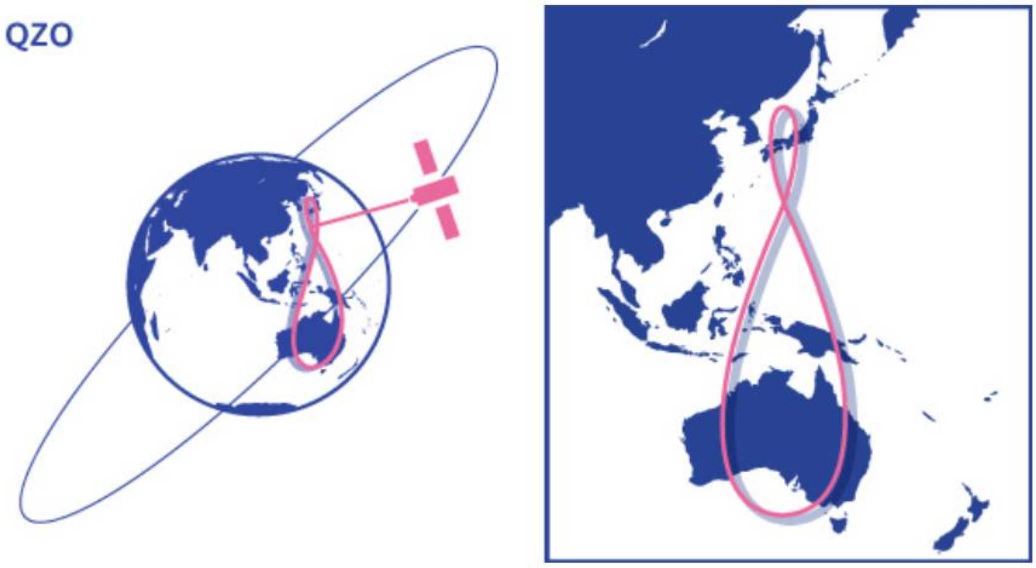


Figure 38 – QZSS constellation (source: QZSS National Space Policy Secretary)

5.1.2.1.1 QZSS Services

The QZSS provides three classes of public service:

- The **PNT service** complements the signals used by the GPS system, providing additional ranging signals. The service broadcasts at bands L1C/A, L1C, L2C, and L5C, the same as GPS.
- The **SLAS (Sub-metre Level Augmentation) service** provides GNSS augmentation for GPS and is interoperable with other GPS-SBAS systems. It transmits on L1 frequency.
- The **CLAS (Centimetre Level Augmentation) service** provides high-precision positioning compatible with the higher-precision E6 service of Galileo. The band is referred to as L6 or LEX, for ‘experimental’.

5.1.2.1.2 Main characteristics

The Quasi-Zenith Satellites transmit **signals compatible with the GPS** L1C/A signal, as well as the modernised GPS L1C, L2C signal and L5 **signals**. Compared to standalone GPS, the combined system GPS plus QZSS delivers improved positioning performance via ranging correction data provided through performance enhancement L1-SAIF and LEX signals. It also improves reliability by means of failure monitoring and system health data notifications.

Table 15 and *Figure 39* show the principal characteristics of QZSS signals.

Table 15 – Principal characteristics of QZSS signals

L1			
Signal	L1 C/A	L1 C/B	L1C
Frequency (MHz)	1575.42	1575.42	1575.42
Access Technique	CDMA	CDMA	CDMA
Modulation	BPSK (1)	BOC	BOC/TBOC
Minimum received power [dBW]	-158.5	-158.5	L1CD: -163.0 dBW L1CP: -158.25 dBW
L2			
Signal	L2 C		
Frequency (MHz)	1227.6		
Access Technique	CDMA		
Modulation	BPSK		
Minimum received power [dBW]	-160.0 (Block I) -157.0 (Block II)		
L5			
Signal	L5		
Frequency (MHz)	1176.45		
Access Technique	CDMA		
Modulation	QPSK		
Minimum received power [dBW]	-157.9 (Block I) -157.0 (Block II)		
L6			
Signal	L6		
Frequency (MHz)	1278.75		
Access Technique	CDMA		
Modulation	BPSK		
Minimum received power [dBW]	-155.7 (Block I) -156.8 (Block II)		

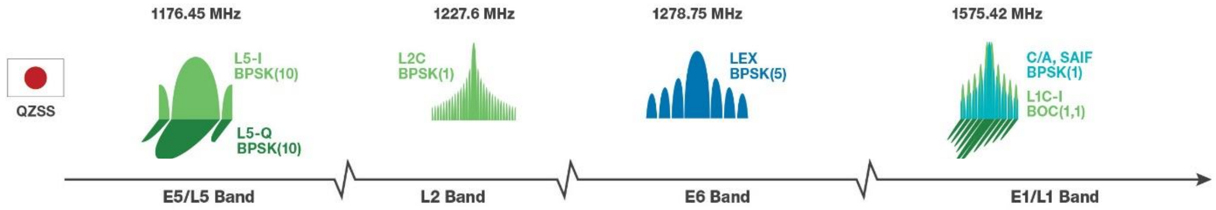


Figure 39 – QZSS signals (Credit: Navipedia)

To exploit QZSS signals, users just need to have a compatible receiver and QZSS can serve an unlimited number of users at the same time.

5.1.2.1.3 *Performance*

The performance of QZSS is described on technical reports available on the Governmental Cabinet Office of Japan. SIS Accuracy of QZSS satellites over 2021 is displayed in Figure 40.

Satellite	NAV Message	SIS Accuracy (95%) [m]					
		April	May	June	July	August	September
SVN001 (PRN193)	LNAV	0.53	0.55	0.76	0.81	0.57	2.75
	CNAV	0.52	0.55	0.72	0.78	0.57	2.73
SVN002 (PRN194)	LNAV	0.88	1.08	1.06	0.71	0.60	0.47
	CNAV	0.88	1.12	1.08	0.71	0.59	0.48
SVN003 (PRN199)	LNAV	0.74	0.81	0.63	0.71	0.64	0.63
	CNAV	0.75	0.76	0.62	0.65	0.66	0.63
SVN004 (PRN195)	LNAV	0.93	0.83	0.88	0.99	0.88	0.92
	CNAV	0.93	0.81	0.89	0.98	0.89	0.95

Figure 40 – QZSS performance

5.1.2.1.4 *Status and modernisation plans*

After the successful launch of QZS-1R satellite in October 2021, QZSS initiated the replacement of the satellite of the constellation. QZSS began service in November 2018 with four satellites. Three additional satellites will be on Inclined Geosynchronous Orbit, Geostationary orbit at 90.5 East Longitude, and Quasi Geostationary Orbit on 175 West Longitude. In addition, 2 geostationary satellites and 1 quasi-geostationary satellite will complete the new constellation. The Japan Aerospace Exploration Agency (JAXA) plans to start a **seven satellites constellation service by 2023** and PPP, authentication services by 2024.

Further information can be also found in Navipedia.

5.1.2.2 IRNSS (NavIC)

The Indian Regional Navigation Satellite System (IRNSS), with an operational name of NavIC (acronym for Navigation with Indian Constellation) is an autonomous **regional** satellite navigation system that provides accurate real-time positioning and timing services. It covers **India** and a region extending 1 500 km (930 mi) around it, with plans for further extension. An extended service area lies between the primary service area and a rectangle area enclosed by the 30th parallel south to the 50th parallel north and the 30th meridian east to the 130th meridian east, 1 500 – 6 000 km beyond borders.

The constellation consists of 8 satellites (7 operational). Three of the eight satellites are located in GEO at longitudes 32.5° E, 83° E, and 131.5° E, approximately 36 000 km above Earth's surface. The remaining five satellites are in IGSO. Two of them cross the equator at 55° E and two at 111.75° E.

5.1.2.2.1 IRNSS Services

NavIC will provide two levels of service:

- The **Standard Positioning Service (SPS)** which will be open for civilian use
- The **Restricted Service (RS)** encrypted for authorised users (including the military).

5.1.2.2.2 Main characteristics

Both NavIC services will be carried on L5 (1176.45 MHz) and S band (2492.028 MHz).[54] The Standard Positioning Service signal will be modulated by a 1 MHz BPSK signal while the Restricted Service will use BOC (5,2). The navigation signals themselves would be transmitted in the S-band frequency (2 – 4 GHz) and broadcast through a phased array antenna to maintain required coverage and signal strength.

Table 16 – Principal characteristics of IRNSS signals

L5		
Signal	L5 SPS	L5 RS
Frequency (MHz)	1176.45	1176.45
Access Technique	CDMA	CDMA
Modulation	BPSK (1)	BOC (5,2)
Minimum received power [dBW]	-159.0	-159.0

Figure 41 – IRNSS signals (Credit: Navipedia)

To exploit IRNSS signals, users just need to have a compatible receiver and IRNSS can serve an unlimited number of users at the same time.

5.1.2.2.3 Performance

Performance of IRNSS is described on technical reports available on the IRNSS Programme website. The User Ranging Accuracy of QZSS satellites over 2021 is displayed in Figure 42.

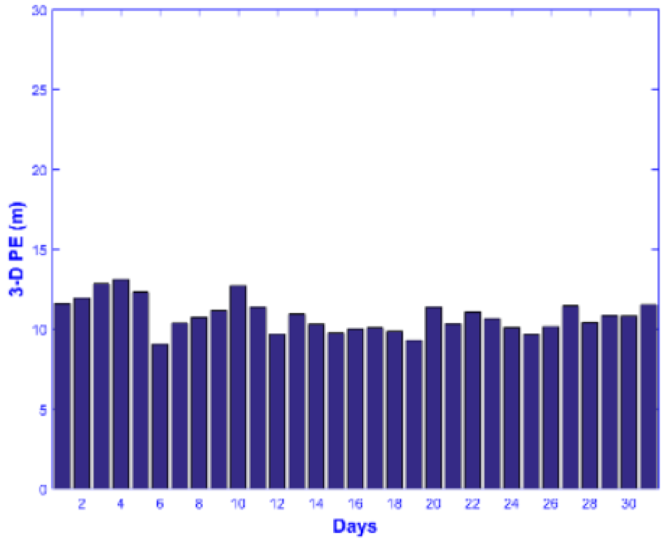


Figure 42 – IRNSS URA in December 2021 (Source: IRNSS Official report Q4 2021)

5.1.2.2.4 Status and modernisation plans

India's Department of Space in their 12th Five Year Plan (FYP) (2012–17) planned the **increase of the number of satellites** in the constellation from 7 to 11 to extend coverage. These additional four satellites will be launched in geosynchronous orbit of 42° inclination.

The Indian Space Research Organisation (ISRO) will be launching five next generation satellite featuring new payloads and extended lifespan of 12 years. The new satellites will feature the L5 and S band and introduces a **new interoperable civil signal in the L1 band** in the navigation payload and will use **Indian Rubidium Atomic Frequency Standard**.

Study and analysis for Global Indian Navigation System (GINS) was initiated as part of the technology and policy initiatives in 2012. The system is supposed to have a constellation of 24 satellites, positioned 24 000 km above Earth. As of 2013, the statutory filing for frequency spectrum of GINS satellite orbits in international space, has been completed. ISRO and Department of Space (DoS) are working on expanding the coverage of NavIC from regional to global that will be independent of other such system currently operational namely GPS, GLONASS, BeiDou and Galileo while remain interoperable and free for global public use.

5.1.2.3 Korean Positioning System (KPS)

The Korean Positioning System (KPS) is the planned South Korea's satellite constellation which Korea intends to build by 2035, providing independent positioning and navigation signals over an area spanning a 1 000-kilometre radius from the country's capital, Seoul. The KPS is expected to be a seven-satellite constellation, with three satellites into geosynchronous orbit and four into inclined geosynchronous orbit above the Korean Peninsula. KPS is planned to improve the accuracy of GPS, from 10 metres to less than one metre.

The first satellite will be launched in 2027, with a trial service scheduled for 2034 and a full-fledged one the following year.

5.1.3 Augmentation Systems

5.1.3.1 Space Based

Space-based GNSS augmentation systems are those where the GNSS corrections are transmitted to users through satellites, and hence provide *wide-area* augmentation information (i.e., on a continental scale).

There are two types of such GNSS augmentation systems, Satellite Based Augmentation Systems (SBAS) and Precise Point Positioning (PPP).

5.1.3.1.1 Satellite-Based Augmentation Systems (SBAS)

SBAS systems provide **augmentation services** to improve the accuracy and provide integrity to the GNSS signals. SBAS systems can also broadcast GNSS ranging signals from their Space Segment. The **accuracy** is enhanced through the transmission of wide-area corrections to the GNSS range errors while the **integrity** is ensured by quickly detecting satellite signal and ionosphere errors and sending alerts to users.

SBAS systems consist of a **Space Segment** (geostationary satellites), **Ground Segment** (reference stations, master stations and uplink stations), a **User Segment** (user receivers processing the SBAS signals) and a **Support Segment** (to support the provision of the SBAS services).

The SBAS reference stations are mainly geographically distributed throughout the SBAS service area and receive GNSS signals which they forward to the SBAS master stations. Since the locations of the reference stations are accurately known, the master stations can accurately calculate wide-area corrections. Those corrections are sent to dedicated stations for uplink to the SBAS satellites which broadcast them to GNSS receivers throughout the SBAS coverage area.

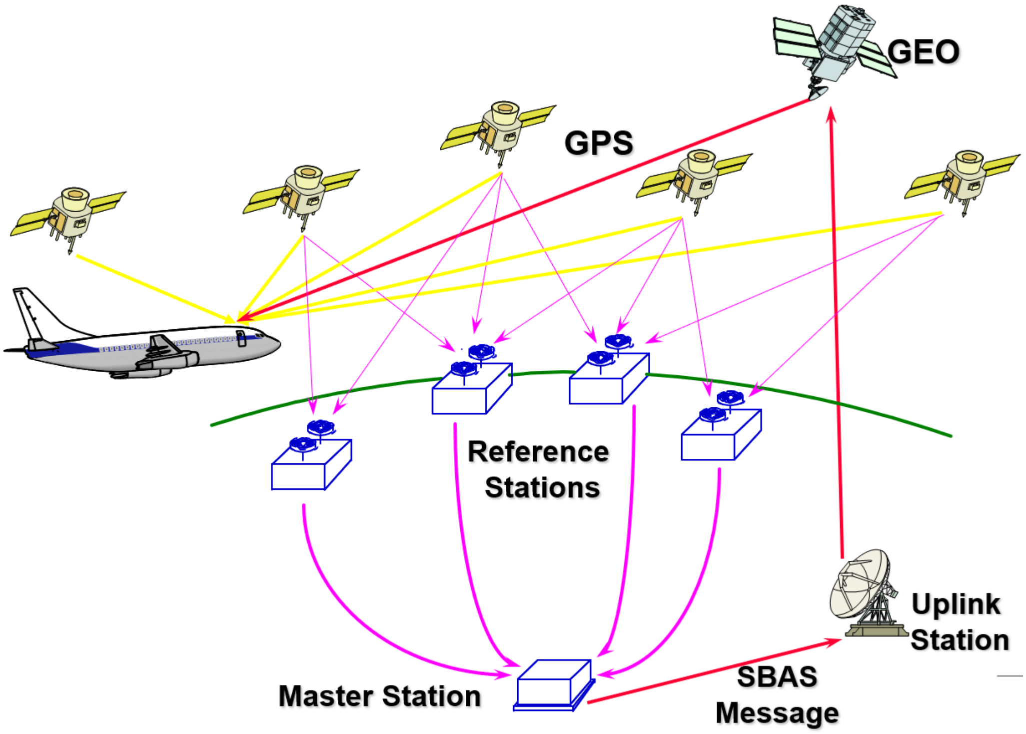


Figure 43 – SBAS Architecture (Source: ICAO)

SBAS services are used for **safety-of-life applications** like aviation. In **Navigation**, SBAS enables LPV approaches (i.e., precision approaches which provide lateral and vertical guidance similarly to ILS approaches but with no on-site ground infrastructure). In **Surveillance**, SBAS enables improved aircraft position allowing to reduce the separation between aircraft and other improved airport operations. Further details on SBAS benefits for aviation can be found in section 3.4.3.

There are several SBAS systems (see Figure 44 for an overview):

- the **European Geostationary Navigation Overlay Service (EGNOS)** is the European augmentation system that improves the accuracy of positions derived from GPS (and Galileo in the future) signals and warns users about the reliability of the signals. EGNOS transmits differential correction data for public use and is certified for safety-of-life applications (operational services since 2011).
- the US Federal Aviation Administration (FAA) has developed the **Wide Area Augmentation System (WAAS)** which provides GPS corrections and is certified for civil aviation industry since 2003.
- The **MTSAT Satellite Augmentation System (MSAS)** is an SBAS that provides augmentation services to Japan since 2007.
- The **GPS Aided Geo Augmented Navigation or GPS and Geo Augmented Navigation system (GAGAN)** is an SBAS that supports flight navigation over Indian airspace since 2013.
- Since October 2014, the Korea Aerospace Research Institute (KARI) is the leading research organisation developing and building the Korea's own Satellite Based Augmentation System (SBAS), known as **Korea Augmentation Satellite System (KASS)** in compliance with ICAO Annex 10. It is expected to provide APV-1 safety-of-life service in 2024.
- The **ASECNA-SBAS (ANGA – Augmented NaviGation for Africa)** is the SBAS for Africa and Indian Ocean Development initiative. ANGA aims to provide SBAS services for NPA, APV-1 and CAT I operations in 2025. Full DFMC services are expected beyond 2028/2030 for CAT I Autoland operations and potentially further ones.
- The **Southern Positioning Augmentation System (SouthPAN)** is the Australia and New Zealand's operational SBAS with plans to reach full operational capability in 2025.
- Republic of China is developing an SBAS system, called **BeiDou Satellite-Based Augmentation system (BDSBAS)** to provide SBAS services in China and surrounding regions. BDSBAS is expected to provide services in 2025 and is integrated in the BeiDou system by using BDS-3 type satellites to broadcast SBAS L1/L5 signal, augmenting BeiDou and GPS.
- Russia is developing **System for Differential Corrections and Monitoring (SDCM)** to provide Russia with accuracy improvements and integrity monitoring for both the GLONASS and GPS navigation systems. SDCM will also provide Precise Point Positioning (PPP) services for L1/L3 GLONASS signals.

