PNT Vision 2035

White Paper

Written by the NAVigation innovation support programme Advisory Committee (NAVAC)

March 2024

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The Navigation Innovation and Support Programme Advisory Committee (NAVAC) is a committee of senior external experts established in October 2018 by the European Space Agency Director of Navigation to provide an independent advice on the objectives, strategy, and relevant technological priorities of ESA's Directorate of Navigation.

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Acronyms

A2AD	Anti-Access Area Denial
AAM	Advanced Air Mobility
ADAS	Automatic Driving Assistance Systems
ADC	Analog to Digital Converter
A-GNSS	Assisted GNSS
AoA	Angle of Arrival
AI	Artificial Intelligence
AR	Augmented Reality
CAS	Commercial Authentication Services
COTS	Commercial Of-The-Shelf
CSAC	Chip Scale Atomic Clock
D2D	Devise to Device
DL-AoD	Downlink Angle of Departure
DL-TDOA	Downlink Time Difference of Arrival
DME	Distance Measurement Equipment
EASA	EU's Aviation Safety Agency
EDA	European Defence Agency
EKF	Extended Kalmann Filter
E-LORAN	Enhanced Long-Range Navigation
EU	European Union
EUSPA	EU Agency for the Space Programme
GEO	Geostationary Orbit
GDP	Gross Domestic Product
GNSS	Global Navigation Satellite Systems
HAS	High Accuracy Service
ICD	Interface Control Documents
IoT	Internet of Things
IF	Intermediate Frequency
INS	Inertial navigation system
KF	Kallman Filter
LANS	Lunar Augmented Navigation Service
LEO	Low Earth Orbit
LCRNS	Lunar Communications Relay and Navigation System
LITS	Linear Ion Traps
LNA	Low Noise Amplifier
LNSS	Lunar Navigation Satellite System
LORAN	Long Range Navigation
MAAS	Maritime Autonomous Surface
MCS	Master Control Station
MEMS	Microelectromechanical systems
MEO	Medium Earth Orbit
Multi RTT	Multi Round Time Trip
NAVAC	NAVigation innovation support programme Advisory Committee
NLoS	Non-Line of Sight
OSNMA	Open Service – Navigation Message Authentication
PKF	Particle Filter
PNT	Positioning Navigation and Timing
PPP	Precise Point Positioning
PRS	Public Regulated Service
PTF	Precise Timing Facility
QKD	Quantum key distribution
QoS	Quality of Service
QZSS	Quasi Zenith Satellite Systems
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency

RTK	Real time kinematics
SAE	Society of Automotive Engineers
SAR	Synthetic Aperture Radar
SBAS	Satellite-Based Augmentation System
SDR	Software defined Radio
SOP	signals of opportunity
SoS	System of Systems
SSR	State-Space Representation
SWaP-C	Size, Weight, Power consumption and Cost
TTFF	Time-to-First-Fix
TTFAF	time-to-first-accurate-fix
TCXO	Temperature Compensated Crystal Oscillator
UAAM	Urban and Advanced Air Mobility
UCO	User Consultation Platform
UHF	Ultra-high frequency
UKF	Unscented Kallman filter
UL-AoA	Uplink Angle of Arrival
UTDoA	Uplink Time Difference of Arrival
UTC	Coordinated Universal Time
VR	Virtual Reality
VRS	virtual reference station
XAI	Explainable Artificial Intelligence

1 Executive summary

PNT market evolution

With already 6.5 billion installed GNSS devices worldwide our businesses, infrastructure, governments and citizens are already crucially dependent on PNT services. An estimated 10% of EU GDP rely on them to some degree. Various studies have demonstrated high economic benefits through the exploitation of these services, whilst other studies have highlighted the potentially major negative social and economic impacts of even temporary interruptions of service, particularly a loss of GNSS. The delivery of accurate timing is the critical use-case, particularly where this supports critical infrastructure such as communications and power distribution networks. This dependence is only set to grow as new applications emerge, especially in the areas of consumer solutions and autonomous systems.

In considering the future direction of PNT services, it is important to consider the main geopolitical trends and general technology advancements. As tensions increase between east and west, particularly following the Russian invasion of Ukraine, cases of cyber-attacks, jamming and spoofing have been steadily increasing. The rise of China as a new super-power to rival the US creates further tensions and risks, raising questions as to how much dependence should be placed on infrastructure (e.g. BEIDOU and GLONASS) and technologies deployed by potentially unfriendly states. At the same time, there are major technological advances in the areas of AI/ML and quantum which could have a major impact on society as a whole (automation and autonomy) and on PNT systems directly. New regulations to protect the public in response to both transformational technologies and the increasing geopolitical tensions become highly likely.

Some of the wider technology trends which will drive PNT demand include the increasing pervasiveness of connected devices (IoT), autonomous driving, advanced air mobility (including air taxis), smart grids and distributed power generation, and autonomous vehicles of all types (land, sea and air). Many of these applications will demand pervasive (including indoors), resilient and robust PNT delivery (availability, continuity, integrity). Meanwhile in the satellite domain, the proliferation of massive LEO constellations opens a door to other means of delivering PNT services from space to complement or as an alternative to traditional MEO.

Consumer applications, IoT and the automotive sector will continuate to dominate the sector in terms of installed devices (smart phones, tablets, wearables, cameras…), representing >90% of the market. Whether these applications are mobile/portable or not, size, weight, power consumption and costs will remain important characteristics influencing the adoption of new systems and devices. Accuracy has been found to be addictive, so going forward, alongside the greater need to an assured service, the demand for accuracy inevitably increases.

Evolving system architectures

To meet the demands of such diverse user applications, PNT will be provided through a combination of alternative, independent and complementary data sources, including multiple GNSS (GEO, MEO, LEO and IGSO) operating in multiple frequencies, cellular networks (5G/6G), terrestrial systems (e.g. eLoran, Wi-Fi, SOP), augmentation systems and a range of improving autonomous sensors (e.g. inertial, magnetic, miniature clocks, terrain models). Within the timeframe, Galileo 2G will be providing authenticated services, GPS IIIF will be coming online and LEO communications constellations will be available, offering different frequencies and higher power levels. Overall, it is foreseen that solutions will progressively make use of “systems of systems” to provide the level of performance required for a given application. The combination of systems must ensure that there is an adequate level of independence to meet the necessary level of assurance.

Whilst it is assumed that GNSS in MEO will remain the backbone of PNT services in the timeframe, there are a plethora of LEO constellations either in development or being proposed, that could potentially provide complementary or independent services. The majority of the deployed or proposed LEO constellations are primarily for high throughput communications, where the delivery of PNT would be an ancillary service. There is also the opportunistic approach of using these signals as "signals of opportunity" (SOP) utilising, for example, doppler measurements to the satellites. It is unlikely this approach would produce comparable accuracy to a dedicated PNT system for various technical reasons. The low orbits and shorter lifespans of such satellites makes them ideal for the "new space" paradigm making use of low-cost COTS components, such that a number of privately funded initiatives are in development.

There are a range of regional and local, space based and ground based, augmentation systems to improve accuracy and/or other key parameters such as integrity. These include classical SBAS and regional IGSO systems as well as RTK and PPP networks, which will evolve and be progressively extended within the timeframe being considered.

Without doubt 5G and 6G will be a valuable terrestrial complement to GNSS in 2035 and whilst typically current base-station implementation makes use of timing from GNSS, as resilience becomes a more important, cellular networks (and other CNI) are expected to have recourse to alternative independent clocks.

Emerging technologies and autonomous sensors

Within the space segment, new technologies are likely to include new signal designs, flexible payloads, new higher power amplifier technologies, advanced clocks, intersatellite links and greater potential for autonomy.

Receiver designs have evolved significantly since the inception of GNSS, with improved techniques and algorithms and massive advances in semiconductors allowing much higher levels of integration and shrinkage in size and power consumption, whilst at the same time massively improving sensitivity and overall performance. Advances include the ability to process multiple channels (satellites and constellations) and frequencies to improve accuracy and reduce multipath effects, as well as to detect and mitigate against jamming and spoofing.

Depending on application and the demands of size and power consumption, software defined radios are available that enable reconfiguration and adaption and may be an appropriate solution to support the new LEO satellite constellations, including processing of signals of opportunity.

At the user level, the PNT solution will be derived from a range of sensors in addition to or independently of the GNSS, depending on application and could include inertial (INS), magnetic, gravitational, star trackers, imaging systems and onboard clocks. Some of these sensors, such as a 6-axis accelerometer (accelerometer and gyro) implemented in MEMS technology may often be integrated into the receiver or could be external and performed at user level. These systems have been in use for many decades and have already undergone many advances as new technology becomes available, for example INS moving from mechanical to laser. These advances will continue, with quantum technologies likely to deliver a paradigm shift in performance.

Fusion of data from multiple sensors is already widely implemented in numerous applications to improve performance but involves many design trade-offs, in particular between accuracy and availability. Multiple sensors feeding into a position determination may improve accuracy when all are working to specification, but if the failure of any one were to cause a total failure, then this would reduce availability. Likewise, with an increasing emphasis on resilience, the fusion of multiple sensors must take account of failure modes and security concerns.

The system engineering challenges of designing new systems, incorporating new technologies and embracing legacy systems should not be underestimated. The task will become more difficult as the demand for assured PNT grows and resilience becomes more a important characteristic.

Conclusions and recommendations

1. **Future Investment** – There is a clear case for investing in future PNT systems. Beyond the economic dependence on GNSS, growing security and defence concerns and a questionable access to some of the existing systems in the future make it advisable to consider the development of alternative and complementary resilient systems. ESA should take account of the potential loss of access to GLONASS and BEIDOU in future programme planning.
2. **Evolving threats** – Jamming, Organised crime, State actors. and of course, underlying environmental risks – solar, orbital debris, etc. – will remain unchanged, if only aggravated by the increasing connectivity demanded by many of the upcoming applications and services. ESA should continuously review risks to the PNT environment and define mitigation actions and programs.
3. **New technologies and better systems** – Future PNT systems will bring more of everything: more satellites; more orbits; more frequencies; more systems; signals of opportunity; smarter processing; integrated systems; advance technologies – e.g. machine learning, AI, and quantum; improved service volume of GNSS to include space uses. All of this will continue as a trend. ESA needs to remain engaged and invest. There will be plenty of opportunities for the Member State companies to create markets, compete and develop new products and services.
4. **New Uses** – New applications and services can be envisaged, some real, some speculative, but many capturing public interest – e.g. IoT, Autonomous vehicles, air mobility, space exploration… The mass market will continue driving the demand and growth, nevertheless accurate timing will remain the main critical use case. With increasing demand and new uses, our dependence on PNT services will also grow.
5. **Resilience** – Bearing in mind our growing dependence on PNT services, existing applications and new ones require higher levels of assurance and resilience. It is unlikely that GNSS systems alone will offer this. This will call for significant investment in the systems engineering to better understand how to create and implement resilience, and also in new technologies needed to add resilience, which include space systems, terrestrial systems and sensors. It is worth noting that future alternative PNT systems, whether space or ground based, must be designed and implemented avoiding interdependencies to the present GNSS (e.g. using GNSS as the time reference for other ground networks).

2 Introduction

The NAVigation innovation support programme Advisory Committee (NAVAC) is a senior advisory body, whose mission is to advise the ESA Navigation Director on the strategic lines of action to take in R&D and future activities aiming at consolidating ESA's leading position in GNSS and to improve the market position of the European PNT industry for the commercialization and dual use of these technologies in the global market, for the benefit of its Members States.

Aiming at this end, NAVAC has undertaken to develop its vision for the evolution of the PNT technology, applications and services until 2035. The present document collects the outcomes of this effort. Thus, this paper is organized as follows:

- Chapter 1 contains an Executive Summary of the complete paper, with a brief overview of its contents and main conclusions.
- Chapter 2 is the present introduction.
- Chapter 3 delivers the NAVAC's view on the present status of the PNT market, with the aim to establish the starting point from where the PNT domain will evolve.
- Chapter 4 describes the main trends as concerns the geopolitical scenario, the relevant technologies and the market dynamics. It includes a brief description of the use cases that will drive the future requirements for PNT systems and services.
- Building on these trends and on the identified starting point, the following chapters discourse on the expected evolution across the whole service chain:
    - Chapter 5 provides a description of the existing PNT infrastructure, both space and ground based, and discusses on its potential evolution in the next decade.
    - Chapter 6 ponders the state-of-the-art of PNY sensors, especially GNSS receivers, and how the evolution of PNT demand and upstream infrastructure may condition its evolution. It also considers how new data processing techniques can affect the overall PNT scenario.
    - Chapter 7 considers system integration issues, and in particular how the evolving system implementations will impact the end-to-end PNT safety and security.
    - Chapter 8 discusses the upcoming end users applications and services, and how these will open new opportunities in the downstream market.
- Finally, Chapter 9 summarises NAVAC's conclusions and recommendations to the ESA's Executive about their future actions concerning PNT systems.

NAVAC is confident that this paper contains a comprehensive view of the foreseeable future of PNT systems and services, that may serve as a guide to define ESA's work plans in this field.

3 PNT market today

Today, our society is crucially dependent on positioning, navigation and timing (PNT) services, increasingly provided by Global Navigation Satellite Systems (GNSS). Systems such as the American Global Positioning System (GPS) or the European Galileo are pervasive to many areas of our daily lives and our economy. The use of GNSS has spread across many different sectors, to the point that today, around 10% of the European Union (EU) Gross Domestic Product (GDP)[1] relies, in one or another way, on them. The installed base of GNSS devices exceeded 6.5 billion units by 2021, and its expected to grow up to 10.6 billion by 2031[2]. The vast majority of them are multi-constellation (i.e. over 76%), but most of them are single-frequency L-band receivers. More than 3.9 billion are Galileo-enabled.