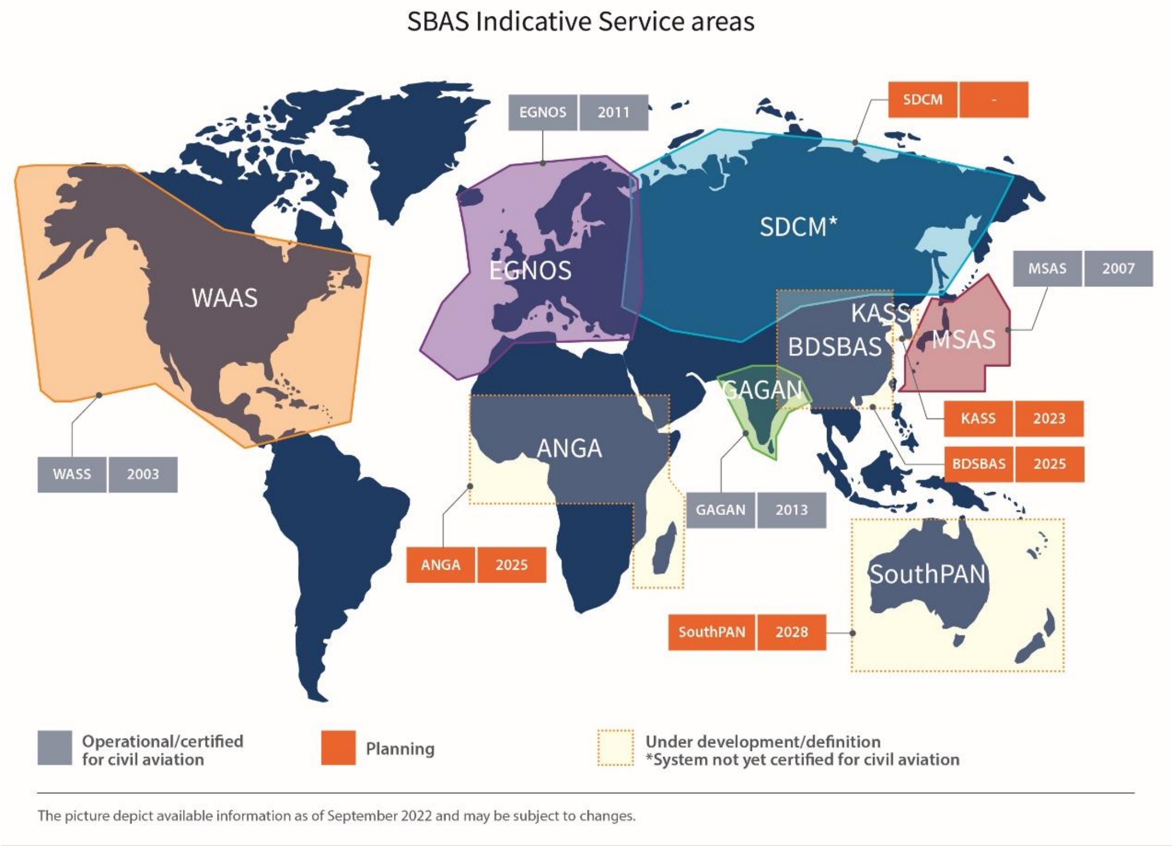


Figure 44 – SBAS systems and indicative service areas (Credit: EUSPA)

5.1.3.1.2 Precise Point Positioning (PPP)

Precise Point Positioning PPP delivers centimetre level accuracy using satellite orbits and clocks corrections distributed through satellites or internet. As very accurate error model is used, this solution requires convergence period to first filter code and carrier observations and then estimate satellite clock error, Zenith Tropospheric path Delay (ZTD) and the float phase ambiguities for all satellites. The accuracy and the convergence time depend on the environmental conditions, the quality of the corrections and EKF (Extended Kalman Filter) algorithm implementation. Less precise code only position is also possible.

There are **several commercial providers of PPP services**, including, Hexagon Veripos, TerraStar, Trimble OmniSTAR, Fugro Seastar, u-blox PointPerfect, Swift Navigation Skylark and Deer StarFire. These providers estimate the satellite position and clock errors and biases through a network of ground stations collecting observations on different signals and constellations. The service provides corrections of the estimated error components and transmit them to the users through satellites or ground channel (e.g., internet). Galileo also provides a PPP real-time service free of charge with a global coverage through, the **Galileo High Accuracy Service** (section 3.2.2).

Traditional PPP high precision positioning presents some limitations related to the convergence time. In fact, it can take several minutes for the receiver to deliver a position with cm position accuracy. It is a valuable solution widely adopted in static applications such as surveying. The potentially harsh environment conditions for dynamic applications (e.g., drones, micro-mobility, precision agriculture, autonomous cars, maritime automatic operations) challenge the performance both in terms of accuracy and convergence time. In these cases, techniques which integrate local sensors and digital maps are needed to overcome the limitations generated by local errors and to provide cm-level position.

5.1.3.2 Terrestrial

5.1.3.2.1 Ground Based Augmentation System (GBAS)

A Ground-Based Augmentation System (GBAS) is a civil-aviation safety-critical system that supports **local augmentation at airport level** of the GNSS constellation signals. The GBAS is intended primarily to support precision approach operations.

The full system consists of a GBAS Ground Subsystem and the GBAS Aircraft (onboard) Subsystem. One GBAS Ground Subsystem can support an unlimited number of aircraft units within its GBAS coverage volume, providing the aircraft with approach path data and, for each satellite in view, **differential corrections**, and **integrity** information. These corrections enable the aircraft to determine its position relative to the approach path more accurately, enabling more demanding operations and guiding the aircraft safely to the runway.

The GBAS ground infrastructure includes two or more GNSS reference receivers at the GBAS-equipped airport which collect pseudoranges from the GNSS satellites in view and computes and broadcasts differential corrections and integrity-related information for those satellites based on its own surveyed position. These differential corrections are transmitted from the ground system via a Very High Frequency (VHF) Data Broadcast (VDB) to the GBAS enabled receiver onboard the aircraft. The broadcast information includes pseudorange corrections, integrity parameters and various locally relevant data such as Final Approach Segment (FAS) data.

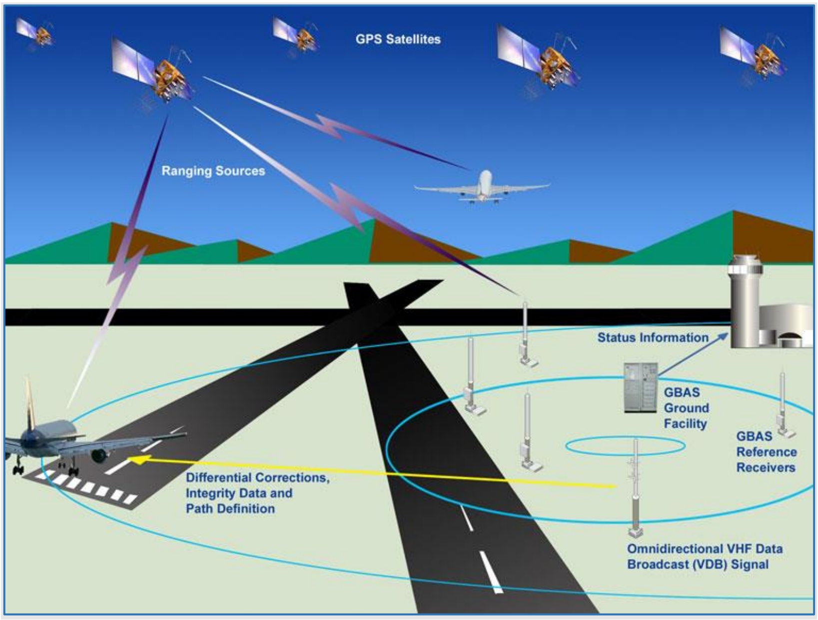


Figure 45 – GBAS Architecture (Credit: FAA)

GBAS provides its service for those equipped aircraft to a local area of approximately 30 km around the airport. The aircraft uses the differential corrections to compute an improved position (with integrity) which the aircraft uses to precisely navigate and transition from the en-route airspace into and throughout the terminal area airspace.

While the main goal of GBAS is to provide integrity assurance, it also increases the accuracy with position errors below 1 m. A GBAS system is usually designed to fulfil CAT I Precision Approach, and very recently CAT II operations have been also enabled (GBAS CAT II operations in Frankfurt).

More information on the GBAS architecture and performances can be found at the Navipedia GBAS.

5.1.3.2.2 Differential GNSS & Real Time Kinematics & Precise Point Positioning

Differential GNSS (DGNSS) is a type of augmentation system based on the use of a network of ground-based reference stations which **broadcast differential information** to the user, also named rover, to improve the accuracy of his position.

The DGNSS is often used to refer specifically to systems that re-broadcast the corrections from ground-based short-range transmitters. For instance, the United States Coast Guard and Canadian Coast Guard run one such system in the US and Canada on the longwave radio frequencies between 285 kHz and 325 kHz. These frequencies are commonly used for marine radio and are broadcast near major waterways and harbours. Australia runs two DGPS systems: one is mainly for marine navigation, run by Australian Maritime Safety Authority, broadcasting its signal on the longwave band; the other is used for land surveys and land navigation, with corrections on the Commercial FM radio band.

Other DGNSS techniques used by high-precision navigation/surveying applications, based on the use of carrier phase measurements, are Real Time Kinematics and Wide Area RTK.

Real Time Kinematics (RTK) is a differential GNSS technique which provides high positioning performance in the vicinity of a base station. A RTK base station covers a service area spreading to maximum 50 kilometres, and a real time communication channel is needed connecting base and rover. RTK achieves performances in the range of a few centimetres.

Wide Area RTK (WARTK) technique, also known as Network RTK, allows the extension of local services based on the real-time carrier phase ambiguity resolution to wide-area scale (i.e., greater than 100 km), for both dual-frequency and 3-frequency users. Using dual-frequency or triple-frequency pseudorange and carrier phase observations together with the received correction data, the user receiver can perform absolute cm-level accurate positioning. The technique is based on an optimal combination of accurate ionospheric and geodetic models in a permanent reference stations network.

In recent years, these established approaches to determining GNSS corrections and delivering them have been combined with PPP into **PPP-RTK** GNSS corrections services (sometimes also referred to as state space representation (SSR) correction services) that deliver the best of both worlds: combining quick initialisation and accuracy close to that of RTK with the ability to operate for short period without corrections, due to PPP algorithms. Like PPP-based solutions, they rely on a model of GNSS errors with broad geographical validity and broadcast the different GNSS error components (or states) using one-way communication. The GNSS receivers then compute the GNSS corrections for their specific location.

It is increasing the number of real time PPP services which are disseminated with a ground channel through internet, therefore also PPP service can be classified as a new category of terrestrial service.

5.1.3.3 Receiver Based

Receivers in safety critical applications use **Receiver Autonomous Integrity Monitoring (RAIM)** techniques to ensure the safety level of the position solution. RAIM is based on consistency check among the measurements from different satellites and warns the user in case an inconsistency is detected. In this case, the satellite can be excluded, or the position service interrupted.

Recent development for Aircraft Based Augmentation System (ABAS) in the aviation sector are focusing on Advanced RAIM (A-RAIM) for dual frequency and multi-constellation users. More details are provided in section 3.2.8.

5.2 Conventional PNT Systems

5.2.1 NDB

A **Non-Directional Beacon (NDB)** is a radio navigation aid that **allows the associated equipment on the aircraft to determine the relative bearing with respect to it**. NDBs are very simple systems, composed of an omnidirectional antenna that continuously broadcasts a carrier signal at a fixed frequency. Aircraft equipped with an Automatic Direction Finder (ADF) can calculate the angle of arrival of that signal (i.e., the bearing to the NDB). Several NDBs can be used to indicate a route.

Figure 46 – NDB site (Credit: Krd, under Creative Commons license – Attribution-Share Alike 4.0 International)

5.2.1.1 Main characteristics

NDBs shall operate in the frequency band from 190 kHz to 1750 kHz and transmit continuously a modulated carrier with identification information. NDB signals follow the curvature of the Earth, consequently, the coverage can reach from 25 NM to 150 NM. The accuracy of the system depends on the ADF equipment installed on-board aircraft, but the **ICAO minimum accuracy for NDBs is ±5°**.

Each NDB shall be individually identified by a code, which will be transmitted at least once every 30 seconds. NDBs shall include a monitor system that detects malfunctioning of the NDB or of the monitor itself. Specifications are in ICAO Annex 10 Volume I Radio Navigation Aids.

The NDB system has no capacity limitations and can serve any number of aircraft.

5.2.1.2 Status and rationalisation plans

NDBs have been part of the ground infrastructure of aids to navigation for air traffic management during decades. However, due to its technical limitations, the appearance of GNSS, and the transformation towards performance-based navigation, **NDBs are expected to end operations in the near future**, following the decommissioning proposal included in the European ATM Master Plan and in order to comply with the Performance Based Navigation Implementing Rule (PBN IR) as well.

ICAO's Global Air Navigation Plan (GANP) expects NDBs to become less important as radio navigation aids, with the opportunity to be decommissioned.

More information can be found in Wikipedia - NDB.

5.2.2 VOR

The **VHF Omnidirectional Radio Range (VOR)** is a system that allows aircraft with a receiving unit **to determine the magnetic bearing from the station to the aircraft** (called the VOR radial).

The VORs use a circular array of antennas, which transmits two radio signals. One signal (**Reference signal**) radiates omnidirectionally so that its phase is equal in all directions. The second signal (**Variable signal**) radiates from a directional array. The phase of the variable signal received at the aircraft is dependent upon the radial on which the receiver lies with respect to Magnetic North. The equipment on-board the aircraft receive both signals and, from their phase difference, the VOR radial is estimated. If the VOR is associated with a DME (see section 5.2.3), aircraft can also calculate their distance to the VOR and determine a position fix. This method is called VOR/DME navigation.

Figure 47 – VOR site (Credit: Marc Lambert, under Creative Commons license)

The intersection of radials from two different VOR stations also allows aircraft to determine a position fix and navigate from one point to another.

5.2.2.1 Main characteristics

The VOR shall operate in the frequency band from 108 MHz to 117.975 MHz, with horizontal polarisation. The accuracy of the bearing information shall be within ±2°. The coverage of the system is limited by the line of sight, up to an elevation of 40°, reaching from 25 NM to 130 NM. **The VOR shall have a monitoring unit** that generates a warning and either removes the navigation content from the carrier or switches off the radiated power if certain conditions of service provision are not met. The same shall happen if the monitor itself fails.

The VOR adequately meets the accuracy to support RNAV 5. Considering a Doppler VOR, the maximum range at which the VOR can meet a 1 NM performance is 23 NM from the VOR, therefore not providing the level of accuracy to support more demanding navigation specifications at a longer range. Specifications are in ICAO Annex 10 Volume I Radio Navigation Aids.

The VOR system has no capacity limitations and can serve any number of aircraft.

5.2.2.2 Status and rationalisation plans

VORs have been part of the ground infrastructure of aids to navigation for air traffic management during decades. However, due to its technical limitations, the appearance of GNSS, and the transformation towards performance-based navigation, we expect VORs to become less important in the following years. The European ATM Master Plan **plans to reduce the number of VORs to a Minimum Operational Network** which would provide some **limited navigation capabilities in case of a temporary disruption of GNSS** as indicated in the PBN IR.

ICAO's Global Air Navigation Plan (GANP) expects VORs to become less important as radio navigation aids, with the opportunity to be decommissioned.

More information can be found in Wikipedia - VOR.

5.2.3 DME

The **Distance Measuring Equipment (DME)** is a system that provides the **slant range distance between an aircraft and the corresponding facility on ground**. DMEs are composed of two elements: interrogator and transponder. The interrogator is located on the aircraft, and the transponder is located on the ground. The interrogator broadcasts a radio signal (a pair of Gaussian pulses), which the transponder receives and processes. After a specified time, the transponder replies with another. The round-trip time serves to compute the slant range distance between the aircraft and the ground station. DME ranges from two different ground stations allows aircraft to know their position and navigate from one point to another. This method called DME/DME is well established around the world.

Figure 48 – VOR/DME site (DME in the tower) (Credit: Hans-Peter Scholz, under Creative Commons license)

5.2.3.1 Main characteristics

The DME shall operate in the frequency band from 960 MHz to 1215 MHz, with vertical polarisation. Normally for conventional navigation DMEs are associated with VORs or ILSs. When supporting PBN applications standalone DME installations can be used. If associated with a VOR, DME coverage shall be at least that of the VOR. If associated with an ILS, DME coverage shall be at least that of the ILS azimuth angle guidance sectors. The DME transponder shall have a monitoring unit that generates a warning and switches off the radiated power if certain conditions of service provision are not met, or even if the own monitor fails. This shall occur in less than 10 seconds since the beginning of the failure. Specifications are in ICAO Annex 10 Volume I Radio Navigation Aids.

The DME/DME positioning accuracy is in the order of a few hundred metres, which leads to **accuracies** in the aircraft position **not better than 0.3 NM** (with the best geometry, i.e., angle of cut 90°) which may not be enough for the most demanding navigation specifications. The use of DME ranges from multiple stations is one of the solutions that will improve the positioning accuracy and integrity. The **enhanced DME (eDME)** uses a combination of one-way and two-way ranging methods and is being proposed to improve the range measurements accuracy and the spectrum usage.

The modern DME systems **can serve up to 200 aircraft**.

5.2.3.2 Status and optimisation plans

DMEs are part of the ground infrastructure of navigation aids for air traffic management. An optimised or expanded network will support performance-based navigation. **DME/DME navigations support RNAV 5, RNAV 2, RNAV 1, and in certain conditions RNP 1 and A-RNP Navigation Specifications**. DMEs might constitute a complementary infrastructure in case of GNSS failure. The European ATM Master Plan proposes to optimise the DME network, also to comply with the PBN IR.

ICAO's Global Air Navigation Plan (GANP) identifies DMEs to be an appropriate backup to GNSS for performance-based navigation. For a good service in case of GNSS outage, the network of DMEs might need to expand.

Moreover, the **eDME** equipment is **expected to support more stringent RNP specifications and improve spectrum efficiency**, leading to reducing L-band congestion. It anticipates the implementation mainly through software upgrades and minimum change to the on-board and ground hardware, while ensuring that the additional capability is fully backward compatible to support seamless implementation. More information can be found in the Wikipedia - DME.

5.2.4 ILS

The **Instrument Landing System (ILS)** is a **precision approach and landing system** that provides aircraft with short range horizontal and vertical guidance just before and during landing and, at certain fixed points, indicates the distance to the reference point of landing.

Figure 49 – ILS (LOC) (Credit: Super Dominicano, under GNU Free Documentation License*)*

An ILS is composed of:

- **Localiser**: system of horizontal guidance embodied in the ILS which indicates the horizontal deviation of the aircraft from its optimum path of descent along the axis of the runway.
- **Glide Path**: system of vertical guidance embodied in the instrument landing system which indicates the vertical deviation of the aircraft from its optimum path of descent.
- **Marker Beacons**: transmitters in the aeronautical radio navigation service which radiate vertically a distinctive pattern for providing position information to aircraft.

  In the current Annex 10, the Marker beacon has been replaced by a means to perform altitude checks and is therefore no longer an integral part of the ILS. In most European airports, the means for the altitude check provided is the DME, a replacement and improvement over the marker beacon.

5.2.4.1 Main characteristics

The Localiser shall operate in the frequency band from 108 MHz to 111.975 MHz. The signals are modulated in AM with a 90 Hz and 150 Hz tone, with each tone predominating in one side of the course, and horizontally polarised.

The Glide Path equipment shall operate in the frequency band from 328.6 MHz to 335.4 MHz. The radiation is amplitude modulated by a 90 Hz and 150 Hz tone and horizontally polarised.

The **Marker Beacons** shall operate at 75 MHz and their signals are horizontally polarised. There shall be two marker beacons in each installation to indicate predetermined distance Typically, the first marker beacon (the Outer Marker) would be located about 5 NM from touch-down while the second marker beacon (the Middle Marker) would be located about 1 NM from touch-down. In almost all European ILS installations, VHF marker beacons are replaced by DMEs co-located with the ILS, which give the pilot continuous horizontal distance to the runway.

ILS approaches are classified per Category and can be flown down to a certain Range Visual Rage (RVR) and Decision Height (DH) by qualified pilots flying suitably equipped aircraft to suitably equipped runways without acquiring visual reference as follows:

- CAT I permits a DH of not lower than 200 ft and an RVR not less than 500 m.
- CAT II permits a DH of not lower than 100 ft and an RVR not less than 300 m.
- CAT IIIA permits a DH below 100 ft and an RVR not below 200 m.
- CAT IIIB permits a DH below 50 ft and an RVR not less than 50 m.
- CAT IIIC[9] is a full auto-land with roll out guidance along the runway centreline and no DH or RVR limitations apply. This Category is not currently available routinely.

An automatic monitor shall transmit a warning if it detects a failure of the system. Specifications are in ICAO Annex 10 Volume I Radio Navigation Aids. The ILS has no capacity limitations.

5.2.4.2 Status and optimisation plans

The ILS is the most expanded system for precision approach and landing today. However, since satellite-based and ground-based augmentation systems (SBAS and GBAS) allow precision approach operations, the ILS infrastructure is planned to be rationalised in Europe. The European ATM Master Plan reflects the need to **rationalise the ILS CAT I network and notably ILS CAT I infrastructure** in the horizon 2030 to comply with the PBN IR which only allows ILS CAT I operations in contingency situations (i.e., upon the loss of the PBN services mandated in the PBN IR).

Moreover ICAO's Global Air Navigation Plan (GANP) identifies the ILS as an appropriate navigation aid for precision approach and landing. More information can be found in the Wikipedia - ILS.

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[9] Note that ICAO will eliminate the CAT IIIABC subcategories and replace them with the Performance Based Aerodrome Operating Minima concept (PBAOM).

5.2.5 TACAN

A **Tactical Air Navigation System (TACAN)** is a radio-navigation system mainly used by NATO and other military forces that provides a military aircraft with bearing and distance (slant-range) to a ground facility, a ship, or appropriately equipped aircraft. In general, it can be described as the **military system equivalent to the VOR/DME system** for navigation purposes. The DME portion of the TACAN system can be considered for civil use. TACAN is operated in air-to-surface and/or air-to-air modes. For the former, aircraft equipped with TACAN can use the system for en-route navigation as well as non-precision approaches. TACAN can be collocated with VOR stations (VORTAC facilities).

Figure 50 – TACAN site (Credit: Nbonfanti underCreative Commons Attribution-Share Alike 4.0 International)

5.2.5.1 Main characteristics

TACAN operates in the frequency band 960-1215 MHz. The bearing unit of TACAN is more accurate than a standard VOR since it makes use of a two-frequency principle, with 15 Hz and 135 Hz components, and because UHF transmissions are less prone to signal bending than VHF.

TACAN range is around 200 NM. Accuracy of the 135 Hz azimuth component is ±1° or ±63 m at 3.75 km. Accuracy of the DME portion must be 926 m (0.500 NM) or 3 percent of slant range distance, whichever is greater. Specifications are in detailed in FAA 9840.1 1982.

TACAN is one of the recognised military systems that is authorised for navigation and is for some aircraft the only authorised system. It is as a proven utility in peacetime and in crisis situations. **A potential challenge is the security of the service provided by TACAN in terms of resilience and vulnerability**. Therefore, TACAN could be replaced in the long-term with a system which has a higher resilience to security threats.

5.2.5.2 Status and rationalisation plans

DME/DME-based positioning has been identified as an essential near-term capability to support PBN operations. **The use of TACAN structures** for en-route and terminal operations is crucial for State aircraft operator to increase airspace flexibility when performing GAT operations and **could overcome potential coverage limitations of the European DME network using the DME component of TACAN**. The reutilisation of military systems is expected to offer compliance and sustain appropriate levels of performance to support PBN specifications.

More information can be found in this Wikipedia – TACAN.

5.2.6 Loran

The **Long Range Navigation system (Loran)** is a hyperbolic navigation system, initially developed in the 1950s. It works by **comparing the time of arrival of signals coming from pairs of synchronised transmitters**. Receiving the signals from one pair of transmitters, and knowing their positions, the user can restrict its position within a hyperbolic line. Reception of the signals from two additional pair of transmitters restricts the position to a second and a third hyperbolic line. The intersection of the hyperbolic lines marks the position of the receiver.

Different evolutions of the Loran system receive different names (LORAN, Loran-A, Loran-B, Loran-C, etc.). Chayka is a Russian system almost identical to Loran. Receivers are typically compatible with both navigation systems.

More information can be found in the Wikipedia – Loran and in the International Loran Association.

5.2.6.1 Loran-C / Chayka

Loran-C was the most extended version of Loran.

5.2.6.1.1 Main characteristics

Loran-C operates in the frequency band from 90 kHz to 110 kHz, with a power output ranging between 100 kilowatts up to several megawatts. Loran-C transmitters are grouped in chains. Each chain has a master station and, at least, two secondary stations. The master station transmits nine pulses at predefined intervals. Each secondary station, after receiving these pulses, waits a specific delay and transmits eight pulses. The pulses are codified so the receiver can identify the different emissions. The location of the master and the secondary stations, the repetition interval of the master, and the secondary transmission delays are all known. Thus, when a user receives all these pulses, it can estimate the propagation time between its position and the different stations. From this information, it is possible to estimate receiver location.

Figure 51 – LORAN-C transmitter (Credit: Bin im Garten, under Creative Commons license - Attribution-Share Alike 3.0 Unported)

The **transmission of very low frequencies at very high powers** needs transmission antenna masts that are a few hundred metres tall. The radiation pattern of these antennas is omnidirectional. Loran-C transmissions need to be accurately synchronised. To do so, each transmitter includes up to three atomic clocks. **Loran-C has an accuracy better than 460 metres, and an availability of 99.7%.** Each transmitter has a typical **coverage of up to several hundred kilometres**. The coverage depends on factors like day/night conditions, weather, and transmission over land or sea.

Detailed information of the Loran-C specifications can be found at Loran-C Introduction website. It has never had ICAO standards written for it and is therefore not considered for Aviation purposes.

Loran-C has no capacity limitations.

5.2.6.1.2 Status and rationalisation plans

The development of satellite navigation systems strongly reduced the number of Loran-C users. Loran-C is still in operation in the Far East Radionavigation Service (FERNS) run by Russia, China, and the Republic of Korea, but many transmitters have been shut down along time. **In Europe Loran-C is not in use** since Spain, Norway, Iceland, Italy, France, and Germany terminated their Loran-C transmissions around 2015.

5.2.6.2 eLoran

Enhanced Loran (eLoran) is a low-frequency, long range Terrestrial Radionavigation System, capable of providing positioning, navigation, and timing (PNT) service for use by many modes of transport completely independently from GNSS.

eLoran transmits pulsed groundwave signals with a central frequency of 100 kHz, which gives the signals their long-range navigation capability from widely spaced transmitters. The receiver's position is determined by the measurement of the times of arrival (or pseudorange) of these pulses. **Pseudoranges from at least three transmitters are required to be measured to determine a horizontal position solution by trilateration**. Since the transmitters are placed on the Earth's surface, altitude of the receiver cannot be determined. Measuring more than three transmissions (preferably five) provides the user with RAIM (Receiver Autonomous Integrity Monitoring) capability in addition to positioning accuracy.

5.2.6.2.1 Main characteristics

eLoran provides a Loran-type service with **higher accuracy (in the order of 20 m), availability and integrity**. The main difference with a LORAN-C system is the addition in eLoran of one or more data channels, transmitted together with the Loran signal, which serves to transmit differential eLORAN and/or DGPS corrections and integrity information, enhancing the performances (accuracy, integrity, availability, and continuity) with respect to the Loran system, but having both the same coverage. It also enables the transmission of additional data, including navigation messages. These improvements require a dedicated secondary terrestrial network of reference stations, which are spaced up to 50 km apart.

The eLoran system is composed of transmitting stations, monitoring sites and a control centre. Monitoring sites check the timing accuracy of the transmitted signals and send corrections to the control centre which collects these observations, processes them, and produces the correction and integrity data to be broadcast by the transmitting stations. These stations transmit the corrections using the data channel. eLoran transmitting stations are equipped with atomic clocks, and transmissions are precisely synchronised to UTC. Signals from at least three transmitting stations are needed to locate a receiver.

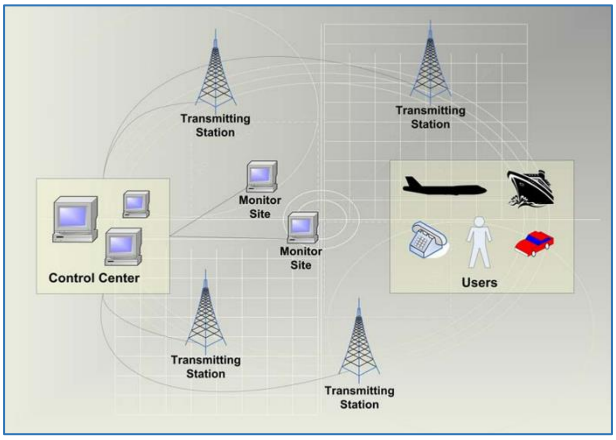

Figure 52 – eLoran system (Credit: eLoran Definition Document)

eLoran positioning and timing accuracies can vary significantly within the coverage area and are poorer than those available from GNSS. Still eLoran signals are transmitted with very high power and at a very low frequency (what requires complex infrastructure, including antennas that can be up to 200 metres high) which means that jamming eLoran receivers becomes very difficult without being detected. In addition, the low frequency signals used penetrate buildings and other areas where GNSS signals are not available.

5.2.6.2.2 Status and modernisation plans

eLoran services are not provided in Europe. In December 2015 the discontinuation of its eLoran prototype service in the UK and Ireland was announced by the GLA (General Lighthouse Authorities). However, system knowledge is at a level where an eLoran service can be deployed relatively quickly.

5.2.6.3 DLoran (Differential eLoran)

Differential eLoran, DLoran, is a **local augmentation system that enhances the performance of eLoran** on a specific area.

5.2.6.3.1 Main characteristics

The **working principle is similar to DGNSS**. Under the area of interest, several DLoran reference stations are deployed. Those stations, whose exact position is known, include an eLoran receiver and a communication link to an DLoran control centre. The reference stations use eLoran to estimate their positions, and send this information to the DLoran control centre, which calculates the errors with respect to the actual positions. Thus, the control centre knows the performance of eLoran in the area of interest and calculates **differential corrections** for the coverage area.

A user of DLoran needs an eLoran receiver and wireless communication link to the DLoran control centre. The user gets his position with eLoran and sends it to the DLoran control centre. The control centre calculates the optimum differential corrections for that position and sends it back to the user. Finally, the **user applies those corrections and gets an improved PNT information**. The communication link between users and the DLoran control centre employs the public mobile telephone network (3G/4G).

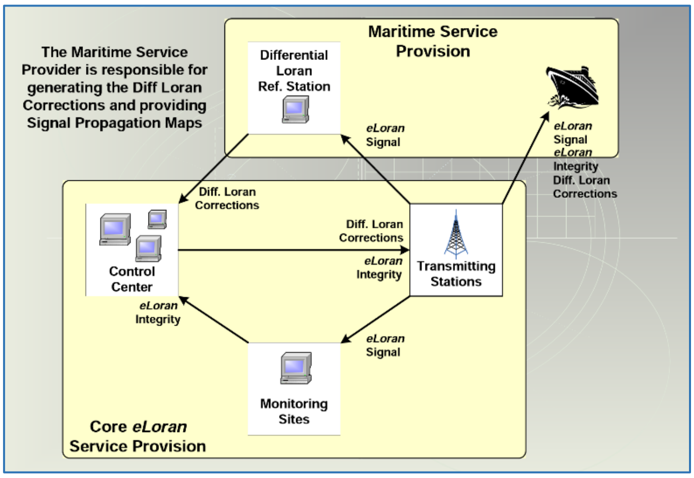

Figure 53 – Example of an DLoran service provision for maritime users (Credit: eLoran Definition Document)

DLoran infrastructure (reference stations and control centre) is independent from the eLoran system.

Dynamic tests performed in the harbour of Rotterdam showed an **accuracy better than ±5 metres**.

5.2.6.3.2 Status and modernisation plans

DLoran is a local augmentation system to eLoran. Since Loran-C and eLoran transmissions ceased in Europe in 2015, **DLoran services are not being provided**.

5.2.7 Longwave time and frequency distribution systems

Longwave systems (e.g., DCF77 in Germany, MSF in United Kingdom and ALS162 in France) have been used in Europe **to distribute legal time and standard frequency** for decades. They employ very low frequencies and high power to reach distances up to thousands of kilometres. Below the characteristics of the DCF77 system are described. These systems are difficult to spoof or jam, and their threats and weaknesses radically differ from the ones of GNSS.

5.2.7.1 Main characteristics

DCF77 is one of the methods used by PTB (the National Metrology Institute of Germany) to disseminate the legal time and frequency standard in Germany. It uses three atomic clocks to generate a carrier frequency of 77.5 kHz. An omnidirectional 150 metres high antenna transmits the signal at an equivalent isotropic radiated power of 35 KW. The antenna is in Mainflingen, and provides a **coverage of around 2 000 km**, meaning most States in Europe (some areas such as Iceland, north of Norway, north of Sweden, north of Finland, Cyprus, Canary Islands, Azores Islands, Madeira Islands, Crete are out of reach).

The carrier is modulated in amplitude to transmit the time and date information. Every second, the carrier's amplitude is reduced to a 15% of its original value. A binary '0' is transmitted if the reduction in amplitude lasts 0.1 seconds. A binary '1' is transmitted if the reduction in amplitude lasts 0.2 seconds. Thus, the system can transmit 60 bits per minute, meaning that the user receives every minute information regarding the year, the month, the day of the week, the day of the month, the hour, and the minute. The second is obtained counting how many reductions in amplitude have occurred since the start of the minute.

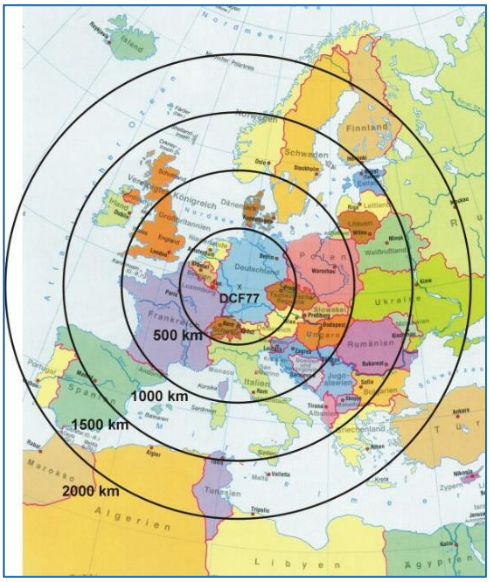

Figure 54 – Dissemination of DCF77 signals in Europe (Credit: PTB)

The carrier frequency has an **average deviation of less than 2x10^{-12} on one day** at the place of transmission. The zero crossing of the carrier **signal is maintained to within 5.5±0.3 microseconds with respect to the UTC** realisation at PTB.

French ALS162 (162 kHz) signal transmitter, operated by TDF (Télédiffusion de France), is located in Allouis (Cher). It is using caesium thermal beam clocks and connected by common GPS views to the UTC(OP) time scale, generated by LNE-SYRTE at Observatoire de Paris.

5.2.7.2 Status and modernisation plans

DCF77 is **operational since 1959** and is still in use to synchronise time keeping systems in German train stations, by TV and radio broadcast companies, in the energy and telecommunication industries, to calibrate frequency generators and by private individuals in possession of radio-controlled clocks. An advantage of DCF77 over GNSS is its ability to **penetrate inside buildings** and in difficult environments. The **availability** of DCF77 in 2016 was **99.79%,** excluding disconnections of less than two minutes. Modernisation for user segment is also possible, with Software-Defined Radio tools.

5.2.8 Atomic clocks

An atomic clock **measures time by monitoring the frequency of radiation of atoms**. Atom's electron states have different energy levels, and in transitions between such states, they produce a very specific frequency of electromagnetic radiation. Measuring those allows to obtain precise time and frequency readings.

Atomic clocks are used as **primary standards for services requiring precise time and frequency distribution**, such as high-speed telecommunications, TV broadcast and GNSS systems. **GNSS require ultra-high precision atomic clocks** both on-board the satellites and in the ground segment to compute a very precise and stable reference time and very accurate Navigation information. Smaller atomic clocks are used in other types of satellites orbiting the Earth (LEO, MEO, GEO) as well as in deep space probes.

Very high-performance atomic frequency standards (Cs and Rb fountain clocks and optical atomic clocks) are also used by the **National Metrology Institutes (NMI)** which play a critical role not only in the realisation of the UTC time and frequency but also in the development of advanced atomic frequency standards and measurement methods. The NMIs maintain high-quality time scales, and many distribute time and frequency via the Internet, with a few also providing VLF radio signals such as WWV.

Further information can be found in Wikipedia – Atomic clock and The Science of Timekeeping.

5.2.8.1 Main characteristics

Clock performance can be described in terms of accuracy and stability:

- **Accuracy** is the measure of how well the device matches the ideal reference. In most PNT applications this means how precisely the clock follows UTC.
- **Stability** determines how well the device maintains its frequency against the standard one (i.e., on the assumption that the sole objective is that the frequency remains the same). The characteristic behaviour does not follow a measurement-time-interval-independent normal distribution (random white noise), so the **Allan standard deviation** is used to estimate the random frequency stability, which is the root mean square fractional difference between values measured a given time apart, after removal of any systematic drift. Since the Allan standard deviation, which is dimensionless, is a function of the measurement time interval, we can use it to distinguish short, medium, and long-term stability.

  Short-term stability is mostly determined (dominated) by clock components, medium-term by environmental perturbations (mostly temperature, but also pressure, humidity, magnetic fields and similar) and long-term by aging (hardware physical properties).

There are mainly three types of atomic clocks, which is in order of cost and accuracy are:

- Rubidium standards (Rb) with good short-term stability but an accuracy in the order of microsecond to UTC up to a day, based on external factors.
- Caesium standards (Cs) with better accuracy (microsecond up to a week) and medium-term stability and yet suffering from small short-term fluctuations (its day stability is worse than Rb).

Both Rb and Cs suffer from pink noise in the medium-term and ageing in long-term. In addition, Cs source becomes depleted over time and its useful timeline of 10 years is shorten than Rb.

- Hydrogen masers (H-masers) with the best accuracy and stability and limited ageing effect in the long-term (still they need to be calibrated for frequency offset).

As GNSS ground system can calibrate both Rb and H-masers in space, GNSS satellites often deploy Rb combined with passive hydrogen masers compensated by ground station clocks.

5.2.8.2 The miniature chip scale atomic clock (CSAC)

Over the past 30 years, research also focused on miniaturising atomic clocks leading to development of the **miniature chip scale atomic clock (CSAC).** These are compact, low-power consumption devices using microelectromechanical systems (MEMS) and incorporating a low-power semiconductor laser as the light source. Current commercial CSACs have a size < 17 cm^3, weight 35 g, and power < 120 mW and operate over a relatively wide temperature range (− 40 to 85 °C). They maintain accuracy of 10^{-7} within a day.

Those characteristics enable a wide range of operations in space, defence, and civilian domains. The autonomous vehicles, drones, tactical PNT devices, LEO satellites, are among the most promising markets.

Virtually any PNT application benefits from the increased quality of clocks.

5.2.8.3 Status and optimisation plans

Looking further ahead, the current **research** work focus on:

- Power consumption and hardware improvements for example improving lasers to replace the discharge lamp in Rubidium clocks.
- Cold-atom clocks for space application, with promising tests conducted by ESA and China, demonstrating capacity of those systems.
- Development of optical clocks (or optical lattice clock) for space missions. While some components are well researched, overall technology is still not mature facing manufacturing challenges and large size and power requirements. Most current experiments focus on the fundamental physics experiments. Nevertheless, their accuracy and stability performance put them in a position to replace the current time standards in the future. Further information about Quantum technology can be found in section 5.3.11.

5.3 Emerging Technologies

This section lists and describes **emerging PNT technologies** with the highest maturity and perceived importance. Due to the nature of the description, a simplification of the concepts was needed, leading to a grouping of the technologies based on the hardware similarity. This appendix includes:

- Radio-based technologies, ground-based (e.g., pseudolites) or space-based (LEO satellites).
- Technologies providing mature timing services with high performance.
- Mobile navigation which is to a certain degree hardware agnostic and depends heavily on sensor fusion, machine learning and backend servers and it is a prominent technology for mass market.
- Non-radio-based technologies such as inertial systems and magnetic sensors.
- Visual, LiDAR or radar-based techniques technologies, which despite not strictly providing PNT are important in sensor fusion.
- Quantum and pulsars, which might offer very interesting performance in the future.