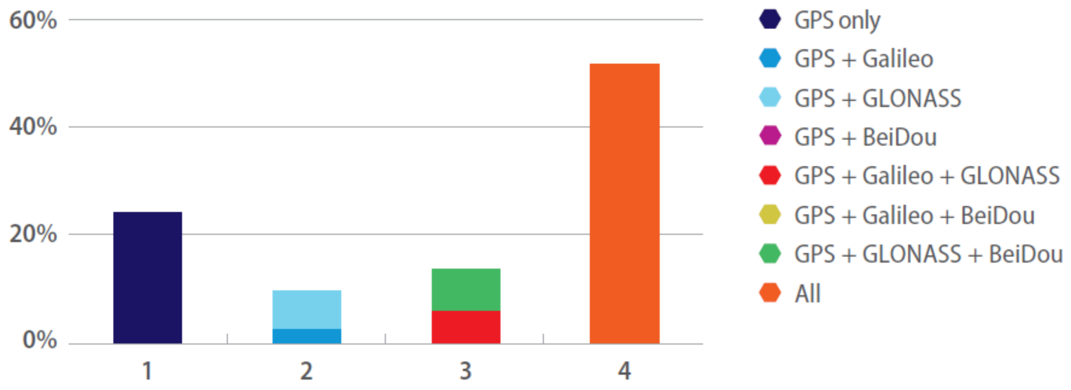

Figure 1.- Supported constellations by GNSS receivers. It shows the percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations (source: EUSPA User Technology Report, Issue 3, 2020).

Among the various different fields of application, the consumer solutions and road and automotive segments dominate the market, representing more than 95% of the global market today. **The trend is even to increase this market** share up to nearly 98% by 2031.

The European contribution to GNSS, Galileo and EGNOS, have been extremely successful and have doubtless been paramount for the development of an industrial fabric able to compete globally in the downstream market. Europe (EU-27) represents c. 20% of the global demand of GNSS devices and services, yet its industry captures c. 25% of the global market. However, it lags behind its Asian and American peers in some of the fastest growing segments, i.e. consumer solutions and drones. On the contrary, the European industry dominates the road and automotive segment.

Yet the massive uptake of GNSS solutions across all PNT application domains comes at the price of building an increasingly strong dependency on such systems. Nowadays, GNSS are crucial for the economy of Europe (defined as the EU-27 plus the United Kingdom, Norway and Switzerland), reporting high economic benefits, but also threatening to cause equally remarkable losses in the case of a temporary outage of their services. Although some of these impacts might be overestimated, there is no doubt of the worldwide impact of these systems on our wealth and well being.

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[1] EU Space General Overview Factsheet, dated March 14th 2022. Last accessed February 26th 2024. https://defence-industry-space.ec.europa.eu/document/download/5d810d48-2316-42e9-a92c-f5323a7326b4_en?filename=EUSpace%20Factsheet%20EN.pdf.

[2] EUSPA EO and GNSS Market Report 2022, Issue 1.

Table 1.- Summary of reported economic benefits and losses[3]

Study focus	Economic benefits (annual)	Economic loss	Economic loss (per day)
UK[4]	GBP 6.7 billion	GBP 5.2 billion (5 days)	GBP 1.0 billion
US[5]	USD 300 billion	USD 30.3 billion (30 days)	USD 1.0 billion
Europe	EUR 69.0 billion	Not available	Not available

As the weight of GNSS in the global economy increases, so do the concerns about the robustness and resilience of the systems against intentionally or unintentional attacks (e.g. jamming, spoofing, interference, adjacent bands). A number of major global incidents over the last few years have demonstrated the vulnerability of GNSS today. Just to mention a few:

- In November 2021, Russia shot down one of its own satellites and announced on state television that they could take out all the GPS satellites used by NATO as a warning not to interfere in the Ukrainian war.
- In January 2022, the Denver Airport in the US experienced a significant GPS outage within a 50 miles radius, with impacts across flight systems – including collision avoidance and air traffic management – and infrastructure.
- In March 2022, EU's Aviation Safety Agency (EASA) warned of GNSS spoofing and jamming in aircrafts flying over Europe.
- In October 2022, Dallas Airport in the US, had a GPS interference for more than 36 hours, impacting air travel across all the country.
- In December 2023 and January 2024, GNSS spoofing incidents were detected and reported by commercial aircraft flying over the Baltic region.

The permanent threats on GNSS are especially worrisome for PNT applications in critical infrastructures. In this regard, it is important to highlight that **accurate timing is the main critical use case**, rather than position or navigation.

Assuring the availability of PNT services thus becomes an issue, and the market demands PNT sources that can provide either an alternative or a complement to GNSS. Unfortunately, the uses of PNT data in critical infrastructure and commercial applications are so diverse that possibly no single system can fulfil all user requirements. On top of that, the efficiency of satellite-based navigation systems has driven so far to the discontinuation of other systems previously providing such services, and other infrastructures than may act as a catalyst for alternative solutions are not completely deployed yet. For instance, 5G/6G networks may certainly introduce an alternative system into the market, however, 5G coverage is still low. Urban areas in Europe are only expected to achieve full coverage by 2030 at the earliest, and although 5G new radio (NR) standard includes dedicated positioning reference signals, measurements and procedures from 3GPP Release 16 onwards, the availability of these improvements depend on the decision of the Telecom operators to deploy the required elements in the network architecture. Telcos do not seem very much inclined to make the investment required to do so unless there is a clear business case for that or, alternatively, regulation (e.g. obligation to provide a universal PNT service) obliges them to do so. Moreover, 5G ultra-low

[3] Source: European Radio Navigation Plan 2023.
[4] Economic impact to the UK of a disruption to GNSS. Showcase Report. April 2017. London Economics. [LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-SHOWCASE-PUBLISH-S2C190517.pdf (londoneconomics.co.uk)](LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-SHOWCASE-PUBLISH-S2C190517.pdf). Last accessed on March 1st 2024.
[5] Economic Benefits of the Global Positioning System (GPS). Final Report. June 2019. https://www.rti.org/publication/economic-benefits-global-positioning-system-gps/fulltext.pdf. Last accessed on March 1st 2024.

latency and high-speed data transmission capabilities are indispensable for enabling real-time communications and data exchange among autonomous vehicles, infrastructure and cloud-based systems, thus being a key enabler for some of the applications that will drive the demand for PNT services in the coming years.

Nevertheless, one must be cautious about potential alternative sources of PNT information today. In many cases, the systems are not entirely independent, thus creating single points of failure. For instance, more often than not, GNSS information is used to synchronize ground-based communication networks (e.g. LTE or 5G). Making GNSS unreliable or unavailable would automatically render LTE/5G useless for PNT purposes.

4 Evolution of PNT market: our vision for 2035

4.1 Main geo-political trends impacting Europe

The following geo-political and social trends will potentially impact PNT systems and service in the future:

- The early part of the 2020's has seen a world that is becoming increasingly polarised between the "Global South" and the "Western World" and between democracies and authoritarian regimes. Of particular significance to Europe is the political shift seen in Russia, which is rapidly recreating the conditions for a new Cold War. Following the Russian invasion of Ukraine and their interventions in Libya, Syria and other nations of Africa, many nations on the borders of Europe are increasingly being put into a position of choosing sides. "Strategic relativism" and irregular war conduct (spying, cyber-attacks, propaganda, fake information, etc) by autocratic and kleptomaniac regimes are infiltrating the western society, what impacts also core infrastructure like GNSS.
- At a global level, the most significant shift is the rise of China as an economic, political, cultural and military superpower to rival the US. Across all the countries of the world China is using its economic muscle to embed itself into the fabric of societies, in particular through the "Belt & Road" initiative investing in infrastructure projects such as railways and ports. A number of flashpoints such as Taiwan and disputed islands in the South China seas could trigger a confrontation with the West.
- Primarily due to conflicts in the Middle East and Africa, but also exacerbated by other factors such as climate induced famines, there is a growing movement of people seeking a better life in Europe, creating a migration crisis across the southern borders of Europe. Mass migration is likely to increase further due to climate change as more regions of the Earth become unviable for human habitation.
- There is big rise in private sector investments into space technologies, including into PNT, which could give rise to new commercial standalone or augmentation systems.
- Massive advances in AI /ML with immense investment into high performance processors, and ultimately once more accelerated as quantum computing becomes a reality, will have an impact in many areas of the workplace and society as a whole, in particularly in the areas of automation and autonomous transport. Huge investments in China and the USA in these technologies, including quantum, and a looser regulation there may leave the European industry lagging behind that of those countries.
- In particular spurred on by political rivalries, there is a new "space race" occurring as the emerging space powers of China and India assert their independence. This is accelerating efforts to move off the earth to the Moon and Mars.

It is anticipated that all these trends will continue into the 2030's, which will likely impact PNT systems and services as follows:

- **Interference and jamming** - Countries bordering Russia of North Korea have already seen a marked increase in incidences of interference and the loss of GNSS services. If global tensions continue to increase, then these incidences are likely to increase close to contested areas. For critical applications resilience will become increasingly important.
- **Cyber and spoofing** - there are already numerous examples of aggressive, non-military attacks on Western nations such as interference in elections and cyber-attacks on critical infrastructure. Europe's PNT space and ground infrastructure could well become a target for malicious cyber-attacks or spoofing of signals.

- **Loss of access to foreign GNSS** - in the event of rising political tensions it is possible that GNSS infrastructure operated by foreign nations, in particular GLONASS and/or Beidou could be denied to users considered 'non friendly'.
- **Regulation** - recognising the significant economic and social impact of a loss of PNT services and in the light of rising geo-political tensions and the risks of loss of access to foreign GNSS infrastructure, as well as potentially increasing threats of jamming and spoofing, there is a likelihood that national or European regulators will implement new regulations to govern how user equipment will operate under such circumstances.
- **Drive to develop alternative and autonomous systems** – driven primarily by the military and critical national infrastructure demands, there will be increased priority given to reducing dependence on any single system.
- **Advances in AI/ML and other new technologies** – will both enable advances in PNT systems and services but will also spawn new applications and tend to increase the dependency on the PNT solutions, particularly in the use of autonomous vehicles.
- **Moving beyond Earth** – will require the adaption of PNT systems to work in new environments and will require the deployment of PNT infrastructure beyond Earth.

4.2 Technology trends

Beyond geo-political trends, the evolution of other technologies across different domains will unavoidably influence the demand for PNT services by 2035. Without the aim of being exhaustive, this section discusses briefly below some of the most relevant in relation to the future of PNT demand and systems.

One of the most important is Internet of Things (IoT). A world of **massive IoT** is envisioned, with over 1 trillion devices ubiquitously deployed. Although it is clear that not all of them will require PNT services, it is fair to assume that a large share of them will, and for those, the most critical demands will be low size, weight, power consumption and cost of the PNT devices, and probably, the time-to-first-accurate-fix (TTFAF). Hyperconnectivity and accessing to crowd-sourced data from IoT devices will open interesting opportunities for the implementation of collaborative PNT solutions.

Another technology that will break through the market by 2035 is **autonomous driving**. It is estimated that over 37 percent of the cars sold around the world by that date will implement Level 3 or higher autonomous driving systems[6]. Some experts question the pace at which autonomous driving L4 and L5 systems, obviously with more demanding PNT requirements, will penetrate the mass market. However, there is little doubt that autonomous buses, taxis and shuttles will represent the lion's share of the urban mobility fleets in the developed countries by that date. As an example, in German cities there will be more than 740,000 autonomous taxis and shuttles by that date[7].

But urban mobility may change in more than one way. **Advanced Air Mobility (AAM)** market for passenger and cargo is expected to reach approximately USD 115 billion by 2035 in the US[8]. Most of the eVTOL vehicles serving this market will be autonomous and will rely heavily on assured PNT services. The cargo segment will develop faster and will still be the largest by that date. Yet less challenging that the passenger segment, cargo AAM will require to resolve a number of technical issues until then, such as collision avoidance, on-board navigation sensors or cognitive systems.

As concerns the passenger air mobility services, by 2035 there will be around 15,000 air taxis in operation worldwide. They will operate between 1,000 – 2,500 air mobility stations ("vertiports") in c.

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[6] Autonomous driving's future: Convenient and connected. McKinsey Center for Future Mobility, McKinsey & Co. January 2023.
[7] Data Nation Germany – Urban Mobility and Autonomous Driving in 2035. How robotaxis will affect cities and automakers. Deloitte. September 2019.
[8] Advanced air mobility. Can the United States afford to lose the race?. Deloitte Insights and Aerospace Industries Association. 2021.

30 cities worldwide[9]. Although the challenge to developing reliable hardware and certifying the vehicles is still opened, the work in these areas is progressing fast: Volocopter expects to be the first company to have its piloted air taxi certified in 2024, and Lillium is expected to follow suit by 2025. Nevertheless, a lot remains to be done, not just as concerns onboard technology for these vehicles, but also regarding the supporting infrastructure, e.g. air navigation traffic control and aids in urban areas.

Two current trends in the power industry will also drive the requirements for resilient PNT:

- The first one is **distributed power generation**. As the renewable energy generation technology evolves, the sources of power will become more distributed, more dynamic and less controllable. This will add complexity to the algorithms required to control the phase across the grid, and in turn demand more stringent requirements for time synchronization of the devices supporting this process.
- The second one is **Smart Grid**, the data network superimposed on the power distribution grid that interconnects the millions of devices to be managed, and that requires not just the localization of these devices, but again precise time synchronization to operate together.

Cloud computing will continue to expand at a significant rate during the next decade. Be them public, private or hybrid clouds, the datacentres where they reside will have increasingly higher relative synchronization requirements, so that data transactions can be orderly performed with the minimal "guard" or "wait" time. Sync accuracy determines the efficiency of multiprocessing.