In addition, the use of advanced concepts such as the signal of opportunity or sensor fusion is discussed but not detailed.

It is interesting to notice that most of the selected mature technologies on the market offer time distribution. The need for the alternative timing was recently mentioned by the US Executive Order 13905 and the UK National Timing Centre Programme. **Time distribution is actively developed in the EU**, enhanced by the unique network of the National Metrology Institutes (NMIs). As those play important role in the realisation of the UTC and frequency and the development of advanced atomic frequency standards, it is natural that an ecosystem of companies focused on time distribution sprang around them. The long wave time systems, eLoran and atomic clocks are technologies described in the prior appendix that are able to provide (and maintain) UTC time.

Literature research and alternative PNT testing campaign conducted at the JRC show that technologies that provide **full PNT are very difficult and expensive to bring to market-ready maturity**. Technologies described in this section benefit from years of existing experience (e.g., Silicon Valley or Australia research hub) as well as years of investment. It is difficult to match this advantage, as the market for the services is limited. Here, eLoran, described in previous appendix is worth mentioning.

These **emerging technologies** differentiate from the other ones, described in prior appendixes, by:

- They are designed as part of the combined offering or sensor fusion approach.
- They do not only provide position but also create an efficient time distribution, though some might need a connection to the UTC.
- They embrace modern hardware and software development practices, leading to rapid development and over-the-air updates. This also means that all units are connected and usually do not need manual intervention after installation.
- They have capabilities for monitoring, reporting and fault identification by themselves.
- They have improved cybersecurity, integration with other systems, user experience and flexibility.

Detailed information on those technologies, including description of the algorithms discussed in this section can be found in: *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications, Y. J. Morton, F. S. T. Van Diggelen, J. J. Spilker, and B. W. Parkinson, Wiley/IEEE Press*.

5.3.1 White Rabbit (WR)

EEE-1588-2019 High Accuracy (HA) profile, widely known as White Rabbit protocol is a **time & frequency distribution protocol**, developed by CERN, which combines PTP packets with the frequency base of Synchronous Ethernet (SyncE) to provide **sub-nanosecond time transfer accuracy**. A new PTP version 2.1 includes White Rabbit generalised as its High Accuracy Profile.

This technology is developed by commercial companies, that offer hardware and software as a Time-as-a-Service (TaaS) solution. They also offer monitoring and resilience capacity, with a focus on:

- Seamless switchover between time sources in case of failure.
- Detection and raising alarm if a time source goes out of specification, allowing for the switchover to a valid time source.

5.3.1.1 Main characteristics

The technology requires at least two sources of time (GNSS, atomic clock, NMI, etc.) in the uninterrupted fibre network. Those sources are acting as backup to each other to ensure time & frequency transfer with sub-nanosecond accuracy and picosecond precision in case of failure of one of the time sources. JRC-based lab tests demonstrated the accuracy of around 60-90 ps peak to peak level.

Existing WR networks, such as GEANT, were developed to support scientific efforts across Europe with technology adopted by different research institutions such as CERN and GSI for High Energy Physics (Particle Accelerators) and also distributed astronomy platforms such as HISCORE, CTA, SKA, KM3Net, etc. Other active users are data centres, telecommunications companies, and financial institutions, such as Equinix or Deutsche Börse.

5.3.1.2 Status and optimisation plans

The **technology is mature** while further research is conducted in two areas:

- Extending WR to act as over-the-air (OTA) monitoring service. In this mode system monitors and corrects other devices, with a drifting time source, using their transmitted radio signal. Results from JRC tests demonstrated that external devices can be maintained within +/-200 nanosecond boundaries.
- Work on using WR OTA, investigated as an option to provide full PNT. This requires a dense timing infrastructure in place, which is not yet available. A pilot SuperGPS project from Technical University Delft should be able to obtain 10 cm-level positioning accuracy based on expected network time synchronisation at the 100ps level. The concept could provide position out and indoors. It is intended for smart transport applications including dense urban areas and tunnels for the self-driving car’s line keeping.

5.3.2 Computer network time distribution

One of the options for the **time distribution via computer networks** is Dynamic synchronous Transfer Mode (DTM) which includes time division multiplexing and a circuit-switching optical network technology. Designed to provide a guaranteed quality of service (QoS) for streaming video services, it can be used for packet-based services as well. The DTM architecture was standardised by the European Telecommunications Standards Institute (ETSI) in 2001.

The technology is used by several companies to distribute time over network. Companies use DTM standards, though some created an additional time protocol to increase the integrity of the time information transmitted (NTP STS). The network monitoring allows for the time logging and enhanced cybersecurity. Overall, two types of services are offered:

- Hardware implementation and subsequent maintenance (monitoring) of the network while the network itself is managed by the client.
- Time-as-a-Service (TaaS) solution, when the company manage the network itself, offering turn-key solution for the client.

An existing network is used with the only additional hardware of network boxes (nodes) that redistribute time, using DTM, to all its neighbours. Boxes interconnect directly or over commercially available WAN links including fibre, WDM, MPLS and microwave links. The updated network offers redundancy and network resilience to path or node failures. This implementation can be country wide, with atomic clock backups and includes the time source (traditionally GNSS but other means are also possible).

5.3.2.1 Main characteristics

The **accuracy depends on the jitter and network asymmetry**. The first factor is directly related to the intensity of the other, non-related traffic. This can be mitigated by increasing the packet rate to probe the delay more often, which require guaranteed amount of bandwidth. Practical experience indicates that requesting the right quality from the MPLS network is the critical and sufficient requirement for the below microsecond accuracy, though this can be expensive.

The second factor **requires calibration of each new path**. This in turn requires the careful error-budget design and balance of number of nodes installed. Each node provides monitoring and auto-calibration of overlapping links. Given the cost, the effort to maintain the accuracy might be focused on main backbones with other connections managed on a ‘best effort’ basis, as long as those connections are not too long (which limit both the number of possible paths and the traffic effect). Results from the JRC testing also suggest that calibration on ‘best effort network’ using GNSS as time source is not enough to maintain reliable service.

5.3.2.2 Status and optimisation plans

DTM standards is designed for streaming video services, so time application requires hardware-overheads that might not be required. It would be logical to assume that simplified time-only protocols and hardware might be used in the future. Some of the current offerings utilise microwave links, and this is expected to increase, limiting infrastructure cost.

Commercial networks based on this technology are deployed for 15+ national or regional DVB-T/DAB transmissions. Current development activities focus on upgrades in terms of size, interfaces, and scalability, to create a more specialised product adapted to a particular market over diverse type of links. Operators are separately adopting non-GNSS means of transferring and maintaining UTC time reference.

5.3.3 Pseudolites

Pseudolites are a **terrestrial positioning technology** that uses a **network of ground-based transmitters** providing a robust radio-positioning signal within a specific area.

The earliest known prototype was the proof-test of the GPS concept at the Yuma Proving Ground in the early ’70s. Signal was transmitted using terrestrial transmitters and rovers flown aboard an aircraft, in reverse to how the system is used now. The GPS Gold code PRN 33-37 were reserved for terrestrial use, but with the increase in satellite availability, the focus has shifted from availability and accuracy to integrity and concerns about transmitting other signals in the GPS frequency. Currently, pseudolites might still use Gold code but tend to use different frequencies, mostly to avoid any possible future restrictions. Two recent examples are WiFi frequencies and the dedicated 921.8845 – 927.0000 MHz band with varying transmitting power, 23dBm for the former and 30Watt for the latter, which requires dedicated permits.

The network is synchronised on the nano-second level to **provide position and time**. There are two solutions – the use of precise oscillators (such as atomic clocks) or internal synchronisation (using frequency alignment).

Pseudolites are commonly used either independently or as an augmentation to GNSS and tend to be based on GNSS hardware allowing for the reuse of GNSS receivers hardware and correlators. Due to different frequencies, integrated receivers tend to be de-facto two receivers.

5.3.3.1 Main characteristics

Any terrestrial positioning technology faces multipath, the near-far effect and the tropospheric delay, among other limiting factors. Mitigation measures to achieve cm-level accuracy may include time-Hopping/Direct Sequence Code Division Multiple Access (TH/DSCDMA), spatial and frequency separated signal, a particular pulsing scheme and multipath resistant beamforming antenna. Hardware design tend to follow GNSS receivers and include OXCO clocks.

The **operation range**, limited by the near horizon, near-far effect, and existing spectrum regulations, is 5 – 15 km. Precision Timing and Frequency applications require only one transmitter to be in view, while Positioning and Navigation require signals from three or more transmitter locations. The density of the network depends on the visibility, with a cluttered urban environment requiring the largest density. Assuming a typical transmitter range in a cluttered suburban environment, one needs about four beacons required per 100 km^2 (10 x 10 km). Site-specific studies need to take into consideration user requirements and signal availability, which will increase number of transmitters.

An important consideration is a small difference in height making the system much more accurate in planar than horizontal. A solution to both problems could be the use of a High-Altitude Platform Systems (HAPS), travelling at altitudes up to 20 km. They are sensor platforms and communication providers, intended to glide over a specific area for long periods using solar power and wind. Energy constraints limit their payload. Currently, their main purpose is rapid communication deployment with minimal ground network infrastructure, for example, for backing up terrestrial networks damaged by disasters. Their characteristics make an ideal augmentation for a pseudolite system, but it would require changes to the correlator (part of receiver front end) to accommodate for movement. Some manufacturers deploy pressure sensors to alleviate height issues. Those are solutions to **code-based systems**, that provide **5 - 10 m accuracy** but not the one utilising **carrier-based** ambiguity resolution with **mm accuracy**.

Test at JRC demonstrated the following performance:

- Internal and external (to UTC) time transfer 0.2 - 15 ns.
- 2D kinematic position outdoor and indoor using code 10 – 15 m and using carrier and VRay antenna 5 – 11 mm.
- OTA multi-hop time transfer over 106 km, with accuracy of 0.7 ns peak to peak.

5.3.3.2 Status and optimisation plans

These technologies are tested and currently used in mining, car testing, indoor logistics and harbour and dry port operations. Given their performance, technology is considered for intelligent transport systems and vertical take-off and landing, but no implementation was conducted.

Technology development focus on the correlator performance and the antenna characteristics. With increased volumes of units shipped some producers indicate miniaturisation as the next step.

Another interesting technology is **Ultra Wideband (UWB)** technology used for transmitting high-frequency impulses at small distance. By transmitting over the large bandwidth, the technology is, to a certain degree, resilient to multipath and suitable for indoors position without direct visibility. Commercial units have been demonstrated for emergency services but unfortunately two factors have limited their commercial appeal:

- Limited outdoor range.
- Permission requirements.

The idea recently was revisited as low power devices entered the market, still offering dm level accuracy and recently Apple have introduced this technology into their mobile devices. Yet, the overall trend seems to limit UWB utilisation to indoors and mobile devices.

5.3.4 5G and cellular networks based PNT

In 2012, the Radiocommunications Sector of the International Telecommunications Union (ITU-R) launched the 'IMT for 2020 and Beyond' Programme, with objective of defining the fifth generation of mobile communications systems – commonly referred to as 5G. In June 2016, ITU-R Working Party 5D published a timeline for IMT-2020, shown in Figure 55. Since then, industry and academia stakeholders have collaborated through various international forums, such as 3GPP, the DECT Forum, Korea IMT-2020, China IMT-2020, etc.

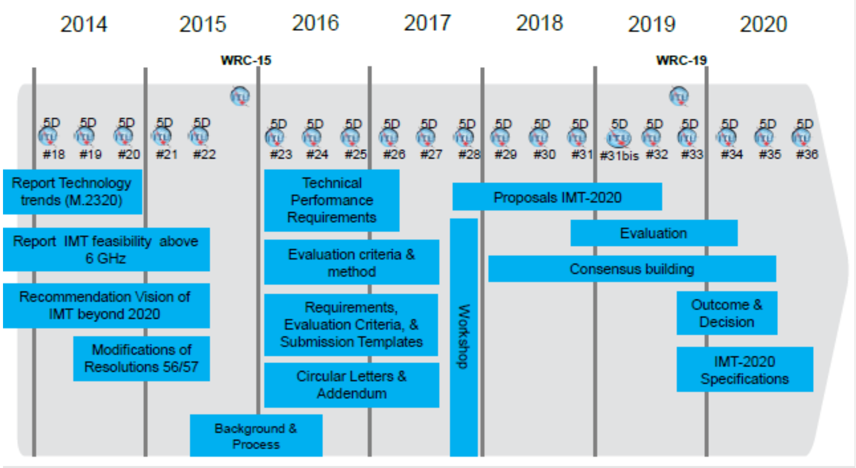

Figure 55 - Timeline and process for IMT-2020 (source: ITU-R)

From October 2017 to June 2019, candidate technologies were submitted, and four technologies were officially considered to meet IMT-2020 specifications:

- 3GPP 5G-SRIT (Set of Radio Interface Technologies), 3GPP 5G-RIT (Radio Interface Technology) represent the well-known standalone (SA) and non-standalone 5G deployment models of the Third-Generation Partnership Project (3GPP) cellular communications technology.
- 5Gi was developed by Telecommunications Standards Development Society India (TSDSI). 5Gi is an updated version of 3GPP 5G-RIT, designed mainly to improve rural coverage.
- DECT 5G-SRIT was designated as a non-cellular and autonomous, decentralised technology to support a range of use-cases – from wireless telephony and audio streaming to industrial Internet of Things (IoT) applications, particularly in smart cities.

Out of the above four technologies, **3GPP 5G (in both its standalone and non-standalone operation modes) is the most popular and widely deployed** IMT-2020 technology worldwide.

The network infrastructure to relay voice and data amongst end users and the Internet is commonly referred to as 'radio access network', 'transport network' and 'core network'. **Support for user location in the network infrastructure is a key requirement for the normal operation of cellular networks**, particularly during the paging (reception of an incoming call/data flow) and handover (transition between neighbouring base stations due to user mobility) procedures. As there are currently more mobile devices in use than humans in the world, the communication and positioning capabilities of commercial mobile networks and devices is very important.

5.3.4.1 Main characteristics

Figure 56 shows the **5G New Radio (NR) positioning architecture**. The positioning process starts when an external client sends a request to get the position of User Equipment (**UE**). A Location Management Function (**LMF**) processes the request and receives measurements and assistance information from the Next Generation Radio Access Network (**NG-RAN)** and the UE. The LMF estimates the position of the UE and sends the estimated position to the client that originated the request. Different to 4G, the positioning of the UE can be estimated also on the UE itself not only by the network. Another interesting feature of 5G is that the positioning request originates and finalises in the LCS client, which may correspond to the UE device or not.

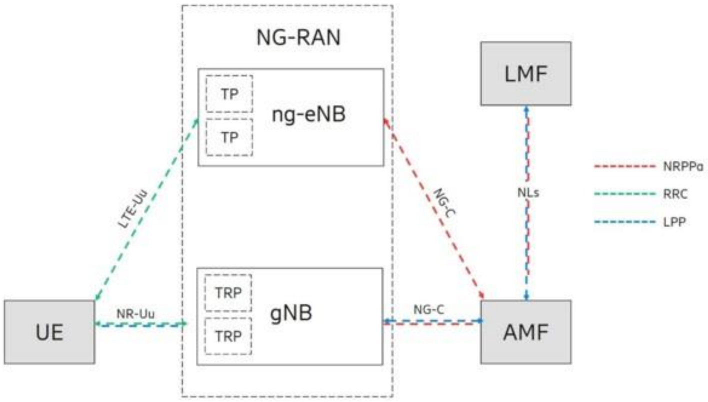

Figure 56 – 5G positioning architecture (Credit: Ericsson)

The most basic user location estimation is by identifying the base station that serves the cell phone and knowing its location and the coverage area. To improve the performance, it is possible to triangulate using signal (distance) from three or more adjacent base stations. LTE networks also support positioning based on observed time difference of arrival, which is a similar approach to eLoran described in the previous section.

5.3.4.2 Status and optimisation plans

The **evolution** of mobile communication networks, with **smaller cells**, **higher data rates**, **higher frequencies and narrower beams** will bring an increase in the accuracy of the positioning solution. First version of 5G networks is already operational in Europe, especially the non-standalone (NSA), which basically operates on a legacy 4G LTE core network. This limit NSA capabilities compared to pure 5G standalone (SA) network. For example, NSA supports LTE positioning rather than native 5G NR positioning. This platform allows the use of hybrid solution combining GNSS and 5G time synchronised signal to address the positional requirement mandated by FCC as part of E-911.

The SA technology is more mature, and technological advances will enable to fully benefit from 5G capabilities such as wide bandwidth for better time resolution, new frequency bands in the mmWave range, and massive MIMO for precise angle measurement.

More and more 5G Test Beds, based on SA technology, are operational across the world. For example, at the MWC held in 2022, Qualcomm Technologies showcase precise positioning with the mmWave spectrum, for indoor and outdoor deployments such as smart factories. Rohde & Schwarz demonstrated a GNSS-backup system based on the 5G Broadcast[10] technology. The positioning reference signals are transmitted together with information about the location of the transmitters. Such terrestrial infrastructure using 5G broadcasting towers act as a GNSS backup. This solution provides the same signal to a multitude of mobile and fixed receivers simultaneously like smartphones, tablets, cars, and wearables and achieve a metre-level accuracy. In addition, the content broadcasted by 5G transmitters can be enhanced with RTK and PPP corrections to bring the accuracy down to cm-level.

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[10] 5G Broadcast is based on 3GPP technology that is used for cellular 4G and 5G networks reusing of already established broadcast deployments (e.g., Radio, TV, etc.). It enables mobile reception of audio-visual content using a highly efficient broadcast mode.

5.3.5 Ranging mode (R-Mode)

Ranging mode (R-Mode) is a terrestrial positioning system that **uses** the **frequency bands of existing maritime radio infrastructure** for the **provision of timing signals**. Signals from at least three independent transmitters have to be received to perform R-Mode-based positioning. At present, R-Mode testbeds in Europe, Asia, and North America, utilises:

- The Medium Frequency (MF) band of the maritime radio beacon system or
- The maritime Very High Frequency (VHF) bands of the VHF Data Exchange System (VDES).

The radio navigation system consists of **three components**:

- The R-Mode transmitter uses existing maritime radio infrastructure, that is upgraded to enable the transmission of modified signals in case of MF or specific messages in case of VHF (IALA Guideline 1158) beside the legacy service of that infrastructure.
- The R-Mode monitors, which are implemented as near-field or far-field, in the service areas of the transmitter sides. They monitor the performance and availability of the R-Mode service and generate supplementary information to increase the R-Mode service performance.
- A Command and Control centre, not yet implemented in the test beds.

Figure 57 – Ranging mode (Credit: R-Mode Baltic)

The R-Mode system can also support a small region like a port and act as a backup to the port approach. In this case, at least three transmitters must be implemented, and R-Mode service will be available in the common overlapping service area. To enlarge the R-Mode service area additional MF and VDE transmitters need to broadcast R-Mode. MF and VDES stations have different transmitter ranges and properties. A combination is ideal to benefit from it and to achieve a good geometry.

In general, an EU-wide or world-wide implementation should be aimed to support vessels, acting as backup, when they are in coastal areas during their voyage from berth to berth, excluding near shore. In this case, the cooperation of the R-Mode service providers of the different countries is necessary to enable the maritime user to use the signals of different providers at the same time.

A large-scale implementation would be beneficial for maritime users notably during critical voyage phases. To develop the full potential of R-Mode it would be is necessary to harmonise the R-Mode system and service from the different national maritime service providers to enable R-Mode support in areas between the countries. A framework of R-Mode standards and guidelines and an international R-Mode coordination group would be then necessary.