Quantum technologies will keep evolving in the coming years. **Quantum key distribution** (QKD) over long distances – e.g. using satellites – will be a reality by 2035. In fact, the US National Security Agency (NSA) expects the owners and operators of the American national security system to migrate to post-quantum cryptography by that deadline[10]. **Quantum clocks** and **quantum detectors** will also be available at form factors that allow its use beyond the laboratory, and at affordable costs. This will open new avenues for the development of resilient PNT services.

Artificial intelligence and **machine learning** will be fundamental enablers in many different technology fields, including PNT. Within a ten years horizon, **Explainable Artificial Intelligence** (XAI) will improve the predictability and trustworthiness of AI models and ease its use in safety critical applications and systems (e.g. autonomous driving). Moreover, AI will also open new data processing techniques for multiple applications.

By 2035, **5G networks** will provide full coverage of urban areas worldwide. The deployment of **6G services** will have started, although with limited availability. The technology advances in data processing and antenna arrays will allow to achieve high accuracy positioning in challenging environments by combining Uplink Time Difference of Arrival (UTDoA) and Angle of Arrival (AoA) observations with base-station selective exclusion methods to eliminate measurements affected by Non-Line of Sight (NLoS) propagation.

Distributed and networked time scale infrastructures, like the one being built by the UK's National Timing Centre[11], will enable innovation for resilient timing applications independent from GNSS.

The battling against climate change will continue, calling for more efficient transportation means. Optimizing logistics chains, transport routes for both air and shipping freight will be a priority.

[9] Air taxis: onward and upward. Porsche Consulting GmbH. March 2022. Air Taxis: Onward and Upward - Porsche Newsroom. Last accessed March 4th 2024.
[10] National Security Memorandum 10 (NSM-10) on Promoting United States Leadership in Quantum Computing While Mitigating Risk to Vulnerable Cryptographic Systems. May 2022. National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems | The White House. Last accessed March 4th 2024.
[11] For more information, see National Timing Centre NTC - NPL. Last accessed March 29th 2024.

Similarly, sustainable economic growth will also call for improvements in the efficiency across all the industries, from agriculture to manufacturing, that in turn will demand further technological advances in **connectivity, robotics** and many other fields.

An important driver for the development of advanced technologies until 2035 is **space exploration** and, eventually, space exploitation. More than 30 space missions to the Moon are planned between 2023 and 2030. Within a decade, the Lunar Gateway platform will be orbiting the Moon, helping the humankind to test the technologies and capabilities required for a sustained human presence in deep space.

Moreover, several **satellite mega-constellations** in Low Earth Orbits (LEO) will be available, providing mostly communication services, in many cases compatible with 5G/6G ground networks. Some of these constellations may be devoted to PNT services or carry onboard PNT payloads. Crowded orbits will oblige to the space powers to develop space traffic control mechanisms.

It is important to note that this paper is not intended to provide a broad technical vision. The focus is PNT, not future technologies. The growth/market dynamics of – to give examples – air mobility and autonomous driving, is highly uncertain. What is not in doubt is the impact the prospect of these markets is already having on those planning and developing PNT systems.

4.3 Demand evolution

4.3.1 Overview

The PNT demand by 2035 will be conditioned by the applications across several domains, from consumer services to space. Consumer solutions and road applications will still dominate the market, although IoT will have grown to become an important segment. Nevertheless, the demand will also grow in the professional market segments with more demanding requirements.

As concerns the user requirements, from a general perspective the following trends can be anticipated:

- **Accuracy** is addictive: users in all domains will push for higher accuracy (even if not needed!).
- The users will demand a more **robust** solution, less susceptible to natural or man-made disruption, e.g., radio frequency interference (RFI), and cyber threats, including supply chain threats and vulnerabilities.
- **Resilience** (that is, the ability to return quickly to a previous good condition after problems) will be an important driver as well.
- Road applications will likely drive the requirement for service **integrity, reliability and continuity**. Besides, Automatic Driving Assistance Systems (ADAS) will require faster TTFAF.
- **Assured PNT** demand will grow tenfold until 2035, also in physically challenging environments (e.g., indoors, multi-story buildings, urban canyons, and underground facilities).
- Performance levels might not be necessarily the same over the complete service volume.
- Size, Weight, Power consumption and Cost (**SWaP-C**) reduction will be a key driver for many applications, especially in the likely largest market segments.

The key drivers for the design and implementation of future PNT systems and services will depend on the application domain. The various use cases will demand different performance and operational requirements, which may lead to the implementation of different solutions by combining diverse alternate and / or complementary systems. Anticipating the evolution of PNT requirements will therefore imply the consideration of at least some of the most relevant use cases foreseen in ten years from now.

4.3.2 Use cases

Given the relative weight of the different market segments, it is obvious that two of the use cases that must be considered in this document are consumer solutions and road applications. These two segments alone will account for over 90 percent of the total installed base of PNT devices, and consequently, a similar share of the total PNT business, by 2035. Whatever the future PNT systems may look like by that date, they cannot ignore the demands of these segments.

The User Consultation Platform (UCP) of the EU Agency for the Space Programme (EUSPA) provides a useful reference for the future use cases in the consumer solutions community[12]. These consumer services encompass a broad range of applications, supported by different categories of connected devices, mostly smartphones and tables, but also wearables, personal tracking devices, digital cameras or laptops. According to the conclusions reported from the last consultation conducted in 2022, emerging applications will require a much more stringent level of horizontal and vertical accuracy. In addition, some others will require location and time authentication to protect users or service providers.

The future **consumer** applications and services will share a number of common demands, for instance:

- Most, if not all, of the mass user devices will run on batteries, which implies that they must remain small and lightweight. This will have an impact on the selection of frequency bands for future GNSS, as this may affect the design of components and receivers. Tracking two different frequencies will certainly result in higher accuracy and robustness, but also in higher power consumption and (marginally) in size. The implementation of multifrequency solutions will require a careful trade-off between the two aspects.
  Another implication is that most of the devices will have to remain in a sleeping state for as long as possible, and then activate quickly when needed. Thus, Time-to-First-Fix (TTFF) and in some cases TTFAF will have to be as short as possible. Assisted GNSS (A-GNSS) will be an important feature in many use cases.
- The users will demand to access these applications and services regardless of whether they are outdoors, indoors, under canopy or in an urban canyon. Seamless PNT service will be the standard. This will require sensor fusion and hybridization at the user device.
- Miniaturization. Either embedded on a smartphone, a camera or a wearable, the size of the PNT sensors will definitely matter. It may even impose an impossible constraint on some sensors whose suppliers may have to seek out other applications and markets because of SWAP limitations.
- Connectivity. Many of the mass market applications and services will rely on a combination of PNT and communications. Bearing in mind the demand for miniaturization, this will be a strong driver for the integration of PNT sensors and communications into a single chip.
  The need for connectivity works against resilience and cybersecurity. This may cause the market to split.
- Trustworthiness. In many cases, consumer services may not be critical in the sense of safety of life or assets, but for the common users to uptake some future services, the PNT solution must be robust and resilient enough.
- Cost. This is fundamental driver in non-professional markets, especially considering that the market price of the consumer devices where the PNT sensors are embedded tend to fall over time, at least in relative terms.

There will be though some high-end applications and services with more demanding requirements. One of them is **mobile Augmented Reality** (AR). AR will be used across many different applications to enhance the user experience in fields such as gaming, broadcasting and live events, navigation,

[12] Report on Consumer Solutions. User Needs and Requirements. EUSPA. 2023.

travel applications, or education and training. The combination of cameras, GNSS receivers and high-speed connections in smartphones and wearables (e.g. glasses) enables the development of this kind of applications, where accuracy requirements are high (sub-meter level).

Another example is **banking services**. This includes for instance location-based billing (LBB) for automated fare collection systems in public transit, smart parking or mobile phone roaming. These applications demand high Quality of Service (QoS), short TTFF and indoor availability. High accuracy and robustness are also important to endure that customers are charged the correct tariffs. Banking services also include fraud management, where accuracy, availability and continuity both indoors and outdoors are important, but also require some kind of authentication mechanism. Last but not least, the growth of fintech applications will also drive the demand for accurate timing services on mobile devices.

Figure 2.- Mobile augmented reality applications will grow to offer the consumers a realm of new services.

Another relevant use case to consider in the evolution of PNT demand is **autonomous driving**. The consulting firm McKinsey estimates that by 2035, at least one third of the cars will be equipped with advanced AD technologies (Level 3or 4). In an accelerated scenario, the share of AD enabled cars would exceed half of the vehicles[13].

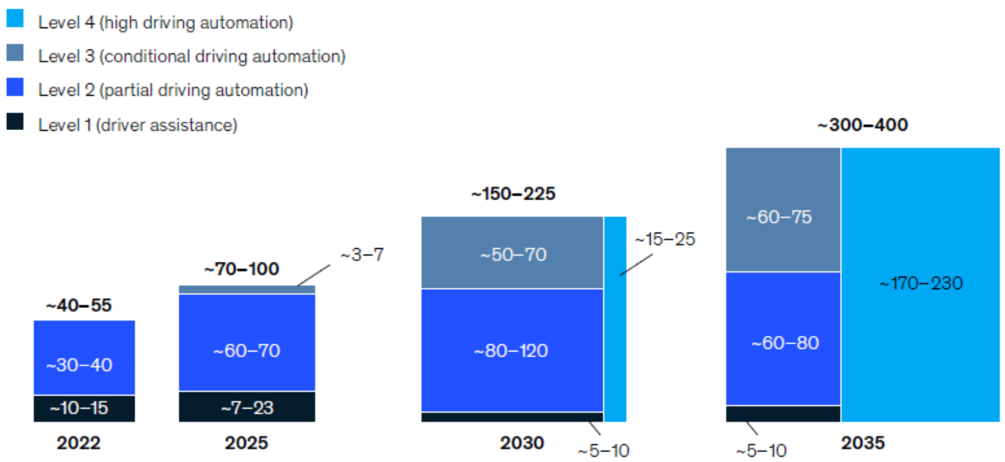

Figure 3.- Advanced driver-assistance systems (ADAS) and autonomous-driving (AD) revenues, USD billion (Source: McKinsey Center for Future Mobility).

[13] Autonomous driving's future: Convenient and connected. McKinsey Center for Future Mobility, McKinsey & Co. January 2023.

Car manufacturers will roll out autonomous vehicles featuring advanced sensors and computers, but sizable revenues will be generated through new business models: for example, pay as you go, which offers AD on demand, software upgrades or new subscription services.

PNT technologies are doubtless a key enabler for autonomous driving applications. However, they are just part of the AD technology stack. PNT suppliers must decide if they want to be full-stack players for the most advanced systems or concentrate on dedicated areas of the stack, which could be either hardware components or software elements. The required functional safety poses additional complications for realizing AD.

Support from regulators is essential to overcoming AD safety concerns, creating a trusted and safe ecosystem, and implementing global standards. Safety certification may become an issue for the industry.

As concerns **security and defence** uses, the priority will be to assure PNT services in Anti-Access Area Denial (A2AD) scenarios. Ensuring the availability of PNT solutions for armed services and defence systems will be critical for enhanced military mobility – one of the European Defence Agency (EDA) priorities –, autonomous systems in all the operational theatres, from space to underwater, as well as for critical defence and security communications and combat cloud – because of time synchronization needs – and weapon systems functionality. GNSS will be subject to, and will have to counteract, cyberthreats, jamming, spoofing and meaconing. More robust GNSS services and alternate PNT systems will have to be implemented to guarantee the continuous availability of PNT solutions for defence and security applications in a world where temporary or more permanent disruptions in the use of some space systems can be expected, and others, like GLONASS or Beidou, could simple not be available to the European armies in a new Cold War scenario.

Urban and Advanced Air Mobility (UAAM) will have become a reality in 2035. Three potential use cases can be envisaged[14]:

- Last-mile delivery: Rapid delivery of small packages from local distribution hubs to the receivers. Deliveries are unscheduled and routed as online orders are placed.
- Air metro: Similar to current public transit options, with schedules routes and fixed stops. Vehicles are autonomously operated and can accommodate 2 to 5 passengers at a time.
- Air taxi: The air taxi use case is a near-ubiquitous (or door-to-door) ridesharing operation that allows consumers to call mostly electrical vertical take-off and landing aircraft (eVTOLs) to their desired pickup locations and specify drop-off destinations at rooftops throughout a given city. Rides are unscheduled and on demand like ridesharing applications today. Like the air metro case, vehicles are autonomously operated and can accommodate 2 to 5 passengers at a time, with an average load of one passenger per trip.

The growing UAAM business will require the implementation of urban air traffic control services and landing infrastructures (i.e. Vertiports) that will enable the operation of both manned and autonomous passenger and cargo air vehicles in urban areas.

[14] Urban Air Mobility (UAM) Market Study. NASA. November 2018. 20190002046.pdf (nasa.gov). Last visited, March 9th 2024.

Figure 4.- Vertiports and receiving vessels for packages are key enablers for the development of the UAAM market. However, other infrastructures, like e.g. alternate or complementary PNT systems will be required to allow the operation of autonomous air vehicles in densely populated urban areas.

UAAM will also rely heavily on assured PNT services in those urban areas, prone to occultation and multipath effects. It is foreseeable that these PNT services will in turn require the deployment of local infrastructures to generate GNSS corrections or of alternative and complementary PNT services.

The way in which all the required services, i.e. infrastructure availability, PNT, communications or others, reach the end-user, for instance an air taxi company or a logistics operator, is still far from being defined. Nevertheless, mobile communication operators and infrastructure companies are likely players in this market.

Maritime Autonomous Surface Ships (MAAS), either remotely controlled or fully autonomous, will carry aboard a large share of the world's commerce. GNSS and autonomous sensors (e.g. CSAC and inertial sensors) will be the PNT data source of choice at sea, where access to other ground-based RF networks will be limited at best. Ensuring the availability of PNT services will be critical to allow the optimization of routes to reduce the cost of goods transport.

Last but not least, **Robotics operations in the Moon surface** – or controlling the space traffic in crowded Earth orbits – will require high performance PNT services beyond the current GNSS service volume, at least for the Earth-Moon transfer orbit, Lunar orbit, and descent, landing and ascent of lunar vehicles. High-sensitivity receivers, onboard dynamic filters and high-gain antennas will help to enlarge the space service volume, but the required level of performance will demand the transmission of additional ranging signals from the Moon orbit and the Moon surface, or alternatively autonomous sensors (e.g. atomic clocks) with the possibility of synchronizing periodically to time and spatial references.

4.3.3 Expected performances and operational requirements

The following table summarizes the expected performances and operational requirements of the PNT solutions for different users and critical applications by 2035:

Table 2.- Foreseen performance and operational requirements for different user types and critical applications.

User type	Application	Accuracy (H / V)	Availability	Continuity	Integrity	Alert time	Alert limit	Geo coverage
Aviation	CAT I – III landing	16– 3 m	99 – 99.999%	>1 -8.10^{-6} in any 15 s	>1-2.10^{-7} per approach	6s – 1s	4 -1 m	Regional or local Outdoors
Marine	MAAS harbour approach, waterways	10 – 2 m	99.8 – 99.9%	99.97% in any 15 min	TBD	10s		Global Outdoors
Road	Collision avoidance, autonomy L3 and above	10 cm	99.90%	>10^{-8}/h	1-10^{-8} / h	5 s	20 cm	Regional or local Outdoors, indoors, urban
Agriculture	Precision irrigation, cultivation	15 – 2 cm	99.90%	TBD	TBD	5 s	25 cm	Regional or local Outdoors
Geomatics	Kinematic survey	6 – 4 cm	99%	10^{-4} /h to 10^{-6}/h	TBD	1s	TBD	Regional or local Outdoors
Railways	Positive train control	1 m	99.90%	TBD	TBD	6 s	2 m	Regional or local Outdoors Tunnels Urban
Precise timing	5G and DVB	10 ns	TBD	TBD	TBD	TBD	TBD	Global Outdoors Indoors

5 Evolved system architecture: the upstream view

5.1 Overview

By 2035, assured PNT will be provided by a combination of alternative, independent and complementary data sources, including:

- Multiple GNSS in different orbits (MEO, GEO, IGSO and LEO), operating in several frequencies.
- Cellular communications networks, providing 5G/6G functionalities and potentially including satellites in LEO.
- Ground based RF networks, e.g. eLoran or Wi-Fi, and SoOP.
- Augmentation systems, both local and regional, including regional correction PPP-RTK networks.
- Autonomous sensors, e.g. inertial, quantum, magnetic, star trackers, miniaturized atomic clocks (e.g. CSAC), as well as high precision digital maps and digital terrain models.

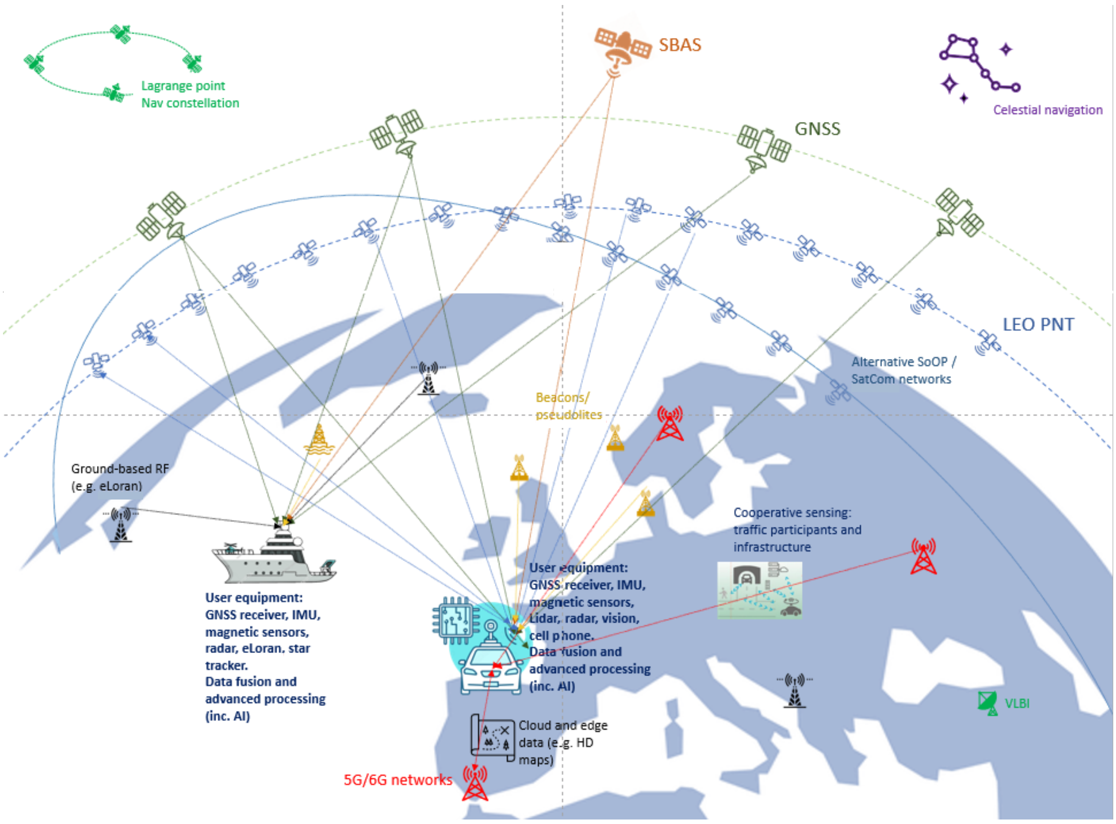

Figure 5.- Assured PNT services by 2035 will depend on diverse combinations of systems. In fact, PNT infrastructure is likely to consist of a series of systems-of-systems for different uses and not necessarily providing global coverage.

Galileo 2G will be fully deployed, providing improved High Accuracy (HAS), Authentication (OSNMA) and Commercial Authentication (CAS) services. Moreover, Europe will take advantage of the deployment of LEO constellations for governmental communications (e.g. IRIS2 second generation) to complement MEO GNSS services with higher power, lower latency signals. This system will operate in a different frequency band than traditional GNSS, possibly UHF or C-band.

5G and partially deployed 6G networks will also provide complementary radio navigation services for mass applications, largely ensuring the performances required for seamless indoor positioning and navigation.

Critical infrastructures and security applications will rely on other independent dedicated networks. Autonomous sensors and clocks will ensure the robustness and resilience of the services.

As concerns PNT for space applications, the GNSS service volume will extend beyond the limit of GEO by using dedicated navigation satellite constellations at the Lagrange points.

The next sections discuss on the foreseen evolution of PNT infrastructures and on the technologies that will enable them.

5.2 PNT Infrastructure: a system-of-systems

The task is to predict the probable PNT infrastructures in 10 years from now in the year 2035. A basic view is that PNT infrastructures will move more and more into a "System of Systems (SoS)". What is understood under a "Systems-of-Systems"? Although there are many definitions in the literature, we retain in this paper the following one as a working assumption[15]: A System-of Systems is a system consisting of a set of interacting systems, each of which can be considered a system in itself. The main characteristics of a SoS are: "*Each system can interact independently and has its own purpose, the individual systems of the quantity are independently organized to fulfil their purposes, the combination of systems delivers results that cannot be achieved by individual systems.*"

Applying this definition, a "System-of-Systems" indeed exists in satellite navigation (SatNav) today. In the context of the GNSS2 (Galileo, Beidou) developments a first SoS approach was outlined. Within the concepts of compatibility and interoperability, a satisfactory level of combinability in GNSS is a fact today. Brad Parkinson – the "father of GPS" – went a step further[16]. He added the requirement of interchangeability. However, interchangeability between different SatNav turned out to be too idealistic, because SatNav service providers (US, China, Russia) are treating their SatNav concepts as dual use systems, with a strong focus on military and governmental use. They are not willing to open the governmental part (national security) to the world. Europe in fact does the same with the PRS (Public Regulated Service). Very interesting is the SoS aspect in the multi-layer concept developed by ESA. Here the plan is to integrate further terrestrial systems like 5G/6G in an entire PNT System-of-Systems concept.

5.2.1 Space-based PNT Infrastructure

Space-based PNT infrastructures consist of global systems in the MEO and LEO orbit, and many regional augmentation systems. Most of the regional systems are SBAS (Space Based Augmentation Systems) making use of geostationary satellites. There are three exceptions from this: The Japanese QZSS (Quasi Zenith Satellite Systems) makes use of inclined elliptical orbits, the Chinese Beidou 3, which makes use of geostationary satellites and IGSOs (Inclined Geosynchronous Orbits), the Indian NavIC is using a mix of GEOs and IGSOs. Local augmentation systems like active RTK, PPP-RTK networks and reference networks for precise Point Positioning (PPP) also can also be considered in a sense as space-based infrastructure.

The following paragraphs provide a description of the existing and planned space-based infrastructure.

5.2.1.1 MEO-PNT

The MEO-PNT systems will be also the GNSS backbone in 2035. In 2024, the 1st – 2nd generation systems are nearly launched, and the next generation systems (G2G and GPS IIIF) are under developed and ready to be launched from 2026 onwards (GPS IIIA launched since 2018). With a

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[15] Karlsruher Institut für Technologie (KIT). See IPEK - System of Systems (kit.edu). Last accessed March 29th 2024.

[16] See GNSS Year in Review: Three Trends That Matter - Inside GNSS - Global Navigation Satellite Systems Engineering, Policy, and Design. Last accessed March 29th 2024. See also The Future of Satellite Navigationv11.ppt (stanford.edu). Last accessed March 29th 2024.

design life of 15 years, they will be still present in 2040+. MEO-PNT provides the open signals free of charge. The space electronics is based on advanced parts (materials) and processes. Although expensive, the result is high quality of satellite hardware and software. Except for Galileo all the MEO-PNT are officially declared as dual use systems (civil & military).

MEO-PNT systems and their regional augmentation systems have gained high maturity with potentially about 120 MEO satellites and 6.5 billion GNSS L-band receivers in the world market. We have **four** (nearly) operational global systems (the question on future use of GLONASS is open) and four operational SBAS systems (plus five SBAS systems under development) available. We have to add the regional systems QZSS and NavIC. On the other hand, the user requirements became increasingly stringent for autonomy and safety critical applications over the last decade. For many applications of this kind, significant performance and robustness gaps exist with respect to interference, jamming, spoofing, and availability, integrity and other performance issues like multipath.

Galileo:

Currently, the system built for the 1st generation (G1G) is under delay. 28 satellites are in orbit, but only 23 are working nominal. The last successful Soyuz launch happened in December 2021. After Russia began the war against the Ukraine the planned Soyuz launches for 2022+ were terminated. This came together with technical delays in the new Ariane 6 launcher. Consequently, ten G1G satellites are still grounded. The plan is to launch four G1G satellites by two consequent Falcon 9 (SpaceX) launches in 2024. The first G2G launch is planned in early 2026. G2G will offer many optimized and improved features[17]: New open service signal for IoT low-end signal processing; flexible payload; more & smaller atomic clocks; efficient high-power amplifier and equalizer; RF-Inter Satellite Links; electric propulsion system (EPS; new services, e.g. Space Service Volume (SSV), Advanced RAIM, EWS (Emergency Warning Service), more effective PRS (Advanced PRS). Additionally, range authentication (SAS) will be used for anti-spoofing and a better HAS (High Accuracy Service). The GSEC (Ground Segment) will also be improved.

GPS:

GPS modernization started in 2005 by launching the modified GPS IIR-M satellites. Concerning the legacy signal structure a big up-grade in the signal structure was done: A new civil signal on the 2nd frequency (L2CS) and a new military M-code. The next modernization step was based in 2010 on the GPS IIF satellites where a 3rd civil broadband signal was added on the L5-frequency. The final step of GPS modernization happens in the frame of GPS III. Besides many technical improvements, a modernized civil signal (L1C, same as Galileo E1) will be transmitted. Additionally, the plan is to provide regional high-power (+ 20 dB) for the M-code by aid of spot-beams. The Block III launch plan was in 2017 divided into a bridging phase with 10 GPS IIIA satellites (6 are already in orbit). The final GPS modernization with all improved civil and military features (full NAVWAR capability) will be realized via the 22 GPS Block IIIF satellites. The first GPS IIIF launch is planned for 2027. Currently, 38 GPS Satellites are in the constellation, of which 31 are set healthy. In GPS modernization two major problems exist: The new operational control system (OCX) is still under delay (since 2016, "Nunn-McCurdy Breach" in US Congress because of heavy cost overrun) and will not be finished before mid-2025. The second issue is that new military M-code capable receivers (MGUE, Modernized GPS User Equipment) are under delay for several years[18].

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[17] See Galileo: From the First to the Second Generation. Eissfeller, Bernd. April 2022. zfv_2022_4_Eissfeller.pdf (geodaesie.info). Last accessed March 29th 2024.

[18] La Pena, 2023. See also US GAO Report to Congressional Committees on GPS Modernization, June 2023, available at GAO-23-106018, GPS MODERNIZATION: Space Force Should Reassess Requirements for Satellites and Handheld Devices. Last accessed March 29th 2024.