5.3.5.1 Main characteristics

Theoretical analysis, simulations and measurement campaigns indicate that depending on the distance, signal strength (or signal-to-noise ratio) and geometry of mobile user and transmitter sites, the system can offer **positioning accuracy** significantly **better than 100 m**, though it can't operate so efficient at night. Optimisations of the transmitted network would increase this performance but it is not clear whether 10 m accuracy can be achieved (note that the suggested horizontal positioning performance for a GNSS backup is 10 m for port approach and restricted waters and 100 m for coastal waters - IALA Recommendation R-129 on GNSS Vulnerability and Mitigation Measures.

Hence, R-Mode is designed for **coverage in coastal and restricted waters** where the highest risk for degradation of the GNSS signals due to intentional and unintentional interferences is expected. In contrast to GNSS, with global coverage, the R-Mode system cannot achieve global coverage due to the limited range of the MF and VHF signals. For MF-based R-Mode the problem of sky-wave interference, which degrades the system performance during the night, is unsolved so far. A challenge for VDES R-Mode is the channel load caused by the number of transmitters in an area. Further, the collocation between VDES R-Mode and existing AIS installations has to be solved.

5.3.5.2 Status and optimisation plans

The R-Mode system is in an **early stage of development of fundamental technology** and hardware on several permanent or temporary testbeds in Europe, North America, and Asia. Within the same framework, prototypes for R-Mode transmitter equipment were developed and are used in the R-Mode testbeds which have currently a TRL of 4-5. For the ship side, the activities are conducted with research platforms. The R-Mode receiver designs are developed but further activities are necessary to enable R-Mode-based positioning.

Like GNSS it can provide absolute position, although with reduced accuracy and spatial availability, limited to up to about **250 km from the coastline**. R-Mode is expected to act as a candidate for the desired terrestrial component described in the 'IMO Performance Standard for Multi-System Shipborne Radionavigation Receivers' (IMO MSC.401 as amended).

R-Mode is currently dependent on GNSS for synchronisation. To provide temporarily independence from GNSS, each R-Mode transmitter is equipped with an atomic clock which provides holdover for few hours. In the future, the timing source will be replaced by an GNSS independent solution for frequency and time transfer, e.g. optical fibre or R-Mode signals.

The **standardisation of R-Mode is ongoing**. With the recognition of requirements for R-Mode in the new VDES standard (ITU-R Recommendation ITU-R M.2092-1) and the IALA Guideline 1158 about VDES R-Mode first documents are available. Further work is being conducted at IALA regarding a guideline for the implementation of R-Mode using transmissions in the MF and VHF frequency bands. Furthermore, navigation messages are under development, which should become part of the RTCM data messages. According to an internationally agreed roadmap, it is expected that the standardisation will not be finished before 2027.

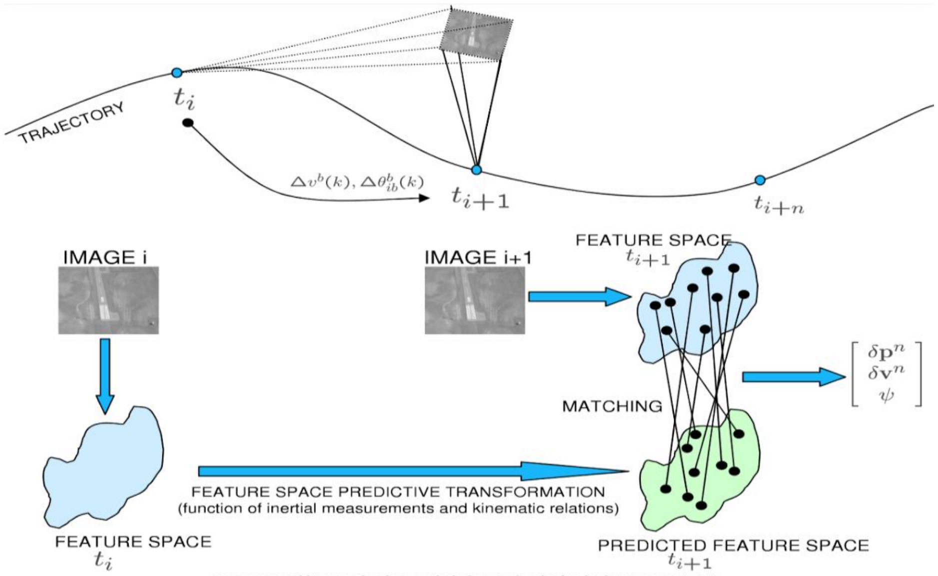
5.3.6 Visual navigation

Visual navigation (or image-based navigation) is becoming more and more prominent as hardware gets cheaper (mobile phone cameras cost less than EUR 1) and algorithms mature. This section will address both **image** and **LiDAR-based navigation**, as they are both very popular - prior in mobile devices and later in self-driving cars. While this technique works very well both **indoors and outdoors**, it does **not** provide any **timing information**, so it is expected to act as part of the sensor fusion, likely combined with GNSS and IMU.

5.3.6.1 Main characteristics

An image is a 2D projection of a 3D world, which means that unlike in the LiDAR case discussed later, depth information is missing. To solve for this missing dimension, the same point must be identified on multiple images (hence creating a moving baseline of a known length), as shown in Figure 58.

The identification and matching of the same features from image to image, disregarding light changes and camera dynamics is the biggest challenge for this navigation type. This can be a challenge for aviation. In the terrestrial and pedestrian scenario, the problem is simplified due to limited movement and rotation in the height axis and was demonstrated to provide reliable results. If a simple movement algorithm is used, we can de-facto use any well-lit feature or even repeated pattern. In the case of aviation, IMU information is essential.



Source: "Position, Navigation, and Timing Technologies in the 21st Century"
Morton, van Diggelen, Spilker, and Parkinson. IEEE-Wiley 2020

Figure 58 – Overview of image-aided sensor fusion with IMU (Credit: pnt21book.com)

LiDAR a method for determining distance to the object by measuring the time for the reflected light to return to the receiver. It is commonly used to create high-resolution models and maps. It **can** also **be used for navigation**, using one of two approaches:

- Featureless approach when the spatial distribution of measurements (point cloud) is used directly to compare with existing data. The algorithmic challenge here is the sub-selection of points for matching (identification of the overlay area). Selection is then used for the best match in the reference data and optimised (rotated) to minimise the cost function (fit error). The identification of the area to compare is critical to optimise the search. Initial known position and orientation are very useful.

- Feature-based approach when features are first identified and exacted from the data (point cloud). Navigation is then based on identifying them and using them for position estimation. Those features usually are much simpler features than descriptive man-made objects and tend to be points or simple geometric features. Once extracted the perceived movement between them and the scanner (user) can be used to estimate the movement, orientation, and position.

5.3.6.2 Status and optimisation plans

LiDAR-based navigation support mechanisation (integration) with odometer or IMU is possible. This is frequently used during Simultaneous localisation and mapping (SLAM) when collected data can be used to improve existing maps. LiDAR can be used for vehicle or pedestrian-based navigation. **Optical methods** have similar characteristics.

For both a recursive SLAM algorithm is very popular due to its speed and efficiency. The position is estimated as relative, yet if some of the features have known positions, object movement can also be mapped to the global reference frame. When the same location is re-visited (loop closed) the position accuracy can be estimated, and the previous estimation corrected if needed.

An alternate approach is the particle filter (PF) which uses a probabilistic approach to estimate the position, as the object is moving until the position can be provided with enough confidence.

There are several considerations for visual navigation:

- Large data volume is produced, hence firstly data is reduced, by identifying specific areas of interest, by sub-sampling. This also includes removing outages, such as moving vehicles or pedestrians. Secondly, most algorithms use iteration to arrive at the local minima.
- It is different to differentiate observation uncertainty in range and angle measurements. In the case of LiDAR, this depends on the angle and the surface reflected, for an image this is related to lenses and the light conditions.
- Integration with other sensors requires careful preparation including lever arm estimation and stability.

A space application of these principles is the star tracker and sun sensor. Both devices use **celestial navigation** to compare known views of the stairs using photocells or a camera. The method requires clear visibility of the stars, which is night sky for a terrestrial user, and is predominantly used by the space-borne platforms, offering both position and orientation when combined with IMU.

Technology is used in practically all space missions. Usually, a mission has both star and sun sensors. First, the latter is used for the coarse attitude determination, usually after spacecraft separation of the launcher. The star tracker is used for the fine attitude determination and IMU reading for the sensor fusion approach to obtain smooth orientation and position.

Sun sensor accuracy is 3 - 0.005 ° and star tracker of 0.01 - 0.0003 °. The sensor can be either tracker or scanner, suitable for rapidly rotating (spinning) spacecraft. The method requires pre-filtering to remove noise, such as stranded light or reflections, avoid being blinded by the sun or moon and require stabilisation of reading (for which IMU is used).

Due to the increased quality and decreased size of the components, the simplified technology is used for LEOs and investigated for the CubeSat missions. Apart from commercial offerings, an open source algorithm exist, used for the CubeSat platforms. Measurements are conducted in the celestial reference system, which would require transformation to GNSS ITRF or similar.

5.3.7 Mobile based navigation

Smartphone nowadays is the primary navigation source, replacing TomTom or Garmin's dedicated navigation devices, as well as the paper maps. In 2020 there was more than 4 billion GNSS enabled smartphones. Hence it is interesting that its GNSS capacity happen almost by accident. In 1999, the Federal Communications Commission (FCC) mandated positional requirement, as part of the E-911. The triangulation from the mobile tower network was not precise enough. Instead, a positioning using GPS chipset was suggested.

The **mobile phone is not intended as a GNSS/GPS receiver**. It has a simple inverted-F monopole, a linearly polarised antenna with low gain and noise suspension. It has low-quality clock and are prone to self-interference due to component placement. Why those are important? GNSS position is based on time difference between the satellite (so stable local oscillator is important) using very low power signal, frequently below the noise floor (hence good antennas are essential). By itself, **smartphones have low performance as GNSS receivers**.

Assisted GPS (A-GPS) eliminates those flaws by increasing sensitivity and the Time To First Fix (TTFF), with the assisted data reducing the frequency search space but not the delay space. This also changes the chipset architecture, which is based on massive parallel search capability. As the chipset main limiting factor is the chip memory size, to minimise all parallel hypotheses, the manufacturers are searching first on one GNSS constellation (typically GPS with short codes) and once acquired, the chipset will then do a fine-time narrow search for other GNSS longer codes. For Galileo, the chipset tracks the Galileo Data Component (E1B–OS-NMA) only at the beginning of the location request; once data is obtained, chipset starts tracking the pilot code. Technical details can be found in F. van Diggelen, A-GPS: Assisted GPS, GNSS, and SBAS. Artech House, 2009.

5.3.7.1 Main characteristics

GNSS capacity is provided by the A-GPS (A-GNSS) architecture. In addition, two recent advances are worth noting, both described from the Android perspective since the Apple approach is not well documented.

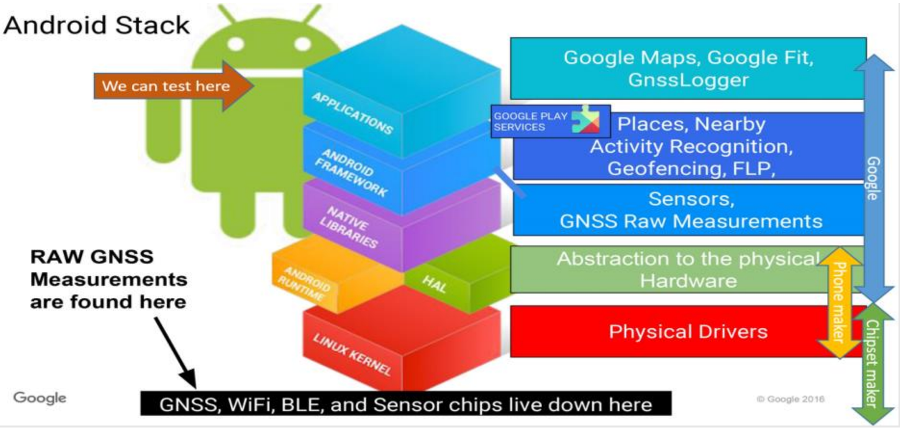


Figure 59 – Overview of the Android stakeholders' control of the stack, adopted after Google (Credit: Google)

Android Google Play services

The modern phone is a very complex ecosystem that contains multiple sensors, including inertial, WiFi and Bluetooth, and is run by the operating system. This is utilised by Android via Google Play services' Location Application Programming Interface (API) encapsulation. It does everything from geofencing and detecting activities to identifying places near you. Its most important element is the Fused

Location Provider (FLP) which provides a smart location and battery saving. This offers the possibility to navigate indoors using the strength of the nearest WiFi access point (AP) and indoor maps to fingerprint (identify) your location. Combined with machine learning this is used by the Android Emergency Location Service (ELS). This service activates when an emergency call is placed and provides precise location to the emergency services, including elevation and correct floor. This service requires separate arrangements with phone operators and is enabled in some EU countries.

The RAW measurements

Since 2016 Android Location API provides direct access to the GNSS chipset (bypassing a few layers of the stack). Those **GNSS observations** are **known as RAW measurements**. The A-GPS-based phone's chipset acquires the observations before the time is precisely synchronised, leading to observations in a more raw format than those of the typical GNSS receivers.

Access to the RAW measurements opens the door to more advanced GNSS processing techniques that, until now, have been restricted to more professional GNSS receivers. New signals (E1/L1 and E5/L5 frequencies), differential observations and other advanced algorithms can be used. These underpin applications such as assured time, atmospheric monitoring, or interference detection.

Despite the **mobile phone** having **several limitations** such as not handling properly dynamics or multipath well, it can utilise **more advanced algorithms**, for example, differential solutions. A presentation during the EUSPA Raw Measurements Taskforce showed the post-processing results of data collected during slowly walking over the GOOGLE letters. Left to right, we see the simple RAW measurements algorithm, then a Kalman filter algorithm using pseudo ranges, this is similar to FLP. The last image shows the improvement with using the carrier phase, something that is not possible for FLP. It is worth noting that, at the current stage, it is difficult to outperform the FLP unless in an open environment.

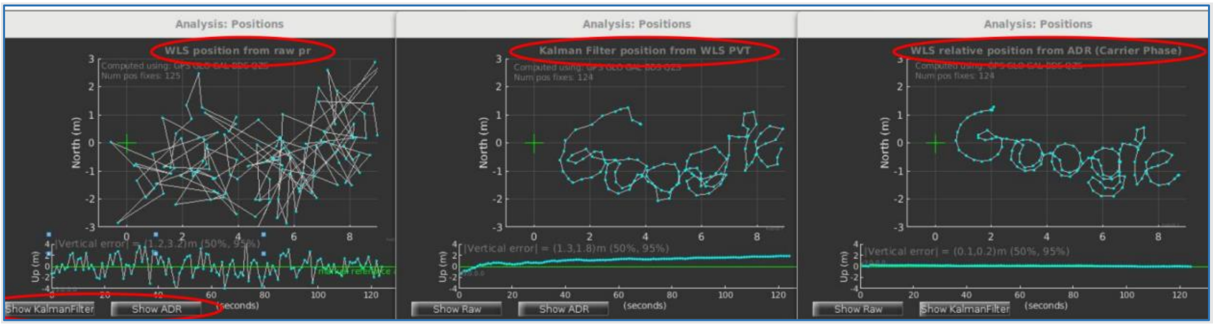


Figure 60 – Improving position using RAW measurements (Credit: Frank van Diggelen)

More details in the EUSPA White Paper on using GNSS Raw Measurements on Android devices.

5.3.7.2 Status and optimisation plans

A new algorithm proposed by Google and intended for pedestrian use aims to combat the multipath problem. It first estimates the user location; ideally identifying the street's side the user is on, based on the buildings' photo-realistic models. Then, it provides this information back to the chipset to improve the GNSS position directly. Data models cover all the European cities and most of the world. The algorithm is focused on Google's Pixel series (starting with the 5G version of model 5) with a planned roll-out to other Android handsets.

The API layer now communicates directly with the GNSS chipset by providing corrections and the Android stack is now a two-way communication channel. In short, **a mobile phone can be used as a modern GNSS receiver**.

5.3.8 IMU Dead-reckoning

Dead reckoning is the process of calculating position of a moving object by having a determined position and then incorporating estimates of speed, heading direction, and course elapsed time. While several technologies utilising this estimation exist, we will focus on the inertial systems, common in aviation and transport.

An **inertial measurement unit (IMU)** is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body. IMUs consist of three gyros and three accelerometers and usually includes magnetometers and determine three axis orientation of the moving body. To determine absolute position with respect to the reference frame the starting position, velocity and orientation of the body should be known. If the gyro accuracy is well below earth rotation (15 °/h) the attitude can be estimated based on gravity and earth rotation.

The cost of the hardware varies, depending on the quality of the components, as seen in Table 17. A low-cost microelectromechanical system (MEMS) used in mobile devices usually cannot be used on its own and requires sensor fusion - those tend to be GNSS, Bluetooth and WiFi – while the ring laser gyro (measuring light frequency difference in two directions) is the most performing and costly.

Table 17 – Overview of dead-reckoning systems

Type	Ring Laser Gyros	Fiber optic gyros	MEMS	Low-cost MEMS
Cost [euro]	100 000	20 000	< 2 000	< 1 000
Gyro drift	0.003 °/h	1 °/h	360 °/h	3 600 °/h
1 m drift	~ 2 min	~ 30 s	~ 5 s	< 5 s

Note that the values reported in the table follow the constant speed dynamics.

5.3.8.1 Main characteristics

Inertial navigation works by **integrating sensor measurements** over time in a process known as drift. The high-end units can determine earth rotation and work independently yet most commonly those are used in combination with GNSS receivers.

As errors grow with time, the ideal approach is the combination of the IMU sensor measurements with GNSS position fixes in a Kalman Filter which steers the body position towards the good quality GNSS position fixes while having a high update rate in between. An example is the Inertial Navigation System (INS) which obtain the body's position, orientation, and velocity without the need for external references. This system can bridge short GNSS outages, aid RTK ambiguity resolution and assist with cycle slip detection and mitigation. In case of tightly coupled solution this also means that position can be obtained with less than three visible satellites.

Technical details about the IMU, mechanisation and sensor fusion can be also found in Principles of GNSS, inertial, and multisensor integrated navigation systems, P. Groves, Artech House, 2013.

5.3.8.2 Status and optimisation plans

With the first usable IMU produced in the 1950s and the technology matured around '80s, the development has since focused on miniaturisation and development of IMS - loosely, tightly and coupled as well as Kalman Filter. **IMUs are now widespread, with low-cost IMUs powering mobiles.** The current development is to decrease size, cost and increase performance using new materials. The Quantum section describes the development of a new very promising hardware approach.

5.3.9 Magnetic navigation

The usage of magnetic maps for navigation dates to the missile navigation in the 1960s where **changes in terrain were used to identify user position**, by comparing the continuous readings with the recorded morphological map. To be useful for navigation, those observations need to be stable over time and provide enough difference to distinguish one area from the other.

5.3.9.1 Main characteristics

Magnetic navigation is one of the oldest forms of navigation. The earth's magnetic core was used to determine north and maintain constant azimuth. The modern approach focuses on anomalies instead, as those are stable over time. The magnetic reading is the superposition of all magnetic sources, that is Earth's core, Earth's crustal field and man-made and space weather effects.

The **Earth's core** (95 - 99% of the whole magnetic force), while well described by existing models and measurable from space, has large spatial wavelengths and a time-varying nature, which makes it not suitable for map-based navigation. The **Earth's Crustal Magnetic Field** (1 - 5% of the total magnetic effect) is very stable and shows local differences. This magnetic field differs across the globe and extends under the oceans, covering the whole Earth's surface. **Man-made effects** can be split into static and time-varying. Only the first is useful for navigation, and many long man-made features can be useful for determining location. In this context **space, weather effects** introduce the equivalent of the measurement noise.