Beidou:

The operational system of Beidou (BDS-3)[19] was formally completed in 2020. BDS-3 is a hybrid constellation consisting of 24 MEO, 3 GEO and 3 IGSO satellites. BDS-3 provides on the one hand global services (PNT, Global Short Message Communication, SAR), and on the other hand Asia-Pacific related services (Regional Short Message Service, PPP, SBAS, Ground-based Augmentation System). In comparison to GPS, Galileo, GLONASS the Chinese were able to integrate more or less all GNSS service elements under the Beidou-3 umbrella. The future plans for Beidou are not as clear. No BDS-3 modernization was announced. They go into the following directions: Development of back-up satellites, optimization of production and status to ensure the stable and continuous operation, adoption of standardized solutions to meet common needs, a comprehensive PNT system (this is the Chinese LEO-PNT constellation) will be established with BDS-3 as the core. On December 26, 2023, two BDS-3 MEO satellites were lunched successfully into the orbit by a Long March 3B rocket. The pair will act as backups and reduce the operational risks to the Beidou-3 system, according to a CASC (China Aerospace Science and Technology Cooperation).

GLONASS:

Originally, the Russian GLONASS system was a fully accepted global element in the international satellite navigation scene. In 1999 in the EU (Communication, Feb. 1999) even a significant role for the Russian Federation in the Galileo development was suggested. Currently, the GLONASS constellation consists of 26 satellites (24 are operational & two are in flight-test mode). The GLONASS modernization was starting in 2003 with GLONASS-M and was continued with GLONASS-K in 2011 and GLONASS-K2 in 2023. At the beginning, GLONASS was a FDMA like system. During the modernization phases CDMA signals were implemented in parallel to legacy FDMA signals. Russia has a close cooperation with China in satellite navigation. After the invasion of Russia into the Ukraine the question is on the table, how to handle GLONASS in the multi-frequency and multi-system scenario. For obvious reasons the Russians are not invited anymore to international meetings. They are only present on UN level in the ICG (International Committee on GNSS) working groups. The risk is, that Russia will change system and signal features, which are not documented any longer in their Interface Control Documents (ICDs). Multi system receivers are under a certain risk.

5.2.1.2 Dedicated LEO-PNT and LEO-augmented GNSS

Since 2018 several dedicated system proposals were developed for satellite navigation from the low earth orbit (LEO-PNT). LEO-PNT will add a new infrastructure element to the space-based PNT infrastructure. We could expect 3-4 systems in the orbit in 2035. Currently, about 10 proposals are on the table. Some of them will turn out to be not viable.

[19] Beidou Navigation Satellite System. LI Zuohu. China Satellite Navigation Office. 16th ICG Meeting, October 2022. Available at Microsoft PowerPoint - Beidou Navigation Satellite System Construction and Development_221010.ppt (unoosa.org). Last accessed March 29th 2024.

Table 3.- Planned LEO PNT infrastructure

System	Constellation	Orbits Height, i	Satellite SWAP	Frequency Band	Higher Power
IRIDIUM Next STL, Satelles (USA)	66 SVs on 6 planes, global	780 km, i = 86.4° polar	3 m, 860 kg, 2200 W, DL < 15 y, Iridium Next Bus	L = 1621 - 1626 MHz, Iridium MSS	+ 30 dB dedicated signal
APS-Globalstar (USA)	32 SVs on 8 planes, global	1410 km, i = 52.0° inclined	3 m, 700 kg, 2400 W, DL < 15 y, Globalstar Bus	S = 2483 - 2500 MHz, Globalstar MSS	Yes (TBD) SOOP
OneWeb (UK, EU)	648 SVs on 18 planes, global	1200 km, i = 86.4° polar	1.3 m, 150 kg, 210 W, DL < 5 y, (Airbus) Arrow Bus	Ku=10.7-18.1 GHz (TBC)	Unknown, UK GPS, on hold
PULSAR (USA)	260 SVs on 6 planes (TBC)	1000 km, i = 52.5° inclined	0.6 m, 150 kg, 200 W, DL = 5 y, Proprietary Bus	L = 1260 MHz & C = 5020 MHz (TBC)	+ 20 - 30 dB
TrustPoint	≈ 300 SVs, Planes TBD	500 – 800 km, i = TBD	6 U cube sat, 10 kg,60 W OAP	C ≈ 5000 MHz, no L-Band	No, PSD as legacy GNSS
Synchrotube (F)	TBD	TBD	6 U bus	L-Band (TBD) to S-Band (TBD)	TBD
Black-Jack (USA), Merging into proliferatedLEO	4 (20), down-sized	550 km, i = 97.6° sun-synchronous	1 m, 200 kg, 108 W, X-Sat Saturn Class Bus (Blue Canyon)	L- ,C-Band & higher; optical: visible to IR (TBC)	Unknown, experimental PNT-Payload SEARGANT
Centispace (CHN)	1)120 SVs / 12 planes + 2)30 SVs / 3 planes 3)40 SVs / 4 planes	1) 975 km, i = 55.0° , inclined 2) 1100 km, i = 87.4° , polar 3)1100 km, i = 30.0°, inclined	1.3 m, 100 kg, TBD W, DL < 10 y, CAS Microspace WN-100 Bus	CL1= 1569-1581 MHz, CL5= 1170-1182 MHz	Yes, + 3 dB (TBC) compatible with BDS (GNSS)
GeeSpace/Geely (CHN)	240 SVs/ planes (TBD)	620 km, i = TBD, inclined	GeeSat GSP100, 100 kg, < 1500 W (TBC), DL=5 y	L-Band (TBC)	Unknown, compatible with BDS
IRIS² (EU)	≈ 200 SVs / planes (TBD)	TBD	700 kg (TBC)	L, C, Ku, Ka (TBD) Com+Nav	Unknown, PNT Hosted Payload
INES (F, EU) (historical)	70 SVs on 7 planes	1416 km, i = 62.8°, inclined	Unknown	E1 = 1589.74 MHz, E4 = 1258.29 MHz	No, compatible with GPS
TRANSIT (USA) (historical)	10-12 SVs on 5-6 planes	1075 km, i = 90.0°, polar	1.0 m, 140 kg, 45 W, DL = TBD	f_1 = 149.98 MHz, f_2 = 399.98 MHz	Unknown

The common mainstream characteristics of these proposals is that a Low Earth Orbit (LEO) will be used and that on space segment level (low-cost) commercial or proprietary satellite busses and navigation payloads are developed which make use of Commercial Of-The-Shelf (COTS) components. The smaller orbital height of the LEOs allows the use of small-satellite technologies in order to obtain reasonable carrier power levels on the earth-surface. The utilization of many Nano, Micro and/or Mini satellites is matching very well to the New Space paradigm. Main differences between the concepts consist in the orbital altitude and inclination and in the envisaged frequency plan and transmitted power levels. Some proposals move the technical load to the user-segment and keep the space-segment lean. They need directive antennas (CRPAs) at user level to come-up with a stable and robust link-budget. Other systems are implementing full compatibility with the current MEO-PNT in L-Band. They have the advantage that the existing GNSS user segment may be re-used to a large extend. Minimal investments of the receiver manufacturers are needed to prepare the user segment for LEO-PNT in L-Band. However, some requirements may be lost (e.g. higher power for better anti-jamming).

5.2.1.3 Fully opportunistic LEO-PNT

In fully opportunistic LEO positioning existing mega constellations (Starlink, Oneweb, Orbcom, Kuiper, Telesat) are used. The primary use of these systems is high through put (HTS) communication. The idea is to utilize features of the communication signals for navigation. The simplest way is to measure the Doppler shift on the carrier frequencies and apply the principle of Doppler positioning. This is similar to the historical concept of TRANSIT. In the Doppler concept, eight visible satellites (which is no problem in a mega constellation) are required because three position, three velocity and two clock states have to be determined.

Table 4.- Opportunistic LEO-PNT constellations.

Constellation	Number of SVs in final design	Altitude [km]	Frequency Bands	Planned initial service
OneWeb	600 - 900	1200	Ka, Ku	2021
Starlink (SpaceX)	800 – 42000	340 - 1150	Ka, Ku, V	2020
Telesat	300	1000 - 1200	Ka	2022
Kuiper (Amazon)	3236	590 - 610	Ka	TBD

In general the communication signals do not fulfil the requirements of robust and precise satellite navigation: Partly the signal and data structures is proprietary information of the service providers, the orbit accuracy is on the 100-200+ m level, the onboard clock synchronization is not accurate, no precise models for the atmospheric delay and frequency errors are available. Because of the high carrier frequencies, heavy parabolic and/or array antennas are standard to provide a high gain in the direction to the satellite. Currently, several academic institutes are doing research on opportunistic LEO-PNT. However, the future use in performance driven PNT is unclear. Most likely, the role might be found in a rigorous resilience concept in the case that all the MEO-PNT and dedicated LEO-PNT systems are lost by jamming and spoofing.

5.2.1.4 DLR Kepler Concept

A modified MEO-PNT concept, called Kepler, was first presented by the DLR institute of Communications and Navigation (Operpfaffenhofen) in 2018. Kepler is a system proposal for a 3rd generation satellite navigation system[20]. Kepler is based on the networking of MEO satellites by means of optical inter-satellite links, which enable precise distance measurements as well as time transfer between two satellites at a time. They also allow fast communication in the network so that the satellites can synchronize with each other. In addition, a small constellation of satellites in Low Earth Orbit (LEO) allows observations of the radiated signals without atmospheric interference. Together with precise optical ranging between selected satellites, this provides orbit determination capabilities with unprecedented accuracy. The Kepler infrastructure thus consists of three main components: A constellation of MEO satellites, e.g. G2G networked by means of optical inter-satellite links within the orbital planes. A small constellation (six) of LEO satellites for observing the

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[20] Kepler – 3rd generation satellite navigation. DLR - Institute of Communications and Navigation - Kepler Program. Last accessed March 29th 2024.

radiated signals, for time transfer between the MEO orbital planes and as carriers of some long-term stable clocks, and at least one ground station to maintain the system's coupling to the Earth's rotation.

Thus, in summary Kepler is not a LEO-PNT system, but it is making use of LEOs to interconnect the orbital planes of the MEOs and provides a type of space-based integrity monitoring of the MEO signals in the LEO. Optical laser ranging terminals establishes the connections and synchronization links between the MEOs and MEO-LEO. The general concept behind Kepler is to minimize the SISE (Orbit and Clock error of the MEOs) to nearly zero. The concept is not to provide additional robustness and dynamics to the user segment with improved signals like LEO-PNT does.

Kepler has strong and weak points:

The *strong* arguments are to introduce laser based ISLs (OISLs) in the MEO space segment and cavity-stabilized lasers with very good short-term stability (10^{-15} over 10 s).

There are several *weak or idealistic* arguments:

Only *six* LEO satellites by RF- and Laser ranging between the orbital planes do the synchronization. In an A-Sat (anti-satellite weapon) scenario, the removal of six LEOs is a minor problem. Thus, the security issues of PRS in Galileo were ignored. No contingency scenario for synchronization was integrated into the system. Only intra-plane laser ranging is foreseen for the MEOs: This leads to observability problems in ODTS. The assumption of only one monitoring station on the earth-surface is highly idealistic. To determine the instantaneous earth-rotation axis (vector) plus the magnitude (LOD or length of the day) and polar motion is not possible with one vector of station coordinates (X, X, Z in ITRF2020), because a rotational degree of freedom around the station vector is not observed. Additionally, the entire geodynamics of the earth-crust (tidal deformation, ocean loading effects, polar tides, post-seismic deformations) are not observed. In addition, the monitoring system with one station does not observe the ionospheric and tropospheric error situation. Thus, a significant risk exists in Kepler that the space-segment decouples from the earth-surface where most of the GNSS users are located. By the way, this discussion is not new: It was on the table when the US military introduced UHF-ISLs in GPS IIR together with AUTONAV mode (autonomous ODTS with ISL) in the early 90ties.

5.2.1.5 Regional Augmentation Systems

SBAS (Space Based Augmentation Systems):

Historically, SBAS systems were developed in the early 90ties because Selective Availability (SA) in GPS was switched on and GPS did not provide integrity. The goal initially was to support air-navigation in the phases of flight down to Non Precision Approach (NPA) and later LPV-200 (Local Precision with Vertical Guidance, 200 feet). The classical four SBAS (WAAS, EGNOS, MSAS, GAGAN) are operational and certified for aviation. They play an important world-wide role to precision landing (near) CAT-I performance. Additionally, five SBAS systems are under development. It is often forgotten that the software for the SBAS ground system is developed under aviation standards (DO-178 B). In the first generation of SBAS only GPS L1 was augmented and corrected. In the 2nd generation, e.g. EGNOS V3 the 2nd civil frequency GPS L5 is added. This is leading to a significant performance enhancement from 2027+ onwards. In the meantime, in Europe more than 800 LPV procedures are published and 67% of the runway ends are equipped for EGNOS landing procedures. Thus, we could be confident that dual frequency SBAS will exist in the year 2035.

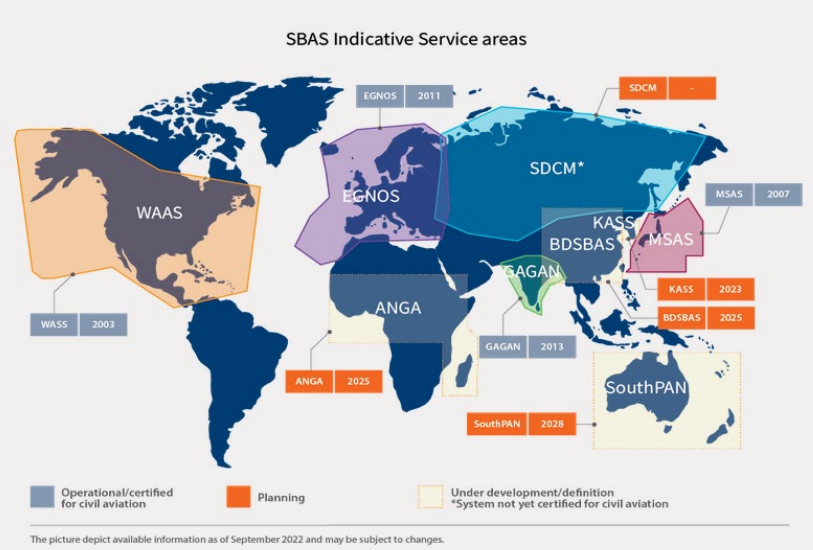

Figure 6.- Existing and planned SBAS.

QZSS (Quasi - Zenith Satellite System):

The Japanese Quasi – Zenith Satellite system (QZSS) is in contrary to GPS, Galileo and Beidou not a self-contained system. It is a specific augmentation system with focus on GPS. The design goal is to provide GPS like signals in deep urban canyons (Tokyo, Yokohama) under high elevation angles > 70°. The QZSS satellites are flying on an inclined eccentric (i = 43°, e = 0.075) orbit (24 h orbit). The ground track in the pacific area and over Japan is an asymmetric figure-of-eight. The carrier frequencies are fully compatible with GPS, i.e. L1, L2 und L5. In addition, an experimental signal LEX is transmitted in the Galileo E6-Band.

NavIC:

NavIC is the Indian regional navigation satellite system. It provides a SPS (civilian) and a RS (restricted) service in the GPS L5 and S – Bands. Service area is India and 1500 km beyond its geo-political boundaries. The nominal constellation consists of 7 satellites (3 GEO and 4 IGSO). In future a civil signal in the L1 – band is foreseen.

5.2.1.6 Precise Augmentation Systems (RTK, PPP, PPP-RTK) networks

Precise augmentation systems (local, regional, global) are complementing the space-based satellite navigation infrastructure. In the high precision field, (accuracy < 1 cm) local real time kinematic networks of reference stations are used. Many CORS (continuous operating reference stations) were implemented. In Germany, the SAPOS network consists of 280 permanent GNSS reference stations. However, not a worldwide coverage is realized, we have more nationwide coverage in some areas. Different concepts have been developed over the years: The main idea behind RTK and PPP is to eliminate the errors on the pseudorange and carrier-phase (satellite orbit, clock error & delay biases, ionosphere & troposphere) with reference receivers in a precisely known position.

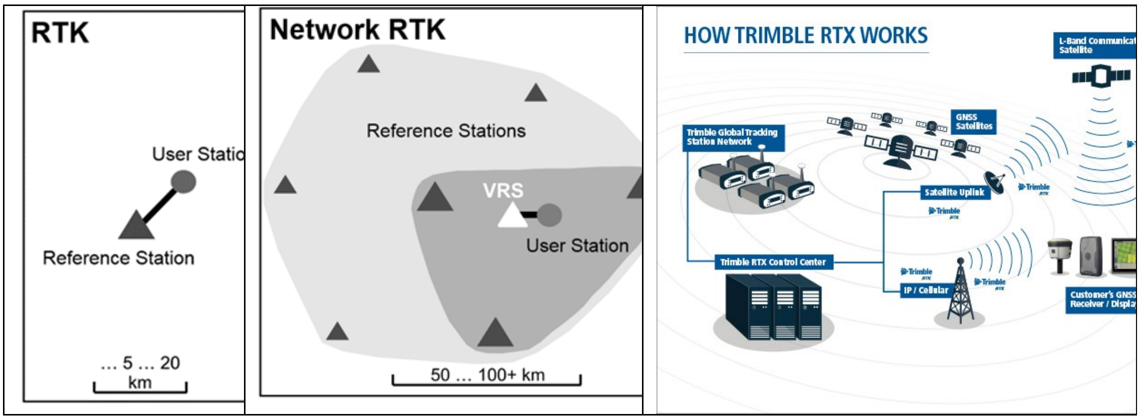

Figure 7.- RTK Kinematic Networks basic operation concept.

RTK and Network RTK (Real-Time Kinematic):

RTK is based on the classical concept of differential GNSS with carrier-phases. We have two types of GNSS stations: The mobile user and the reference station(s). The method works in the observation space (OSR). A widespread method is the VRS (virtual reference station). The user is sending via an NMEA message his approximate position to the central data processing facility. The processing center is selecting a nearby virtual reference station. For this VRS a complete data set of carrier-phase observation is computed and interpolated out of the network. The center sends this reference data stream via a communication link to the user (a 2-way link is required). The mobile user solves for his (nearly error free) position by applying single and/or double differencing to the data.

PPP (Precise Point positioning):

In precise point positioning (PPP) a global network of 100+ reference stations is used. The dual or triple frequency observations for code and carrier-phase are transmitted to a central processing facility. In the processing center orbit, clock, bias errors of each satellite and ionospheric models (vertical TEC) are refined. Because all errors are individually determined and isolated, we speak about a state-space representation (SSR). The PPP user is correcting the respective broadcast ephemeris of the GNSS. After this a dual frequency code and carrier-phase combination (in most cases the ionospheric-free linear combination) is performed. In a filtering process (Kalman filter) over the time axis the remaining unknowns, especially the float and/or integer ambiguities are determined. This process needs some time (convergence time) on 10 minutes level (or better). The Kalman filter may be constrained by using ionospheric (VTEC) up-date information, which is determined by regional active networks. The Galileo HAS (high Accuracy Service) belongs also to this class of methods (PPP, SSR).

PPP-RTK (Integration of PPP in RTK networks):

PPP-RTK is a fusion of the two methods: The mobile user is performing a PPP solution. The same is done in the network of reference stations by each reference station. Thus, in the network the remaining errors in the PPP solution may be determined. They are mainly due to ionospheric and tropospheric uncertainties. The processing stays in the state space (SSR). The corrections to the PPP data determined in the CORS network are simply transmitted into the user domain. Only a one-way link (broadcasting only via DAB) is required and no raw data has to be transferred. Currently, the CORS networks are not ready for PPP-RTK. It will take some time to integrate the new functions. Depending on the innovation speed in the CORS networks PPP-RTK will be ready e.g. in Germany from 2025 on. The PPP-RTK scenario will be present in 2035. PPP-RTK has the potential to replace the VRS.

5.2.2 Ground-based PNT Infrastructure

5.2.2.1 5G/6G

5G is a mobile communication standard, which was introduced since July, 2016. 5G has several advantages with respect to its predecessors: Faster data rates, smaller latencies, real-time transmission, and higher network capacities. The standard was developed by the 3rd generation partnership project (3 GPP). Concerning frequencies, 5G is using two frequency bands, below 6 GHz (cm-Waves) and above 28 GHz (mm-Waves).

During Release-16, 3GPP defined a wide range of improved 5G-based positioning techniques: Angle based solutions – Downlink Angle of Departure (DL-AoD), Uplink Angle of Arrival (UL-AoA), and time based solutions – Downlink Time Difference of Arrival (DL-TDOA), Uplink Time Difference of Arrival (UL-TDOA), and Multi Round Time Trip (Multi RTT), which are now included in the positioning protocol. The positioning accuracies range from 10 m down to 0.2 m depending on the location method used, size of service area, user dynamics and frequency band.

Together with enhancements aimed at existing use cases such as mobile broadband, industrial automation and vehicle-to-everything, 3GPP release 17 introduces support for new players including public safety, non-terrestrial networks and non-public networks. Meanwhile, the early planning of release 18 indicates that it will significantly evolve 5G in the areas of artificial intelligence and extended reality.

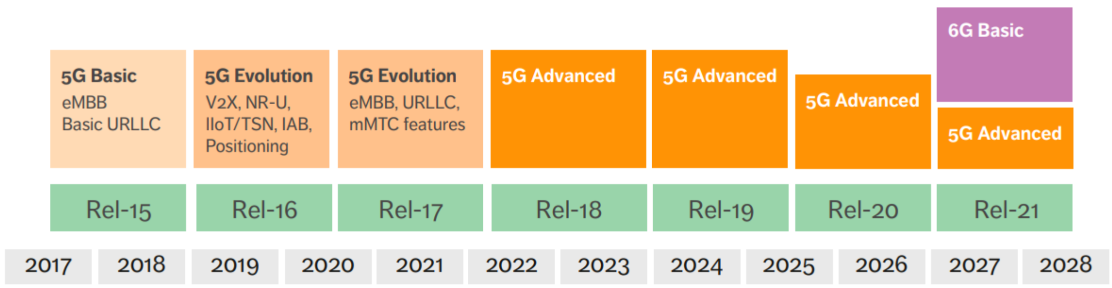

Figure 8.- 3 GPP's 5G evolution tentative time plan[21]

Without any doubt 5 G and beyond (5G advanced and 6 G basic) will be valuable terrestrial complement in 2035. The only issue is that the base-stations are synchronized with GNSS. This implies sensitivity on a common failure in the GNSS. The 5G coverage in Europe differs between 20% and nearly 100%. 5G is a good complement for all terrestrial applications (including UAVs). It is not multi-modal because it is not applicable in the aviation, maritime and space environment.

5.2.2.2 DME (VOR) and ILS

In 2008 an agreement of the aviation stakeholders in Europe was made: A gradual migration in all phases of flight towards GNSS was declared as it will become more robust progressively. Final goal is to use GNSS as a sole means service , although this might be at odds with growing awareness of the need for resilience. Consequently, a rationalized terrestrial infrastructure must be retained for the future. Besides GNSS, the Distance Measurement Equipment (DME) and the instrument landing system (ILS) are here the main infrastructure elements (VORs and NDBs are of minor importance and may be decommissioned). For performance based (PBN) and area navigation over Europe (RNAV) dual aircraft equipment is necessary: DME/DME plus GNSS. DME is a pulsed two-way ranging system first developed in the 1950s. DME is operating in the UHF frequency band between 960-1215 MHz; this part of the spectrum is also known as the Lower L-band. In Germany about 40 DME stations are operational.

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[21] 5G evolution toward 5G Advanced: an overview of 3GPP releases 17 and 18 (ericsson.com). October 2021. Last accessed March 29th 2024.

5.2.2.3 eLORAN

Historically, LORAN-C (Long Range Navigation) was developed, operated by the US Navy during WW II, and later. LORAN-C is a hyperbolic navigation system with precisely synchronized clocks. In the late 80ties LORAN-C was modernized and improved. The result was eLORAN (enhanced LORAN). However, the USA (Obama administration) decided in 2010 to shutdown LORAN. The saving volume was 36 million $US per year which is rather low in comparison to the GPS investments. A study[22] of an Independent Assessment Team, chaired by Dr. Parkinson, which was in favour for eLORAN because the resilience argument was ignored. Europe argued in the same direction and the NELS, North-West European Loran-C System got lower priority with respect to Galileo. On December 1st, the Trinity House (UK) gave a notice to mariners 27/2015 "General Lighthouse Authorities Enhanced Loran (eLoran) Initial Operational Capability (IOC) Prototype And Trials Service Discontinued". In the meantime the assessment of a low-frequency PNT system in the 90-110 kHz band has changed. The awareness on GNSS vulnerabilities was enhanced and some states have reconsidered eLORAN. Loran-C and eLoran operate internationally. Saudi Arabia, China and Russia continue to operate Loran-C or Chayka systems. South Korea has an ongoing project to upgrade its Loran-C chain to eLoran. The United Kingdom is still committed to eLoran, and operates one station that has been used as an alternative time reference to GNSS. In the UK governments, national PNT initiative (October, 2023) the development of a proposal for a resilient, terrestrial and sovereign eLORAN was mandated: On a global basis it is unclear today, if eLORAN will see some kind of renaissance in the year 2035.

5.3 Enabling technologies

The implementation of the PNT infrastructure described above requires the previous development of a number of key enabling technologies. This paper focuses only on those that are specific of the next generation GNSS, including some issues for the user segment. Some of them are already on their way to be implemented in 2nd generation GNSS systems (G2G, GPSIII) and LEO-PNT test missions. Some issues are also a topic in the US NTS-3 experimental PNT mission.

5.3.1 New signals for the open service, higher robustness in signal design

Initially, GNSS signals were optimized for accuracy (low thermal noise, low multipath). This requirement is still important for the high accuracy users. Nevertheless, for most of the safety critical (and mass market) users short TTFF (time-to-first-fix) and robustness against interference, jamming and spoofing is dominant now. Additionally, the PNT signals have to be processed with limited processing power consumption in the user receivers (battery power and small size). Thus, the problem in future signal design is quite tough: On the one hand the signals tend to be more complex with integration new features (e.g. range authentication, like Chimera), on the other hand lower complexity is required to support low-power processing on the low-end chips (IoT). Thus, in future we will need a mix of different signals fulfilling the different user requirements. More emphasis will be on robustness with a priority on interference and jamming. Two concepts in signal design are possible: Higher transmission power and/or larger bandwidth. Higher transmission power could lead to compatibility issues with other GNSS bands. Higher bandwidth will increase the digital processing load on the user receiver. Thus, a reasonable optimization has to be found within certain limits. Here also the question of the carrier-frequency comes into play. Adding C-Band in a LEO-PNT with sufficient power level could be a way out of this dilemma. Moving to much higher frequencies (Ku, Ka) is questionable because the link-budget for typical PNT availabilities (> 99%) is too weak. Adaptive phased-array antennas and array signal processing are needed.

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[22] Independent Assessment Team (IAT) Summary of Initial Findings on eLoran (bts.gov). Institute for Defense Analyses. January 2009. Last accessed March 29th 2024.

5.3.2 Payload technologies

The value chain in satellite navigation systems is longer as 10+ years (from user requirements to signal in space). User requirements alone have much shorter innovation cycles. This leads more and more to the situation that the transmitted signal in space is not compatible with up-to-date user needs. The way out of this dilemma is a *flexible payload*. In NTS-3 an On-Orbit Digital Waveform Generator (ORDWG) will be implemented. The future trend is a software defined radio (SDR) concept for the payload. Theoretically, such a system can be freely programmed with respect to new signal waveforms and data structures (what impacts the design of GNSS receivers respectively).