Magnetic anomalies (i.e., local variation in the Earth's magnetic field) are difficult to measure. In addition, magnetic measurements need to be propagated upwards for higher altitudes as the power of the magnetic field follows inverse square law.

Magnetic force is measured by two types of **instruments**. The scalar one is measuring field intensity and the vector one, such as fluxgate magnetometers, is measuring three orthogonal components. While the latter is less accurate it can remove common errors (due to man or space-borne effects) and provide additional spatial information. Unfortunately, gradient maps are less common than anomaly ones.

As maps are not exact, the position is the probabilistic estimation (the likelihood function), which require initial a-priori information. With this approach a single static position creates multiple possible positions. When user moves, the estimation is updated using the particle filter (PF) to converge, with time, to a single correct position.

5.3.9.2 Status and optimisation plans

Practical results for magnetic navigation indicate that while **indoor accuracy is below metre** and can be even dm level, **outdoor performance** varies from **metres to hundreds of metres**, which then requires a fusion with other sensors. Similarly, flight demonstration using magnetic reading and IMU was shown to be efficient being the main limitation the flight elevation (few to ten metres of accuracy below 1 km altitude, yet at an altitude of 10 km accuracy degrades to hundreds of metres). Precise accurate maps of anomalies at or below the flight altitude are essential.

Magnetic technology is **rapidly maturing**. Commercial companies offer location and navigation services, limited to specific areas, by utilising magnetic data with other sensors (WiFi and Bluetooth and pre-mapped locations). Other companies propose it for rail applications to determine track and current train location while other uses include maritime with a Radar Absolute Positioning which uses the features extracted from radar reading, matched to radar charts to identify user position. All **these technologies require sensor fusion**.

5.3.10 Low Earth Orbit (LEO)

Low Earth Orbit (LEO) systems are constituted of hundreds or possibly thousands of satellites transmitting from an operational altitude between 400 and 1 500 km (avoiding atmospheric drag and solar effects). Until recently, this altitude was predominantly used by Earth Observation (EO) and communication satellites (SatCom) with a constellation not exceeding 100 satellites. LEO orbit offers **low latency** and **high received signal strength** (30dB larger than from MEO orbit) at a low transmission power. Those characteristics make it interesting to mega-constellations aiming to provide wideband internet. The broadband providers aim to utilise high-frequency Ku-band, which should be able to offer data speed up to 8 - 20 Gbps.

Such close orbital positioning to the earth's surface **also has disadvantages**, as the typical satellite footprint (which is the ground area that can be covered by the transmitting antennas) is much smaller (9 LEOs are required to cover the footprint of one MEO). Also, the satellite's relative speed to the ground is much higher. LEO's orbital period is around 100 minutes compared with MEO's of around 12 hours. This means that full earth coverage requires much larger constellations.

The table below is a non-exhaustive selection of LEO services. Given the relatively modest ITU filling cost and the priority advantage (over filings registered later), there is a tendency to file systems even if their operational plans are not yet fully developed so the list below is based on the perceived closeness of constellations to the market and communication mega-constellations. One significant omission from this table is the EO satellites.

Table 18 – Overview of LEO constellations

System	Number of satellites	Satellites in service (Aug 2022)	Altitude [km]
Iridium	66	66	780
Kuiper	3 236	0	590-630
Starlink	4 409	2 268	540-570
OneWeb	4 000	354	1 200
Kepler	6 LEO + 24 MEO	0	7 600 + 29 600
Centispace	120	2	975
XonaSpace	300	1	975

Please note that the values in the table are subject to rapid change.

5.3.10.1 Main characteristics

LEOs constellations provide multiple services including secure communication and broadband connectivity for smart devices and connected vehicles. They do **not include a dedicated navigation payload (except Iridium)** and hence today they can only provide augmentation data to GNSS signals or their signals can be used indirectly for navigation using the Signal of Opportunity (SoO) approach and the doppler navigation.

Currently the only available means of providing position and navigation from a LEO constellation is using **Doppler navigation** whose main weakness is the orbit detection and time synchronisation of fixes (which is partially offset by the calculation method). The increased numbers of LEO satellites can improve positional accuracy (using the SoO Doppler approach) but not the time provision.

Iridium provides a dedicated navigation signal which also provides time synchronisation. In 2016, Satelles Time and Location (STL) was formed as a consortium formed by Iridium, Satelles Inc and Boeing to provide global navigation services. The system infrastructure is mostly space segment with ground segment limited to a single control station (with hot backup active within 10 minutes) located in the US and several passive ground monitoring stations. STL signals-in-space are broadcast on the L1 (1616 – 1626 MH) frequency.

Iridium is designed for just one satellite in the user's view. Each of the 66 Iridium satellites has 48 spot beams. To provide secure and anti-spoofing capabilities, each beam transmits the navigation message with an individual code, which changes every second. Since there is full control over the STL beams, the navigation message can be limited to specific areas (which prevents signal to be received in the areas of no subscribers). The complex, overlapping beam patterns of the satellites combined with signal authentication techniques allow STL to deliver a **trusted time** (synchronised to UTC) **and location capability secure and independent from GNSS**.

STL signals are received on Earth's surface around 1 000 times (30 dB) stronger than GNSS, which allow for **indoor** reception. The satellites do not carry atomic clocks on board. Instead, they are constantly calibrated using a ground station and the inter-satellite capabilities of the Iridium constellation. Subscribers need to pay a service fee.

5.3.10.2 Status and optimisation plans

Only **STL** is a deployed and mature technology for PNT. It can provide reliable time provision, with an accuracy of 100 - 150 nsec, fixed to UTC(k). The **position** is more difficult to obtain, and the current solution is to use the Doppler effect which provides accuracy around 10 m for static users. Once a fix is obtained (which requires up to 20 minutes of convergence if starting at unknown position), the position can be obtained even with a single satellite, but as much reduced accuracy, up to tens of metres. STL can also include assistance data in real-time for satellite clocks, orbits, and message payloads. The rapid geometry changes are expected to improve the multipath mitigation, as its effect over a few minutes will average out.

To overcome the main limitations of using LEO for full PNT (as opposed to time-only provision), namely for orbit determination and time synchronisation, the use of GNSS receivers on board is desirable to estimate both the position and time of the transmission (but then the service is no longer independent from GNSS). This approach, known as the **fused LEO PNT**, is the focus of the **Xona Space** whose Pulsar PNT service claims metre-level accuracy. The first satellite was launched as part of SpaceX's rideshare mission in 2022 and the service is expected operational in late 2023. The actual performance is not yet known.

Kepler is a concept for a fully tailored PNT system using a mix of LEO and MEO satellites. As such, this is completely different from other LEO systems discussed before, as this is a PNT-tailored system instead of a partial optimisation/reuse of an LEO infrastructure designed originally for a different scope, e.g., communication or broadband internet access. Kepler establishes the synchronisation by direct measurements with optical links and can operate entirely independently or in cooperation with Galileo.

Finally, an alternative option is to perform Doppler ranging for any signal transmitted by LEO satellites **or** use those signals as Signals of Opportunity. Both approaches are independent of the system owner, as anyone can use those observations. However, there are limitations since Doppler depends on a large number of visible satellites while SoO on the dedicated ground segment (base station).

5.3.11 Quantum Technologies

Among the new and emerging technologies which can provide substantial advantages to PNT applications, those leveraging **quantum physics effects are particularly promising**. In most cases, however, several years of development are still required for novel quantum technologies to really have the expected impact on PNT applications.

5.3.11.1 Quantum Clocks

5.3.11.1.1 Main characteristics

Continuous progress on atomic clocks is expected to greatly benefit satellite-based positioning systems:

- For the **ground infrastructure**, clocks based on cold atom interferometry can be taken into consideration to substitute the existing ensembles of Caesium clocks and active hydrogen masers which are universally employed to generate the system time. Although cold-atom clocks have reached a rather mature development stage and some commercial products are starting to become available, their use is still largely limited to the scientific community.
- For the **space infrastructure**, better clocks in satellites will improve the signal-in-space user-range-error, but constraints linked to their use in space are presently restricting the possible candidates to ion-based clocks, pulsed optically-pumped clocks, and in the longer term optical atomic clocks based on nonlinear effects such as two-photon absorption and modulation transfer spectroscopy.

Laboratory-scale optical atomic clocks are already in use and will undoubtedly contribute to the implementation of a metrological timescale: although GNSS systems do not need an autonomous realisation of such a time scale, they will likely take advantage of it via time transfer protocols based on carrier-phase two-way satellite time and frequency transfer or coherent optical links in free-space or via optical fiber.

Figure 61 – A commercial cold-atom clock (left) and a prototype of an optical frequency standard based on two-photon transition in Rb (right). Note that in the latter the frequency comb necessary to translate the optical stabilised frequency into a microwave signal is not included [Strangfeld 2021]

5.3.11.1.2 Status and optimisation plans

In the longer term, **novel GNSS architectures may emerge for optical-scale time generation and distribution** to fully take advantage of the stability properties of optical atomic clocks interconnected via optical inter-satellite and ground-to-satellite links.

To give an example, **a future system could be entirely based on space-based infrastructure**, with no need of world-wide distributed sensor or upload stations, which are necessary for present-day GNSS. The space-based infrastructure could include MEO and LEO satellites, equipped respectively with cavity-stabilised lasers and optical atomic clocks, suitably interconnected with optical links to provide ps-level global synchronisation and µm-level accuracy range measurements. In principle, the only ground infrastructure needed is a receiving optical station to keep the system time aligned with the universal coordinated time UTC. The **Kepler** project shows how optical atomic clocks can enable future GNSS architectures with a ~**100-fold improvement in the signal-in-space**.

However, it should be considered that because of ionosphere, troposphere, and multi-path-interference disturbances, a better SIS does not immediately translate in better positioning accuracy for the final user. Complementary techniques such as precise point positioning or real time kinematics must be substantially upgraded if optical-scale GNSS time generation and distribution is to effectively benefit the final users. In addition, a very complex miniaturisation process will be required for optical atomic clocks to reach the chip-scale dimensions and battery-compatible power requirements if they were to be used in high-end man-portable equipment.

5.3.11.2 Quantum Inertial Navigation Systems

5.3.11.2.1 Main characteristics

Quantum physics principles are being exploited also for navigation, with the rationale that harnessing fundamentally **inalterable atomic properties will improve the drift performance of inertial measurement units**. Research has focussed on:

- **Nuclear Magnetic Resonance (NMR)** gyros exploiting nuclear spin and first developed in the 60s', but the competition from ring laser gyros and fiber optics gyros hindered their commercial appeal. Only recently, new devices have been disclosed which exploit miniaturisation technologies for compact navigation grade systems at a competitive cost.
- **Spin-Exchange Relaxation Free (SERF)** gyros, much less investigated, based on the electronic spin of alkali metals (first proposed in 2005) and those leveraging the spin of nitrogen-vacancies in diamonds (in the last decade), both still mainly the object of academic research.
- **Cold Atom Interference (CAI)** gyros, today the most promising systems for autonomous navigation, exploit the fundamental stability of atomic mass to guarantee immunity from drifts, thus eliminating any need for periodic recalibrations. In addition, CAI-based systems measure absolute values of acceleration and rotation rate and not variations with respect to reference values. These advantages come at the cost of high cost, size, weight, and power footprint, since complex enabling technologies are required (vacuum systems, lasers and optical systems, control electronics, etc.), whose progress constitutes a key factor for the development of field-deployable CAI-based inertial sensors.

Table 19 provides a comparison among these quantum gyroscopes and with the conventional ones MEMS and ESG. **Micro Electro-Mechanical Systems (MEMS)** gyros are widely applied in consumer applications but are unlikely to reach the drift requirements needed for autonomous navigation. The performance of mechanical floated gyroscopes and of optical gyroscopes is approaching the limit determined by the underlying physical principles, and any improvement will involve a high extra cost. The **Electrically Suspended Gyroscopes (ESG)** are also considered consist of a two-degree-of-freedom gyro where the spinning rotor ball is supported in a vacuum by an electric field. Atomic gyroscopes (NMR, SERF, and CAI) are projected to become competitive with conventional navigation-grade for the next-generation inertial navigation systems.

Table 19 – Comparisons of gyroscopes based on different physical principles [data taken from Zhang 2016]

Grade	Type	Drift (°/h)	Size (mm^3)	Cost (USD)
Tactical	MEMS	1 000 – 0.1	< 100	< 100
Navigation	NMR	10^{-2}	$10 - 10^{4}$	$10^{3} - 10^{4}$
	Ring Laser	$10^{-2} – 10^{-3}$	~ 10^{5}	$10^{4} - 10^{5}$
	Fiber Optics	$10^{-2} – 10^{-3}$	$10^{5} - 10^{6}$	$10^{4} - 10^{5}$
Strategic	Mechanical floated	$10^{-3} – 10^{-4}$	$10^{6} - 10^{7}$	$10^{5} - 10^{6}$
	ESG	$10^{-4} – 10^{-5}$	$10^{7} - 10^{8}$	$10^{6} - 10^{7}$
	SERF	~ 10^{-4}	$10^{6} - 10^{7}$	< 10^{5}
	CAI	> 10^{-5}	~ 10^{9}	$10^{5} - 10^{6}$

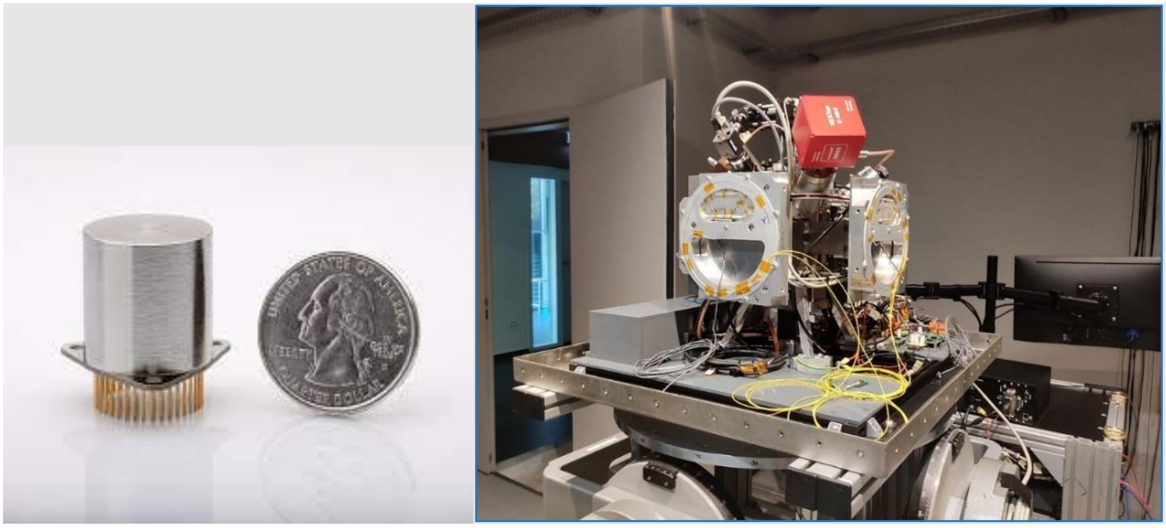


Figure 62 – NMR gyro for tactical applications prototype by Northrop Grumman (left) and a laboratory-based IMU based on the hybridisation of fiber optics gyroscopes and CAI accelerometers developed by IXblue (right)

5.3.11.2.2 Status and optimisation plans

The **path towards a portable CAI-based six-axis IMU** fast, robust, and compact enough to be employed **for inertial navigation** requires negotiating several trade-offs and overcoming several technological challenges, which are likely to call for **several years of sustained efforts**. To take effective advantage from absence of drift embedded in its working principle, reliable and robust technologies able to support long term autonomous operation in harsh environments must be developed and implemented.

Also, it should be noted that a CAI-based IMU unavoidably present dead-time intervals during which atom cooling takes place and will therefore need to operate in a hybrid fashion comprehending also classical devices. An alternative approach could be the use of CAI systems to provide plug-in calibration to fast and sensitive accelerometer and gyroscopes based on other working principles.

Single-axis cold-atom gravimeters used to measure slowly varying gravitational fields along a single axis are already commercially available (TRL=9, i.e., actual system proven in operational environment), while several prototypes of CAI-based accelerometers and gyroscopes have been developed, demonstrating a TRL between 3 (experimental proof of concept) and 4 (technology validated in lab).

As a final note, it should be reminded that atomic sensors to be used for inertial navigation are likely to be considered dual-use items and subject to ITAR export restrictions, as already happens for the high-performance systems based on optical or mechanical effects.

5.3.11.3 References

The reader interested in a deeper analysis is referred to the following references:

- G. Giorgi et al., *Advanced technologies for satellite navigation and geodesy*, Advances in Space Research 64, 2019.
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- M.J. Wright et al., *Cold Atom Inertial Sensors for Navigation Applications*, Frontiers in Physics, submitted on 14 July 2022.

5.3.12 Pulsars' PNT

A Pulsar (from **pulsa**ting **r**adio source) is a highly magnetised and fast rotating **neutron star**, that emits beams of electromagnetic radiation out of its magnetic poles. The electromagnetic radiation can be observed only when a cone of emission is pointing toward Earth. As Neutron stars are very compact objects with short, regular rotational periods, **the interval between pulses is very precise** and ranges from milliseconds to seconds for an individual pulsar. The electromagnetic signal (in particular in the radio, optical and X bands) emitted by the pulsars can be detected by the specialised equipment and each pulsar can be identified based on the light curve reconstructed from the emitted signal. Hence pulsars are not only the source of precise timing but can also be used for navigation on a galactic scale. This idea was first proposed in '74 by G.S. Downs.

5.3.12.1 Main characteristics

Pulsars were firstly considered for the **time provision** (millisecond pulsars offer time stability comparable with the atomic clocks). This idea already has a practical implementation, with the first terrestrial pulsar clock installed in Gdansk, Poland in 2011 to commemorate 400 anniversary of Johannes Hevelius' birth. Since then, several other devices were installed, practically testing the concept of the Pulsar Time Scale, intended as a combination of long-term pulsar observations with the ultra-stable local clocks. Indeed, even the simple combination of an atomic clock and corrections computed from Pulsars observation generate very stable time scale independent from other inputs.

While not every pulsar can be used for precise timing, mostly due to frequency, they are all very stable (some have been monitored since the '70s). Interestingly sources that are less bright are more stable. Each pulsar has a unique transmission profile, in particular the repetition period of the pulses, allowing to identify it. This led to their consideration for navigation, firstly by G.S. Downs.

The main argument was that they are visible from anywhere within the galaxy, and several pulsars (that can be distinguished based on their frequency, much like lighthouses) can form a set of beacons, whose pointing direction is known.