Another aspect is *higher payload integration*: The G1G and G2G payloads consist of many sub-system boxes, which have to be connected with extensive cabling and harness. A complex PDU (power distribution unit) has to be added. This concept might work for rather heavy platforms (Airbus G2G, 2400 kg). But for LEO-PNT higher integration of sub-systems is a must. It is important to gain high performance with limited primary satellite power and mass (200kg, 200 W, DL=5 years). Advanced real-time calibration loops could become an issue in case of higher accuracy requirements as a countermeasure against code and carrier phase bias delays.

5.3.3 Efficient high-power amplifiers

Highly efficient high power solid-state amplifiers utilizing Gallium Nitrite (GaN), and other technologies are a need for LEO-PNT. The requirements get more stringent, if we move to higher frequencies.

5.3.4 Clock technologies

The clock technologies in satellite navigation flown up to now are atomic clocks: Rubidium, Cesium, H-Maser. In the GPS modernization program, initially alternative clock technologies like Linear Ion Traps (LITS) were discussed but finally discarded. GPS IIIA is flying with three Rubidium clocks (proven technology). In clock technologies and system time scale generation several areas of improvement exist for Galileo: Based on the experienced learning-curves in G1G more robust and compact atomic clocks (like the miniaturized H-Maser) are needed. This includes a better understanding of the physics and the shortcomings. Using a heavier satellite bus, more clocks for higher redundancy will be integrated. The clocks should be operated in hot redundancy and a clock ensemble has to be implemented onboard the satellite. New clock technologies available in Europe can be envisaged: Optical clocks, e.g. Iodine and Strontium Lattice clocks could be candidates for the future. Alternatively, optical pumped Rubidium- and/or Cesium or Mercury Ion clocks are possible. The trade-off between PNT improvements of the system versus risks involved by new clock technologies is important. Other areas of improvement on system level: The up-date cycle for the clock parameters in G1G ranges between 30 and 100 minutes. This is clearly too short, because a significant load on the ground segment is associated with the stochastic error growth of the selected clock technologies. Another point in the system time scale generation is to go away from the master clock concept, which is the basis of the PTF (Precise Timing Facility) in Galileo. The state-of-the-art in this field is the application of clock ensemble including all space and ground clocks (i.e. networked time). Clock ensembles lead to a more robust GNSS time scale. Because clock technology is a key technology area in satellite navigation, maintaining the industrial competitiveness in this domain is a must.

5.3.5 Inter Satellite Links

Inter Satellite Links become a standard in MEO Satnav systems. GPS III, Beidou-3, G2G and GLONASS-K2 are making use of RF-ISLs. It is clear that optical inter satellite links (OISL) could replace RF-inter Satellite Links. The RF-ISL terminals in G2G are very heavy with a rotating parabolic antenna. An optimized OISL terminal could come up with a smaller SWAP. However,

originally the OISL links were designed for high data rates in HTS communications. High data rates in SatNav will not be the design-driver. The OISL will be used here as a laser ranging system. Moreover, it is important that the OISLs have full angle freedom of rotation, because inter-plane ranging is necessary. Intra-plane ranging, like proposed in the Kepler concept, is not sufficient. We should also be careful in the euphoria with respect to accuracy: 50 μm ranging performance, claimed by some protagonists, is an inner accuracy. The problem lies more in the "local-ties", i.e. to relate the laser reference points via the rotating axes of the telescope to the satellite center-of-mass and to the antenna phase center. As we know from terrestrial laser ranging systems systematic errors will be present. This leads more to several mm-accuracy and worse in real space borne environments. If everything is done with realistic design and reasoning, improvements for ODTS in the tangential plane will happen in Galileo.
It must be noticed that inter-satellite links could also impact how time is maintained across the system. Where the clocks are located in a networked time infrastructure is really relevant.

5.3.6 Onboard autonomy

Having measured ISL ranging and Doppler on board a satellite opens up the possibility to implement onboard autonomy. However, what looks at the first instance very simple and straightforward turns out to be a very tough problem. Because in the standard concept of ephemeris, clock and system time determination all the observations from the GSS (Galileo Sensor Stations) are transmitted to GMS (Ground Mission Segment) for batch processing (least-squares adjustment). The same is done in GPS where a high dimensional Kalman filter (300 states) is used in the MCS (Master Control Station). Available inter satellite measurements can of course be included into the processing algorithms. We should consider that connecting unknowns (between satellites) like system time scale parameters have to be introduced into the estimation process. Thus, to gain for onboard processing the same results for ephemeris and clocks as in the case of ground processing a partitioning of estimation between the satellites has to be performed. Basic information like the variance-covariance matrix has to be communicated via the ISLs. Basically, this is also known in general terms from the AUTONAV function in GPS IIR.

5.3.7 Resilient system design

During the next decade, new infrastructure elements will be added to the current MEO-GEO-IGSO systems. One infrastructure element that will presumably happen is LEO-PNT. As outlined one or several LEO-PNTs will be in orbit in 2035. In LEO-PNT, the question on a resilient integration into MEO-PNT is already posed. There will be systems like Centispace, which are favouring a ground-based ephemeris and time determination system. Other LEO-PNT systems are making use of space borne GNSS receivers to determine ephemeris and time. This approach has the risk of common mode failure, because LEO-PNT will vanish if the MEO-PNTs are in problem. In terms of resilience, a completely independent LEO-PNT is superior to a dependent LEO-PNT. Thus, the resilience question has to be moved to the foreground.

5.3.8 Integration of communication with navigation

The integration of communication with navigation is a classical vision. Many diverging opinions are formulated in different media. In a coarse look on the problem, one can come to the opinion that the technology domains are very similar and therefore an integration is very natural. A detailed evaluation leads to another assessment: Although technical commonalities exist, the target functions in communication and navigation are opposite. In communication system capacity, high data rates, and BER (bit error rate) are the design drivers. In a radio navigation system, the precise chip transition (sharp auto-correlation peak) and coherent carrier modulation and low phase noise, low (zero) data rates for long coherent integration time, short acquisition time, high metric accuracy on code und carrier phase are the design drivers. In the user segment communication terminals tend to a larger form factor (parabolic & big array antennas), whereas in navigation small form factors (SWAP) are the goal in 90% of the use cases. Concerning the carrier frequencies communication moves to Ku-, Ka-Band and beyond. The reason is larger bandwidth & high data rates for space-based internet (HTS). In navigation, we stay currently with the L-Band. The L-Band sometimes is called the "sweet point" for small form factor receivers. The integration of communication and navigation could happen close to this "sweet point" in L-Band, S-Band may be C-Band (example: Satelles). However, integration is not likely to happen in Ku- and Ka-Band, because doing so will lead to completely different bulky navigation user equipment and cost. As long as MEO-PNT is available, nobody will invest in this equipment.

5.4 Extending the GNSS Service Volume

As already mentioned above, the Moon is the next frontier for in space use of GNSS and other PNT services, but looking into the future, communication and navigation services will be required for space exploration beyond that limit.

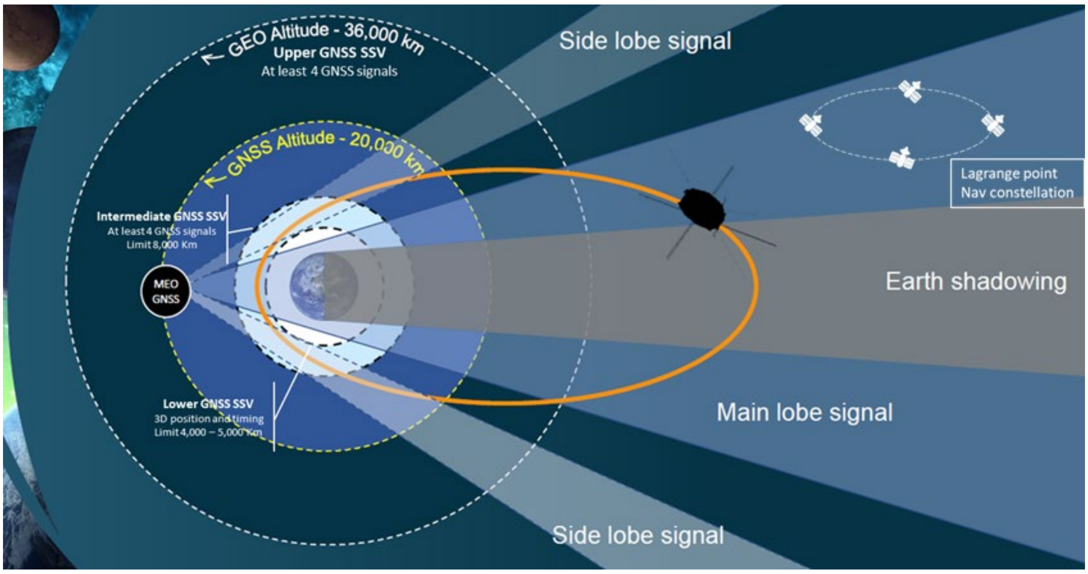

Figure 9.- Limitations of the GNSS Space Service Volume in its present configuration and possible extension with an additional satellite constellation placed at the Lagrange point.

Early Lunar communications and PNT architectures must lower the barriers to entry for new missions and capabilities and supports expanding robotic and human activities on the Moon. The development of the LunaNet framework of standards will be critical to ensure the interoperability of the planned systems that will constitute the initial Lunar Augmented Navigation Service (LANS): Moonlight, NASA LCRNS (Lunar Communications Relay and Navigation System), JAXA LNSS (Lunar Navigation Satellite System) and, eventually, CSA Queqiao. The objective is to ensure interoperability, compatibility, and availability of GNSS and lunar PNT systems that can be seamlessly employed together from the Earth to the Moon.

Europe should develop a higher integrated space borne receiver. Podrix or Leopard solutions at c. 3 Kg – plus 1 Kg for the antenna -, 28 cm per side and 15 W power consumption are too much in most satellite mass and power budgets for fully exploiting the space service volume.

In addition, initial steps to implement a deep space navigation constellation at the Lagrange points will be required to support exploration missions beyond the Moon.

if the technology of autonomous PNT sensors (MEMS, quantum) evolve so much and there is availability of a resilient time source at terrestrial level, then the issue of PNT resilience is limited to solve how to transfer this terrestrially generated resilient time to the autonomous PNT sensor through a resilient channel. In conclusion, we may not need so many navigation satellites, or the effort of the navigation satellites should be put in time transfer and not so much on ranging. This may give a new focus to the design of navigation signals.

6 Components, sensors and devices evolution

6.1 GNSS receivers

6.1.1 Topology of a GNSS receiver[23]

A general GNSS receiver is composed of antennas, a radio frontend, an Analog to Digital Converter (ADC), the Baseband, a navigation data block and an interface to the user. The radio frontend is composed of the components handling the analogue radio signal, down-converting it to an Intermediate Frequency (IF), that is to be digitized. The satellite signal is first intercepted by an antenna, making its gain a significant characteristic. A GNSS's Signal to Noise Ratio (SNR) is generally of the order of magnitude -30dB, that is below the noise floor. The low power signal is amplified by a Low Noise Amplifier (LNA) while imposing the least amount of noise onto it. The designated signal bandwidth is obtained via a band pass filter. Next, the signal passes the mixer component. It performs the signal down-conversion using a reference oscillator and frequency synthesizer. Furthermore, pre-correlation selection, sampling, and separating the signal into In- and Quadrature-phase (I/Q) components is done. The reference oscillator is the basis of the receiver's time keeping. Its accuracy and stability determine the receiver's degree of sensitivity via the coherent integration time. Finally, the conversion into a digital, discrete signal is performed by an ADC.

The digital signal processing performs sampling and coarse acquisition. *Figure 10* visualizes the signal processing as a flowchart. The incoming signal is mixed with the corresponding Intermediate Frequency (IF) per given satellite signal in each channel. Following filtering, the acquired signal is passed onto a tracking loop, producing Doppler shift to be passed onto the EKF (extended Kalmann Filter). The EKF computes the positioning solution, or state vector to be precise in this case. The individual PLL tracking loops are shown in the bottom half of *Figure 10*, as the customization of this loop is of interest. In order to initialize the loops, an FFT on the input signal is performed, that transforms the time domain to frequency domain, resulting in a crude Doppler estimate. Once initialized, the signal Doppler shift is obtained per channel from the output of the PLL.

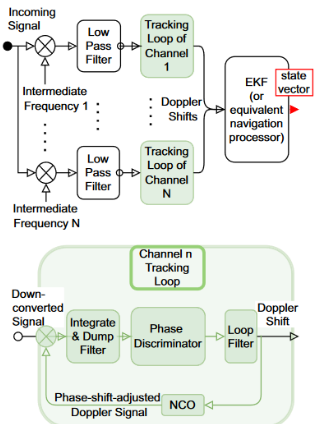

Figure 10.- LEO receiver signal processing loops

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[23] Receiver architectures for positioning with low earth orbit satellite signals: a survey. Christina Pinell, Fabricio S. Prol, M. Zahidu, H. Bhuiyan and Jaan Praks. [Receiver architectures for positioning with low earth orbit satellite signals: a survey (springeropen.com)](). Last accessed March 29th 2024.
A more detailed introduction to GNSS receivers can found under the following links:
Generic Receiver Description - Navipedia (esa.int).
Receiver Types - Navipedia (esa.int)
For more insights into the various aspects of GNSS receivers an overview can found in Positioning and location | u-blox.

As further explained below the performance of the receiver is highly dependent on the details of the various functional blocks. Much progress has been made in perfecting them while receivers have been miniaturized following the continued progress in miniaturized silicon structures down to 7nm nodes for the consumer mass market products like smart phones. Such miniaturization has helped to increase the number of receiver channels, to make receiver multi-band and finally multi-channel. Thanks to increased on-board data processing power, more complex algorithms can be employed, and edge computing combined with cloud computing. Sensitivity, robustness and dynamic performance can further be enhanced based on these functional extensions, and the quest for low cost and highly compact receiver (SWaP-C) is optimally fulfilled. Insofar we can expect that receivers can further exploit the available GNSS constellations and signals for higher user benefits.