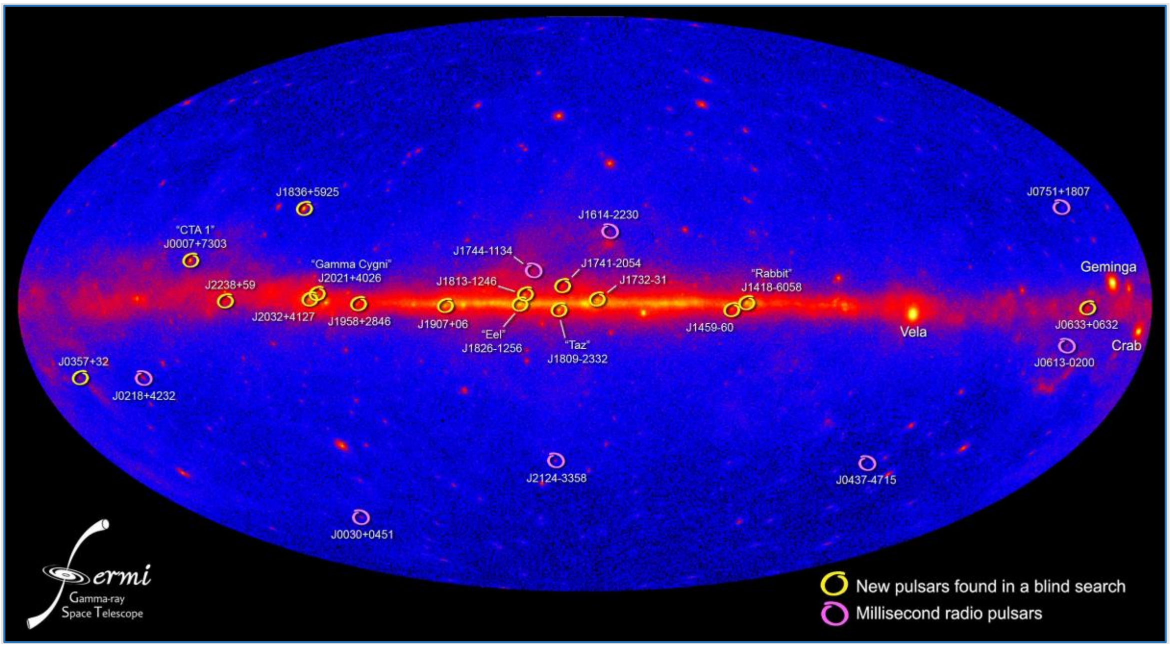


Figure 63 – Known pulsars, plotted along the Galactic Longitude and Latitude (Credit: NASA public domain)

Since then, multiple space missions have observed and identified thousands of X-ray sources, with several of them actively monitored. In addition, other space radio signals were identified such as Gamma-Ray Bursts (GRB) which are recommended for the position and velocity with Bright X-ray sources and Fast Radio bursts (FRB) recommended for relative navigation. Radio band pulsars are also used actively for studies on gravitational waves.

5.3.12.2 Status and optimisation plans

Most of the relevant research output is from NASA and ESA, developing capacity and algorithms. Two **navigation methods** for spacecrafts are proposed:

- Absolute navigation involves just one satellite trying to position itself with regards to an inertial reference point, such as the Solar System Barycentre (SSB). This would require a sporadic connection between the satellite and the ground control for updating the pulsar ephemeris that might occasionally change because of pulsar glitches (time span of years) or other timing irregularities.
- Relative navigation involves multiple spacecraft observing the same sources using only observations on the involved spacecraft Differential observations between two spacecraft flying in formation, with a known distance, were also proposed.

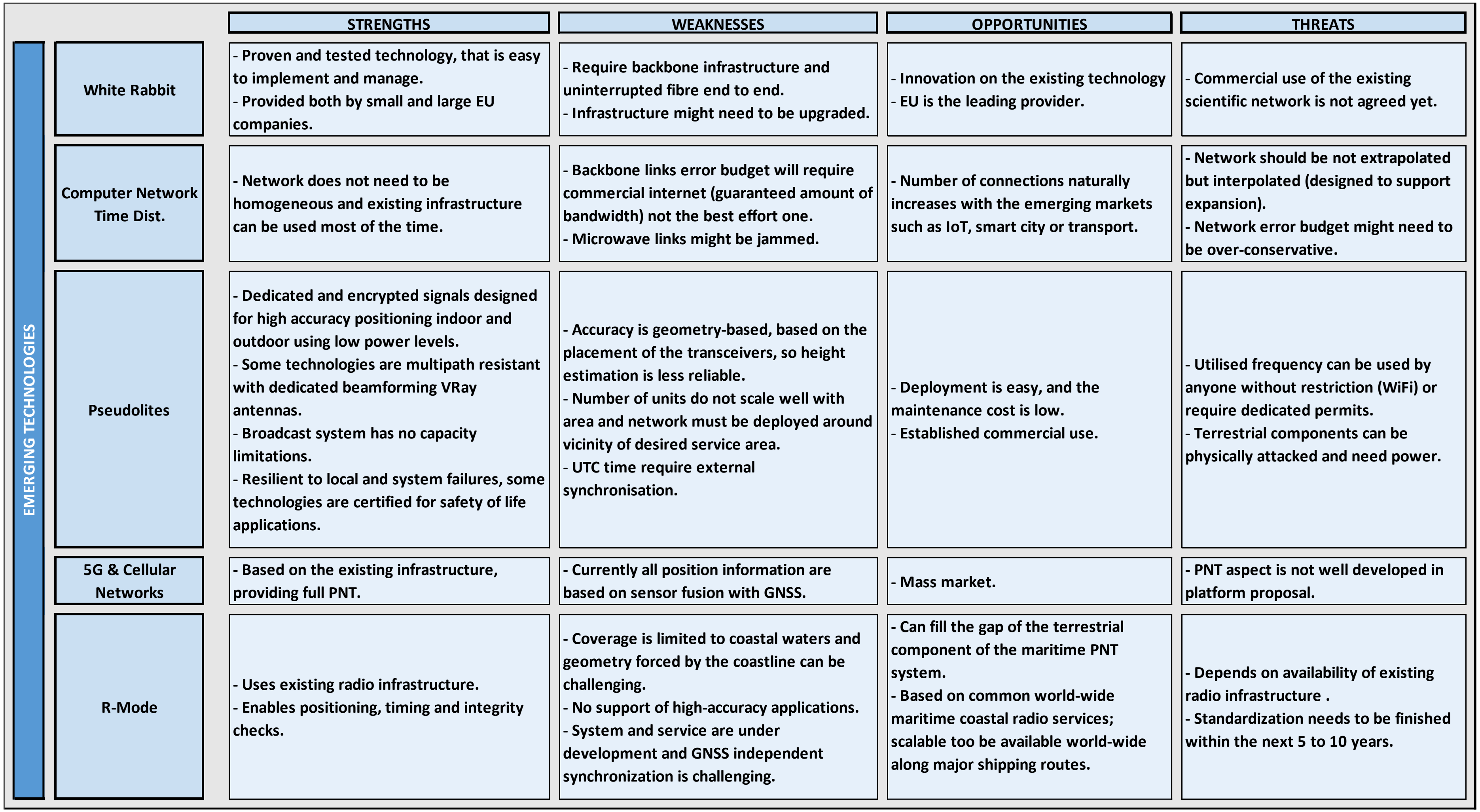
The **main interest of pulsars' navigation is for deep space systems** and interplanetary travel. Most of the existing space navigation systems operate using telemetry and X-ray pulsar-based navigation and timing (XNAV) could significantly reduce the cost and offer flexibility due to increased accuracy. The most appealing aspect is the wide availability of the signals and lack of maintenance (navigation only requires infrequent ephemeris updates of each identified pulsar). X-ray sensors are very resistant to noise in other frequencies, which is very useful for in-space applications. Only pulsars transmitting in those frequencies are considered for navigation, even though other frequency ranges are under study.

A 2004 ESA study found that observation of a single pulsar, estimating distance, requires a moderate antenna size (10 m^2) and signal integration time of about an hour. It also concluded that X-ray pulsar-based navigation and timing (XNAV) could offer 1 000 km accuracy for space missions. As the full system would require multiple antennas for synchronous multi-pulsar observations the total weight of the system was deemed too heavy for the spacecraft.

Since then, several hardware tests and demonstrations were completed. In 2016, China launched X-Ray Pulsar Navigation (XPNAV-1) experimental demonstration mission that demonstrated µsec-level timing resolution and measurement to a single pulsar. The hardware is still to be miniaturised and the signal processing calculations are still computationally intensive. A recent ESA study, with University of Padova, calculated accuracy increases down to a sub-km also reducing the payload size, weight, and power (SWAP, estimated to be 10 kg mass on 30x30x30 cm volume and 10 W power consumption).

Other ESA studies for interplanetary navigation are under way, reducing the number of antennas to one at the expense of more complicated spacecraft operations to acquire sequentially the Pulsar signals. Researchers also forecast that Pulsar measurements in the RF range could be used in the future for navigation on Earth, especially for certain use cases where the size of antenna might not be a problem. Further details can be found at *Use of pulsars for ship navigation: an alternative to the sextant*.

5.4 Summary of Strengths, Weaknesses, Opportunities and Threats



		STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
EMERGING TECHNOLOGIES	White Rabbit	- Proven and tested technology, that is easy to implement and manage. - Provided both by small and large EU companies.	- Require backbone infrastructure and uninterrupted fibre end to end. - Infrastructure might need to be upgraded.	- Innovation on the existing technology - EU is the leading provider.	- Commercial use of the existing scientific network is not agreed yet.
	Computer Network Time Dist.	- Network does not need to be homogeneous and existing infrastructure can be used most of the time.	- Backbone links error budget will require commercial internet (guaranteed amount of bandwidth) not the best effort one. - Microwave links might be jammed.	- Number of connections naturally increases with the emerging markets such as IoT, smart city or transport.	- Network should be not extrapolated but interpolated (designed to support expansion). - Network error budget might need to be over-conservative.
	Pseudolites	- Dedicated and encrypted signals designed for high accuracy positioning indoor and outdoor using low power levels. - Some technologies are multipath resistant with dedicated beamforming VRay antennas. - Broadcast system has no capacity limitations. - Resilient to local and system failures, some technologies are certified for safety of life applications.	- Accuracy is geometry-based, based on the placement of the transceivers, so height estimation is less reliable. - Number of units do not scale well with area and network must be deployed around vicinity of desired service area. - UTC time require external synchronisation.	- Deployment is easy, and the maintenance cost is low. - Established commercial use.	- Utilised frequency can be used by anyone without restriction (WiFi) or require dedicated permits. - Terrestrial components can be physically attacked and need power.
	5G & Cellular Networks	- Based on the existing infrastructure, providing full PNT.	- Currently all position information are based on sensor fusion with GNSS.	- Mass market.	- PNT aspect is not well developed in platform proposal.
	R-Mode	- Uses existing radio infrastructure. - Enables positioning, timing and integrity checks.	- Coverage is limited to coastal waters and geometry forced by the coastline can be challenging. - No support of high-accuracy applications. - System and service are under development and GNSS independent synchronization is challenging.	- Can fill the gap of the terrestrial component of the maritime PNT system. - Based on common world-wide maritime coastal radio services; scalable too be available world-wide along major shipping routes.	- Depends on availability of existing radio infrastructure . - Standardization needs to be finished within the next 5 to 10 years.

Figure 64 – Summary of Strengths, Weaknesses, Opportunities and Threats for the Emerging Technologies

		STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
EMERGING TECHNOLOGIES (cont.)	Image based navigation	- Tested Technology.	- Dedicated hardware calibration required.	- Very promissing in sensor fusion.	- Current solutions are market specfic.
	Mobile based Navigation	- It is ubiquitous service already available en the mobile devices.	- Performance is not homogeneous and depends on the handset. - Technology is developed by different company than handset manufacturer.	- It is mass market and was tested in various commercial conditions.	- It is developed by commercial company (Google, Apple) as value-added offering.
	Dead-reckoning & IMU	- Passive world wide navigation, all attitude and all weather. - Reliable and easy to operate with fast reaction.	- Mechanical noise and error increase exponentially. - Lower cost solutions dependent on availability and quality of the additional information.	- Some of the applications can be addressed by low cost hardware. - Immune to spoofing. - Cost related to the unit performance.	- Cost of high end units. - GNSS required in sensor fusion for global position.
	Environmental maps	- Does not require infrastructure.	- Quality of underlying maps. - Some technologies require sky visibility.	- Difficult to spoof. - Off-The-Shelf hardware.	- Quality of underlying maps is not coherent. - Simultaneous localization and mapping (SLAM) is not efficient in updating data/users do not want to share data.
	Low Earth Orbit (LEO)	- Does not require infrastructure. - Signal 30dB higher than MEO, time delay is comparable with terrestrial infrastructure.	- Large number of satellites needed and large Doppler of constellation. - Apart from Iridium no dedicated PNT signal is used.	- Quick roll-out of updates as satellites have limited lifespan for new LEOs. - With so many signals further Signal of Opportunity (SoO) approaches might be developed.	- PNT service might be too expensive to deploy on top of communication service. - Proposed number of satellites might create problem in the future. - Orbit estimations are not precise enough.
	Quantum Technologies	- Based on fundamental inalterable physical properties.	- Complex enabling technologies are required.	- Improvement in a wide range of performances.	- High cost, acceptance by final users.
	Pulsars' PNT	- Can be used everywhere in the space and only require periodically updated almanacs.	- Require precise holdover clock and precise aligned antennas for each tracked pulsar (each direction).	- Full PNT for the space missions. - Time for Earth operations.	- Hardware cost and size. - Demonstration tests not conducted.

Figure 65 – (Cont.) Summary of Strengths, Weaknesses, Opportunities and Threats for the Emerging Technologies

6 APPENDIX B: Resilient PNT services

As it is shown in the section 4, Position, Navigation and Timing (PNT) services are vital for the EU society and economy, enabling precise timing and location information for critical Infrastructure, the professional and mass market as well as safety of life and liability critical applications.

Disruptions or failures in PNT services can have severe consequences, including financial losses and safety risks, stressing the importance of having resilient PNT services. Inaccurate timing information can cause disruptions in power grids, financial markets, and communication networks; similarly, incorrect location information can lead to accidents in transportation and logistics systems.

Considering that the protection level should vary depending on the criticality of the application, **resilient PNT** requires detection of threats, appropriate response mechanisms and rapid service recovery. It necessitates the development of new hardware (e.g., antennas), software (new algorithms), and alternative systems.

The EU vision advocates for a System of PNT systems to achieve resilient PNT requiring several elements:

- **Redundancy**: PNT services should have redundant systems and backup mechanisms to ensure continuity in the event of failures or disruptions.
- **Diversity**: PNT services should use multiple sources of data and signals to increase reliability.
- **Monitoring, testing and maintenance**: Regular monitoring, testing and maintenance of PNT systems are crucial to detect, identify and address any issues before they lead to a failure.
- **Security/Cybersecurity**: PNT systems should be designed with robust security/cybersecurity measures to protect against deliberate attacks and ensure the integrity of the information.
- **Common position and time reference frame:** to prevent the accumulation of errors when combining PNT services, since individual PNT services provide time and position in potentially different reference frames and timing systems.
- **Standards and regulations**: PNT standardization and regulation can help to ensure that they are designed, deployed, and operated to meet specific performance and reliability requirements, such as:
    - Standards / guidelines **to assess the performance of PNT services**, including test cases and test procedures.
    - Standards / guidelines with **minimum performance requirements** for application domains (e.g., aviation, maritime, timing applications, etc.).
    - Standards / guidelines (testing and minimum performance) for **interference and spoofing detection and mitigation techniques.**
- **Education and awareness** of users and designers about the importance of PNT services together with their potential risks and threats.

By considering all the elements described above, PNT services will become more resilient and their users will mitigate the risks of disruptions and failures and guarantee the continuity of their operations.

7 APPENDIX C: Regulations and Standards

The following table summarises the list of activities identified in section 3.4 to facilitate the uptake of EGNSS in the different market segments:

Table 20 –Summary of activities to uptake EGNSS (mainly Regulations & Standards)

Market Segment	System	Item	Organisation	Title	Timeline	Comment
All	GNSS	Standard		Interference and spoofing detection and mitigation techniques	asap	Growing threat from interference and spoofing
Manned Aviation	EGNOS	Standard	EUROCAE	Minimum Operational Performance Standard for Satellite-Based Augmentation System Airborne Equipment	2023	ED-259A including test procedures
Manned Aviation	EGNOS	Standard	EUROCAE	Minimum Operational Performance Standard for Satellite-Based Augmentation System Airborne Equipment	2024	ED-259B including H-ARAIM and institutional scenarios
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 Amendment 93	2023	Amendment to ICAO Annex 10 including DFMC SBAS SARPs and Galileo.
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 updated version	2024	Amendment to ICAO Annex 10 including ARAIM.
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 updated version	2026	Amendment to ICAO Annex 10 including Authentication.
Manned Aviation	Galileo	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 revied version	2029	Amendment to ICAO Annex 10 introducing DFMC GBAS with multi-constellation capability and possibly multi-frequency.

Market Segment	System	Item	Organisation	Title	Timeline	Comment
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Aircraft System Performance Specification for Required Navigation Performance for Area Navigation	June 2022	ED-75E
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Operational Performance Standard for distance measuring equipment (DME/N and DME/P) (ground equipment)	2023	ED-57A
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Aircraft System Performance Specification (MASPS) for DME Infrastructure supporting PBN positioning	2023	New document
Unmanned Aviation	Galileo / EGNOS	Guidelines	EUROCAE	ED-301 Guidelines for the Use of Multi-GNSS Solutions for UAS Specific Category – Low Risk Operations SAIL I and II	Aug. 2022	Covers the use of GNSS for low-risk drone operations
Unmanned Aviation	Galileo / EGNOS	Guidelines	EUROCAE	Guidelines for the use of multi-GNSS solutions for UAS: Medium Risk	2024	Covers the use of GNSS for medium-risk drone operations
Maritime	EGNOS	Standard	IEC	Test standard for shipborne SBAS (L1) Receiver Equipment	2023	IEC 61108-7
Maritime	EGNOS	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including SBAS (L1)	2023-2024	1y after SBAS test standard The update of the regulation shall include the reference to IEC 61108-7, IEC 61108-1, IMO MSC 401, IMO MSC 112
Maritime	Galileo	Standard	IMO	Update of performance standard for shipborne Galileo Receiver Equipment	2023-2024	Update of IMO MSC 233 Draft proposal submitted for info. to IMO NCSR 10

Market Segment	System	Item	Organisation	Title	Timeline	Comment
Maritime	Galileo	Standard	IEC	Update of test standard for Shipborne Galileo Receiver Equipment	2025-2026	Update of IEC 61108-3
Maritime	Galileo	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including Galileo	2025-2026	Update IMO MSC resolution and IEC 61108-3 issue 2.0
Maritime	EGNOS	Standard	IMO	Performance standard for shipborne DFMC SBAS + ARAIM Receiver Equipment	2025	Proposal to be submitted in MSC 107 in May 2023
Maritime	EGNOS	Standard	IEC	Test standard for shipborne DFMC SBAS + ARAIM Receiver Equipment	2027	2y after the DFMC SBAS + ARAIM performance standard
Maritime	EGNOS	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including DFMC SBAS + ARAIM	2027-2028	1y after DFMC SBAS + ARAIM test standard
Inland waterways	Galileo / EGNOS	Regulation	EU	Update of European Standard for River Information Services, ES-RIS 2021/1	Every 2y	Specific provisions on PNT and GNSS may be covered.
Inland waterways	Galileo / EGNOS	Preparatory Action	EU	EU Space Data for autonomous vessels in Inland waterways	2023-2025	It will assess how EU Space Data from Galileo, EGNOS and Copernicus can be key enablers of the digital transformation.
Rail	Galileo / EGNOS	Standard	ERA	Technical Specification for Interoperability	2022-2028/2029	Standard to meet essential requirements and ensure interoperability of the EU railway system.

Market Segment	System	Item	Organisation	Title	Timeline	Comment
Road	EGNOS	Standard	ETSI 3GPP	Update of 3GPP standard	2024	Evolve 3GPP standards to be compliant to MOPS messages for DFMC GNSS signal dissemination through Mobile Network.
Road	Galileo	Standard	ETSI/CEN	Test Standard for GNSS + HAIS	2024	Set of standardised (and ideally certified) GNSS + HAIS related tests and data bases that would be used for service certification.
Road	Galileo / EGNOS	Standard	ISO	Intelligent transport systems — Low-speed automated driving system (LSADS) service — Part 2: Gap analysis	2023-2024	
Road	Galileo / EGNOS	Standard	ISO	Intelligent transport systems — Seamless positioning for multimodal transportation in ITS stations — Part 1: General information and use case definition	2024-2025	
Road	Galileo / EGNOS	Standard	ISO	Electronic fee collection — Localisation augmentation communication for autonomous systems	2024-2025	
Timing	Galileo	Standard	CEN/CENELEC JTC5	Standards for Galileo Time Receiver	2024-2025	

8 APPENDIX D: EU PNT major stakeholders

European Commission (EC)

The European Commission represents the general interest of the European Union and is the driving force in proposing legislation to European Parliament and Council, administering, and implementing EU policies, enforcing EU law jointly with the Court of Justice, and negotiating in the international arena. Within the European GNSS programmes, the European Commission has the **overall responsibility** for the implementation of the EU Space Programme, including in the field of security. The European Commission shall **determine the priorities and long-term evolution** of the Programme, in line with the user requirements, and shall **supervise** its implementation.

The Directorate-General for Defence Industry and Space (DEFIS) leads the European Commission's activities in the Defence Industry and Space sector. The European Commission shall ensure a clear division of tasks and responsibilities between the various entities involved in the Programme and shall coordinate the activities of those entities. The European Commission shall also ensure that all the entrusted entities involved in the implementation of the Programme protect the interest of the European Union, guarantee the sound management of the European Union’s funds and comply with the Financial Regulation.

The European Commission departments and executive agencies are based in Brussels (Belgium) and Luxembourg.

European Union Agency for the Space Programme (EUSPA)

EUSPA is the operational European Union Agency for the Space Programme, with the headquarters in Prague. Its core mission is to implement the EU Space Programme and to provide reliable, safe, and secure space-related services, maximising their socio-economic benefits for European society and business.

Related to Galileo and EGNOS activities, EUSPA core tasks are to ensure the **security accreditation** of those systems and to undertake **communication**, **market development** and promotion activities as regards their services. EUSPA entrusted tasks consist of **managing the exploitation of EGNOS and Galileo** and implement activities related to the **development of downstream applications** based on the data and services provided by Galileo and EGNOS.

EUSPA is based in Prague (Czech Republic).

European Space Agency (ESA)

The European Space Agency (ESA) is an international organisation with 22 Member States and formal cooperation agreements with all Member States of the European Union that are not ESA members. ESA's purpose is to provide for, and to promote, for exclusively peaceful purposes, cooperation among European States in space research and technology and their space applications, with a view to being used for scientific purposes and for operational space applications systems.

As regards Galileo and EGNOS, ESA has been entrusted with the tasks of **systems evolution and design and development** of parts of the ground segment, and of satellites, including testing and validation and **upstream research and development** activities in ESA’s fields of expertise.

In parallel to the work of ESA on Galileo and EGNOS, ESA is running several R&D programmes aimed to prepare the technology of the main systems and its applications. The main two programmes of ESA on this area related to PNT are the European GNSS Evolution Programme (EGEP) and the Navigation Innovation and Support Programme (NAVISP).

ESA Head Quarters are based in Paris (France).

European Aviation Safety Agency (EASA)

Formed by 31 Member States (the 27 Member States of the European Union plus Switzerland, Norway, Iceland and Liechtenstein), the European Aviation Safety Agency (EASA) is **an agency of the European Union** which has been given specific **regulatory and executive tasks in** the field of **aviation safety**.

EASA **mission** is to promote the **highest common standards of safety and environmental protection** in civil aviation. EASA develops common safety and environmental rules at European level and assist the European Commission with measures for the implementation of these rules and by providing the necessary technical, scientific, and administrative support to carry out its tasks. EASA monitors as well the implementation of standards through inspections in the Member States and provides the necessary technical expertise, training, and research.

EASA is based in Cologne (Germany).

EUROCONTROL

EUROCONTROL is pan-European, civil-military international organisation dedicated to **supporting European aviation**, working for seamless, pan-European air traffic management. It has 41 Member States with a vital **European expertise on air traffic management (ATM),** both leading and supporting ATM improvements across Europe. Among their activities EUROCONTROL supports the European Commission, EASA, and National Supervisory Authorities in their regulatory activities, including for the implementation of GNSS technologies.

EUROCONTROL is based in Brussels (Belgium).

SESAR Joint Undertaking (SESAR JU)

The SESAR Joint Undertaking (SJU) was established as a public-private partnership under Council Regulation (EC) 219/2007. The Council Regulation (EU) 2021/2085 marked the official launch of the SESAR 3 Joint Undertaking (SESAR 3 JU) bringing together the **EU, Eurocontrol, and more than 50 aviation organisations** (civil and military, Air Navigation Service Providers, airports, equipment manufacturers, authorities and the scientific community).

The **SJU is responsible for the modernisation of the European ATM system** by coordinating all ATM relevant research and innovation efforts in the EU. The SJU is responsible for the implementation of the European ATM Master Plan and for carrying out specific activities aiming at developing the new generation ATM system capable of ensuring a safety, green and fluid European air transport over the next thirty years. SESAR 3 Joint Undertaking will invest more than EUR 1.6 billion between 2022 and 2030 to accelerate, through research and innovation, the delivery of an inclusive, resilient, and sustainable Digital European Sky.

The SESAR Joint Undertaking is based in Brussels (Belgium).

European Maritime Safety Agency (EMSA)

The European Maritime Safety Agency (EMSA) provides technical assistance and support to the European Commission and Member States, Iceland and Norway in the **development and implementation of EU legislation on maritime safety**, pollution by ships, oil and gas installations, oil pollution response, ship and port security, vessel monitoring and long range identification and tracking of vessels.

EMSA **ensures the verification and monitoring of the implementation of EU legislation and standards**. The Agency provides technical assistance and scientific advice on matters regarding ship safety standards, and supports as well capacity building by providing expertise, training and research, cooperation, and tools. EMSA also participates in disseminating best practices and promoting sustainable shipping including implementation and enforcement of existing or proposed international and EU legislation and **collaborating with many industry stakeholders and public bodies**, in close cooperation with the European Commission and the Member States.

EMSA is based in Lisbon (Portugal).

European Union Agency for Railways (ERA)

The mission of the European Union Agency for Railways (ERA) is 'moving Europe towards a sustainable and safe railway system without frontiers'. To achieve this, **ERA contributes, on technical matters, to the implementation of the European Union legislation** aiming at improving the competitive position of the railway sector by **enhancing the level of interoperability of rail systems**, developing a common approach to safety on the European railway system and contributing to creating a Single European Railway Area without frontiers, **guaranteeing a high level of safety**.

Train navigation and positioning systems based on satellite applications are future components of the Control, Command and Signalling rail subsystem. Accordingly, ERA is setting the rules for their approval, in cooperation with trials run by railway operators and the system development, which is taking place under the aegis of Shift2Rail Join Undertaking, to which ERA is associated, as the first European rail initiative to seek both research & innovation and market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions.

ERA is based in Valenciennes and Lille (both in France).

European Maritime Radionavigation Forum (EMRF)

The European Maritime Radionavigation Forum (EMRF) **represents the maritime interests in Europe** and **provide expert input to European Policy** on safety of navigation and related matters.

The EMRF gathers different bodies, from maritime administrations to ship owners' organisations, to focus on the coordination of **European maritime interests in the field of radionavigation systems** for development within Europe. In particular, for global navigation satellite systems there are different activities within EMRF to address the use of GNSS, especially the improvements in position and related procedures which Galileo and EGNOS can bring into the maritime domain.

One of its main aims is to promote the **maritime requirements for the safety assessment and certification of future satellite systems**, their augmentation systems and back up, and to develop material to achieve recognition and operational approval of those systems as part of the IMO World-Wide Radionavigation System.

Member States

At the core of the EU are its 27 Member States and their citizens. The unique feature of the EU is that although the Member States all remain sovereign and independent states, they pool together some of their sovereignty in areas where this has an added value.

The role of Member States in PNT includes the support and participation in the development and implementation of regulation, policies and actions related to PNT, the coordination with other Member States and the EU institutions and the contribution to the development of new PNT technologies and applications.

Member States are involved in PTN from different perspectives:

- Key users of Galileo PRS and authorities for SAR.
- National Space Agencies which are key for the European GNSS Programmes.
- National Spectrum Agencies which manage the Radio-Frequency spectrum, ensuring coordination and intervene in RFI incidents.
- Ministries of Transportation which support and oversight the use of Safety of Life applications of GNSS in different domains such as aviation and maritime.

Finally, Member States support emergency management in case of a major RFI incident or GNSS outages, being key in the coordination among impacted stakeholders.

Other stakeholders

The following stakeholders are also relevant for PNT services:

- European Defence Agency (EDA).
- International Civil Aviation Organisation (ICAO).
- International Maritime Organisation (IMO).
- International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA).

9 APPENDIX E: EU reference frames

GNSS positioning is underpinned by the Terrestrial Reference System (TRS, with mathematical and physical foundations for its definition and properties) and the Terrestrial Reference Frame (TRF, a numerical realisation of the TRS). The most widely used is the International Terrestrial Reference Frame (ITRF) which is critical for the continuous monitoring of the earth's tectonic plate movement (1.5 cm / year for most of Europe) or mean sea level using Continuous Operating Reference Stations (CORS), which permanently locate GNSS receivers.

For centuries, each country has maintained its local grid and mapping transformation (i.e., the best fit of country 2D maps into a global ellipsoid), intended to reduce the transformation errors through the varied scale factor. Those national grids have been physically established using trigonometric points. Currently, **countries' mapping services** are moving away from the classical approach and **are widely using Network RTK**, maintained via a network of CORS and hence based on GNSS.

This trend of using GNSS as a global reference is expected to propagate to all aspects of PNT, especially given the expected increase in future PNT high-accuracy services. As the scale factor approach is prone to man-made blunders, even mapping and terrestrial engineering works are moving from national grids to GNSS-delivered local grids (usually using Helmert transformation).

This appendix lists the most important TRFs from the European perspective as well as provide simple best practice guideline on their use.

Reference Frames

The International Terrestrial Reference System (ITRS) was developed by the geodetic community under the auspices of the International Earth Rotation and Reference Systems Service (IERS). Its most accurate realisation is the **International Terrestrial Reference Frame (ITRF)** which is in reality a series of improved versions of ITRF. The latest version is ITRF2020 though some earlier ITRF (usually not earlier that ITRF2000) could be still in use. Transformation between the frames is possible if the definition and epochs of both frames are known. While earlier frames changed up to the dm level since ITRF94 (since ITRF2005 for the height component) differences are on the mm level. The biggest effect, addressed by the epoch of establishment, is the tectonic plate movement.

Galileo uses **Galileo Terrestrial Reference Frame (GTRF)**, realised by the Galileo Geodetic Service Provider and since 2018 managed by the Galileo Service Operator (GSOp). The latest GTRF solution (GTRF19v01) is aligned with respect to the ITRF2014 with mm accuracy. Other GNSS systems also adopted reference to ITRF, and all are currently referenced to ITRF2014.

The **ETRS89 (European Terrestrial Reference System of 1989)** is based on ITRF89, epoch 1989.0 and monitored by a network of about 250 permanent GNSS tracking stations known as the EUREF Permanent Network. As ETRS89 is kept fixed at epoch 1989.0, the ETRS89 and the ITRS are diverging due to the European continental drift (approximately 2.5 cm per year). In early 2023, the difference exceeded 80 cm.

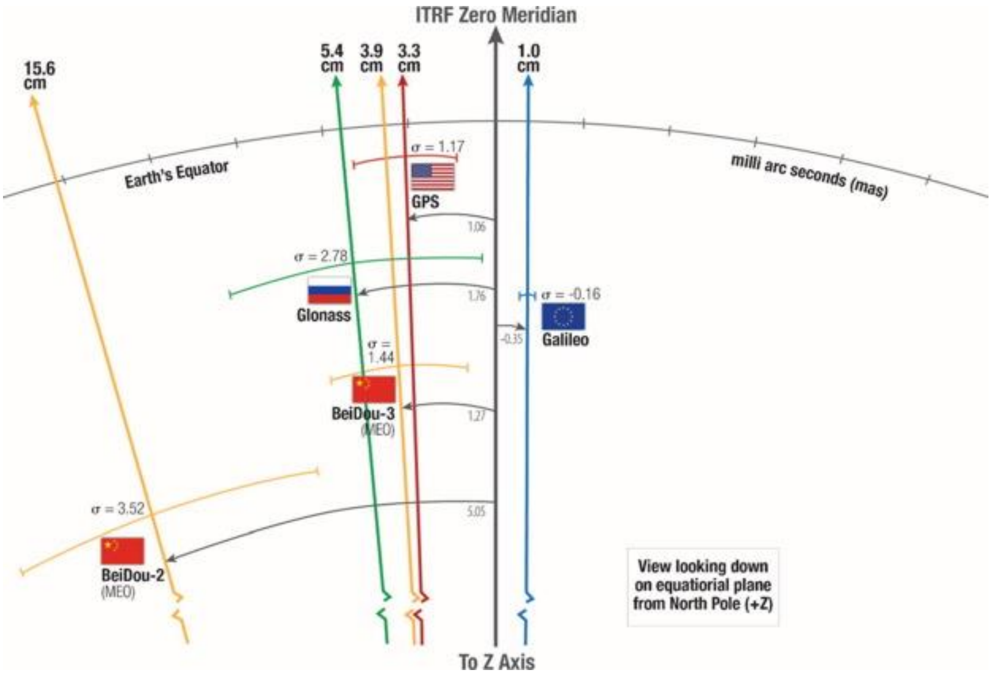


Figure 66 - Comparison of a prime meridian, as realised by GNSS TRF, with respect to the IGS14 zero meridian (Credit: https://www.sciencedirect.com/science/article/pii/S0273117720308292)

More information about the reference frames, transformations and IGS products can be found in:

- P. Teunissen and O. Montenbruck, *Springer handbook of global navigation satellite systems*. Springer International Publishing, 2017.
- Y. J. Morton, F. S. T. Van Diggelen, J. J. Spilker, and B. W. Parkinson, Eds., *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications*, First edition. Hoboken: Wiley/IEEE Press, 2021

Best practice

Based on the above, as a rule of thumb, **all coordinates should be referred to a specific ITRF**, at the specific epoch of establishment. For most continental Europe ETRS89 is the perfect replacement. In certain areas of increased tectonic activity, such as Greece, transformation requires known site velocities. This excludes any discontinuity due to earthquakes (points need to be re-established).

In the case of a GNSS-based system, it is worth noting that NRTK and PPP reference frames tend to differ. In Europe, most of the NRTK CORS are defined in ETRF89 and so are the final coordinates. For PPP the terrestrial reference frame will be defined by the datum of the corrections, usually the latest ITRF. Similarly, EGNOS reference frame is determined by the geodetic coordinates of the EGNOS stations (EGNO Ranging and Integrity monitoring Stations) which are established in ITRF2000.

In the case of terrestrial systems, only small-scale deployments (below 10 km^2) and indoors should use local grid implementation, as long as coordinates are linked to ETRF (ITRF including epoch of transformation). The GNSS-delivered local grids via Helmert transformation are suggested.

For the larger deployment, ETRF/ITRF should be used directly. It is worth noting that the use of the global coordinates is not intuitive (latitude/longitude distance varies with longitude and the Cartesian XYZ height component is difficult to read) so local coordinates will probably be used for visualisation (but not for the underlying system).

10 APPENDIX F: ACRONYMS

The next table provides the list of acronyms:

ABAS	Aircraft Based Augmentation System	ESA	European Space Agency
ACAS	Assisted CAS	ETCS	European Railway Traffic Management System
ADS-B	Automatic Dependant Surveillance Broadcast	ETSI	European Telecommunication Standard Institute
AIS	Automatic Identification System	EUSPA	European Union Agency for the Space Programme
ARAIM	Advanced Receiver Autonomous Integrity Monitoring	FAA	Federal Aviation Authority
ASF	Additional Secondary Factor	FCC	Federal Communications Commission
ATC	Air Traffic Control	FDMA	Frequency Division Multiple Access
ATM	Air Traffic Management	FOC	Full Operation Capability
AtoN	Aids-to-Navigation	G2G	Galileo 2nd Generation
BVLOS	Beyond Visual Line of Sight	GBAS	Ground Based Augmentation System
CAS	Commercial Authentication Service	GEO	Geostationary Earth Orbit
CBA	Cost Benefit Analysis	GIS	Geographical Information System
CDMA	Code Division Multiple Access	GIVE	Grid Ionospheric Vertical Error
CER	Community of European Railway	GLA	General Lighthouse Authorities of the UK and Ireland
CNI	Critical National Infrastructure	GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
CNS	Communication, Navigation and Surveillance	GMDSS	Global Maritime Distress and Safety System
COG	Course Over Ground	GNSS	Global Navigation Satellite System
DFMC	Dual-Frequency Multi-Constellation	GPS	Global Positioning System
DGNSS / DGPS	Differential Global Navigation Satellite System / Global Positioning System	GSC	GNSS Service Centre
DOP	Dilution of Precision	GSS	Galileo Sensor Station
EASA	European Aviation Safety Authority	HAL	Horizon Alert Limit
EC	European Commission	HAS	High Accuracy Service
EDAS	EGNOS Data Access Service	HMI	Hazardously Misleading Information
EGNOS	European Geostationary Navigation Overlay Service	HPL	Horizontal Protection Level
EMRF	European Maritime Radio Navigation Forum	IALA	International Association of Marine Aids to Navigation and
ERA	European Railway Agency	ICAO	International Civil Aviation Organization
ERNP	European Radionavigation Plan	ICG	International Committee on GNSS
ERTMS	European Railway Traffic Management System	IEC	International Electrotechnical Commission

IGS	International GNSS Service
IMO	International Maritime Organization
IMU	Inertial Measurement Unit
IoT	Internet of Things
ISM	Integrity Support Message
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
JRC	Joint Research Centre
LBS	Location Based Service
LEO	Low-Earth Orbit
LIDAR	Light Detection and Ranging
MEO	Medium Earth Orbit
MFMC	Multi-Frequency Multi-Constellation
MOPS	Minimum Operational Performance Standard
MSF	Maritime Safety Committee
MSI	Maritime Safety Information Service
NLOS	Non-line of Sight
NMI	National metrology institute
OS	Open Service
OSNMA	Open Service Navigation Message Authentication
PBN	Performance Based Navigation
PNT	Position, Navigation, and Timing
PPP	Precise Point Positioning
PRS	Public Regulated Service
PVT	Position Velocity and Time
QZSS	Quasi Zenith Satellite System
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RFI	Radio Frequency Interference
RIMS	Reference Integrity Monitoring Stations
RLS	Return Link Service
RNP	Required Navigation Performance
RPAS	Remotely Piloted Aircraft System
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission Maritime
RTK	Real Time Kinematic
SAR	Search and Rescue
SARPS	Standard & Recommended Practices
SAS	Signal Authentication Service
SBAS	Satellite Based Augmentation Systems
SDD	Service Definition Document
SES	Single European Sky
SESAR	Single European Sky ATM Research
SOG	Speed Over Ground
SIS	Signal In Space
SoL / SOL	Safety Of Life
SOLAS	Safety Of Life At Sea
SPP	Single Point Positioning
SSR	State Space Representation
STL	Satellite Time and Location
TEC	Total Electron Content
TOA	Time of Arrival
TSI	Technical Specification for Interoperability
TTA	Time To Alarm
TTFF	Time To First Fix
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UTC	Universal Coordinated Time
VAL	Vertical Alert Limit
VDES	VHF Data Exchange System
WAAS	Wide Area Augmentation System
WWRNS	World-Wide Radionavigation System