6.1.2 Timing receivers

In addition to positioning and navigation applications, GNSS signals are widely used as low-cost precision time or frequency references used by remote or distributed wireless communication, industrial, financial, and power-distribution equipment. By capitalizing on atomic clocks which are onboard positioning satellites, GNSS signals which contain embedded timing information can be used to synchronize equipment to within few nanoseconds, as well as provide accurate UTC time.

For example, the latest timing modules of the u-blox multi-band high precision GNSS receiver platform F10 provide L1/L2/L5 GNSS reception to the most demanding timing applications. This technology delivers nanosecond-level timing accuracy and meets even the most stringent requirements for broadband 5G cellular communication. Concurrent reception of all global and local navigation satellite systems, ionosphere error mitigation, and advanced security and integrity features pave the path for next generation timing applications:

- Fast satellite acquisition by intelligent signal capture algorithms
- Location-independent clock synchronization, even when only one satellite is in view
- Weak-signal optimization, interference removal and multi-path mitigation allowing a small, low-cost GPS antenna to be used indoors or within machinery
- Flexible GNSS-synchronized time-pulse outputs at user-defined frequencies aligned to GNSS time or UTC
- Frequency-Time modules and reference designs add:
    - Disciplined internal or external master reference oscillators with automatic hold-over
    - Time-pulse inputs and message-based APIs for integration with host-based sources of synchronization

Timing receivers are profiting from the mass-market positioning receivers and deliver nano-second accuracy at low cost. Any more specialized timing signals as proposed on satellites would make a new receiver design necessary including the radio part and much increased unitary cost. Therefore, the likelihood is rather low that such new timing signals will find a commercial use in mass markets.

6.1.3 Mixed signal designs of GNSS receiver chipsets

Today GNSS receivers are realized in CMOS technology and incorporate antenna signal amplifier, the radio and the baseband micro-processor. Such circuits are highly complex and need a high competence for making such design highly sensitive in the one hand and robust against internal interference in the other. He combination of analogue and digital circuitry makes the selection of the underlaying CMOS technology and its characterization decisive for a high-performance circuitry. Because of the analogue circuits for the radio, the shrinking of designs to ever smaller nodes is limited.

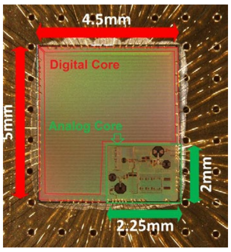

Figure 11 Typical GNSS mixed signal receiver design by Fraunhofer

6.1.4 Multi-Channel and Muli-Frequency

Multi-constellation multi-band GNSS receivers can efficiently exploit the advantages deriving from the modernization of existing GNSS constellations such as GPS and GLONASS as well as from the launch of new ones like Galileo and Beidou. In fact, the utilization of multiple systems can significantly improve the availability of a navigation solution in urban canyons and heavily shadowed areas. In addition, the increased satellite availability guarantees higher measurement redundancy and improved reliability.

Moreover, the excellent inherent noise and multipath mitigation capabilities of the new and modernized wideband signals in the L5/E5a band, combined with the ionosphere error mitigation given by frequency diversity, improves significantly the accuracy in both measurement and position domains.

Dense urban areas pose challenges for GNSS receivers in acquiring satellite signals. The foliage of trees and buildings can interfere with the path of these signals by diffracting or reflecting them, creating what is known as multipath effects.

These multipath effects introduce errors that ultimately affect the accuracy of GNSS receivers, which can be significant. Comparing the receiver's position accuracy in a rural environment to an urban area can vary considerably, for example, from 2 m to 30 m.

Multipath does not affect all signals equally. L5 signals are much more resilient to these effects. So when a receiver combines L1 and L5 bands and a multipath environment is detected, the GNSS firmware algorithm can use more L5 signals for navigation than L1. This combination improves multipath resistance and accuracy of meter-level positioning.

Together with sophisticated algorithms to detect jamming and spoofing attacks such receivers provide high robustness against RF interference from co-located cellular modems.

6.1.5 Low power design

Applications are continuing to push the boundaries on new features and functionality, all packed into portable, handheld, and battery powered devices. For such products, improving the battery life by minimizing power consumption is a huge differentiator and extremely important to their end users' applications.

Low power design is a collection of techniques and methodologies aimed at reducing the overall dynamic and static power consumption of an integrated circuit (IC). The goal of low power design is to reduce the individual components of power as much as possible, thereby reducing the overall power consumption. The power equation contains components for dynamic and static power. Dynamic power is comprised of switching and short-circuit power; whereas static power is comprised of leakage, or current that flows through the transistor when there is no activity.

Techniques for reducing power consumption comprise clock gating for reducing the overall switching activity, multi-voltage by partitioning the chips in several voltage domains, and power gating by partitioning the chips in various power domains that switches of certain circuit domains completely.

The receiver architecture must deal with such a circuit topology and the firmware to handle the power management while still achieving excellent receiver performance.

6.1.6 High RF sensitivity and weak signal compensation

The higher the RF sensitivity of the GNSS receiver, the better it can operate under low signal conditions. During operation, GNSS receivers can be in two operational phases: the acquisition phase and the tracking phase. A multi-GNSS receiver concurrently receives signals from more than one constellation and judges which signals to use for tracking. In good signal conditions, the choice of signals is vast, especially if the receiver is able to concurrently track four GNSS constellations.

In the case of a weak signal scenario, the number of available signals shrinks significantly. Weak signal compensation improves the accuracy of position and speed information significantly over conventional GNSS receivers. Continually improving on-chip computing power will allow to extend such compensation schemes.

6.1.7 Dead reckoning

Dead Reckoning refers to GNSS data fused with inertial sensor data (for more details see chapter 6.4). It is an easy-to-use and robust solution that enables high positioning performance in places where GNSS signals are poor or not available. Inertial sensors are normally a combined 6-axis accelerometer and a gyro (for rotation). Such sensors are made in MEMS (micro-electromechanical system) technology.

Such receivers as e.g. offered by u-blox deliver:

- Independent of any electrical connection to the car
- Leading performance under poor signal conditions
- Real-time positioning update rates up to 20 Hz
- Low cost of ownership, ideal for high volume projects
- Sensor data available for third party applications

The accuracy and drift are high determined by the mechanical form and the reading method for the mechanic deformations. Recently interesting developments are under way for employing optical sensing methods that would improve the accuracy and drift by several orders of magnitude, as proposed by ZeroPointMotion.

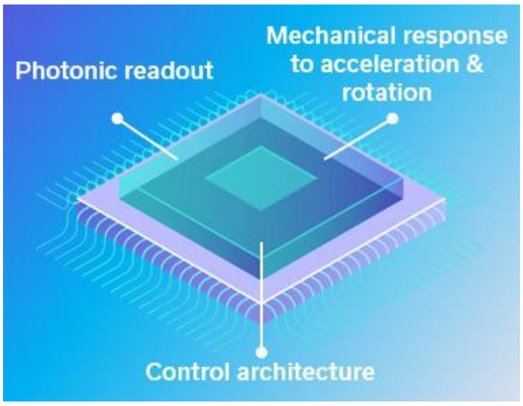

Figure 12 Three axis accelerometer and gyro based on photonics (ZeroPointMotion)

6.1.8 Augmentation

Augmentation of a GNSS is a method of improving the navigation system's attributes, such as precision, reliability, and availability, through the integration of external information into the calculation process. There are many such systems in place, satellite or ground based. Most GNSS receiver manufactures offer additional information about sources of error (such as clock drift, ephemeris, or ionospheric delay), others provide direct measurements of how much the signal was off in the past, transmitted by wireless connectivity to the receiver. This ensures seamless integration with the receiver and assures good performance.

Still challenges persist in collecting the observed signals on a global basis and the cost-efficient delivery of correction data. Also come countries limit the distribution of such data.

An interesting concept is proposed by the Swiss start-up onocoy collecting observation data with a crowd approach and handling the data flow in smart contracts and a token.

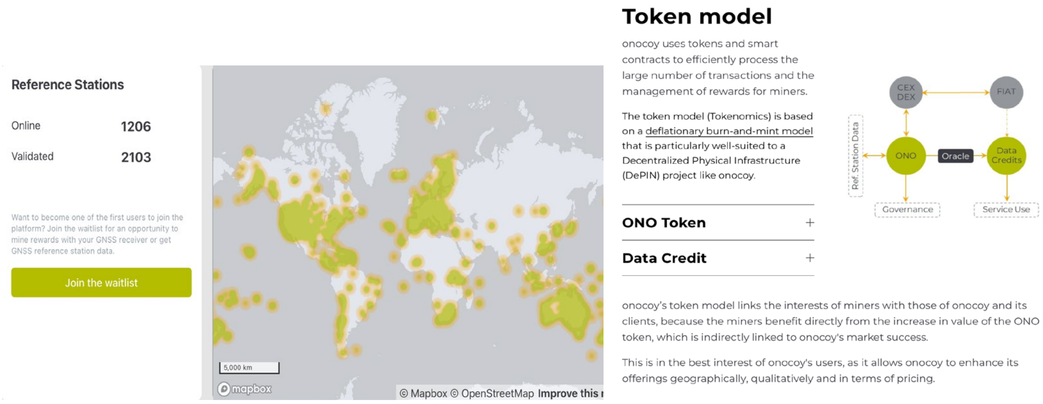

Figure 13 Augmentation service based on a smart contract model (onocoy)

6.1.9 Software Defined Radio[24]

As the name suggests Software Defined Radio is the wireless communication system operating at radio frequency and configurable using software. In SDR, hardware components commonly available in an analogue counterpart are configured in software which is ported either on FPGA or DSP to be used in wireless chain. Following components are configured in SDR typically (see Figure 14):

- Mixers used in up-conversion and down-conversion
- Amplifiers
- Modulator and demodulator modules
- RF detector
- Filters (BPF, LPF) using FIR filter concept

Now-a-days using SDR concept, entire PHY layer and RF chain is implemented in software.

[24] See [Advantages of SDR | Disadvantages of SDR,Software Defined Radio (rfwireless-world.com)](). Last accessed March 29th 2024.

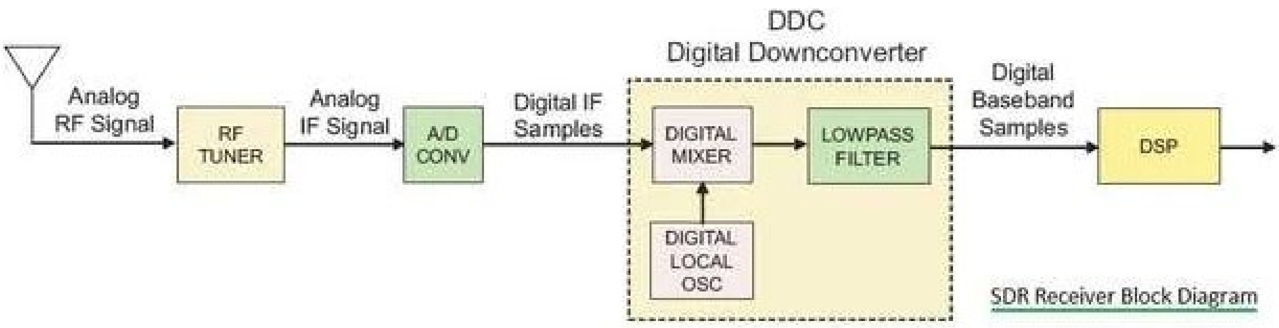

Figure 14.- SDR Receiver Block Diagram

The benefits or advantages of SDR are the following:

- It offers flexible, reconfigurable and programmable framework. This helps to meet varied needs of different users in terms of hardware specifications and adaptability of RF signal definitions.
- SDR hardware prototypes are ready to adapt any future upgrades and protocols.
- It helps in selection of RF carrier frequency, modulation type, FEC techniques, sampling frequency as per system requirements.
- It offers high level of performance which can be tuned by software.

However, there are drawbacks and disadvantages of SDR commonly found during SDR implementations.

- Poor dynamic range in some SDR designs.
- It is difficult to write software to support different target platforms.
- SDR architecture consists of analogue RF front end and digital front end. Hence it is challenging to implement interfacing between analogue and digital modules or blocks.
- Analogue-digital conversion limits maximum frequency to be used by digital part of SDR.
- SDR platform may be very expensive to afford.
- SDR radios need more real estate on the chip and are rather power hungry.

New satellite signal concepts like the NTS-3[25] platform of the US Vanguard program could make SDR based receivers a requirement. However, an overall system view needs to be applied when making such basic decisions.

6.1.10 Functional safe receiver[26]

Emerging autonomous driving applications are setting the pace of the innovation for the on board GNSS receiver. Position accuracy, high availability, robustness of operation and formal integrity of the observables are the priorities, which are giving rise and shaping a new class of automotive receiver components and architectures (see Figure 15). Moreover, because the autonomous driving and ADAS are safety critical, on top of previous requirements there is also the requirement for Functional Safety (informally called FuSa) compliancy. The documents codifying Functional Safety for automotive are the ISO26262 part 1 to part 11. The ISO26262 complements the well-known

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[25] See NAVIGATION TECHNOLOGY SATELLITE – 3 (NTS-3) – Air Force Research Laboratory (afresearchlab.com). Last accessed March 29th 2024.

[26] GNSS Functional Safety for the Autonomous Vehicle October 2019: 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019). https://www.researchgate.net/publication/336457227_GNSS_Functional_Safety_for_the_Autonomous_Vehicle. Last accessed March 29th 2024.

reliability automotive standard AEC-Q100. With respect to FuSa, a system can be defined as functionally safe if it always operates correctly and predictably. More importantly, in the event of failures, the system must remain safe for persons.

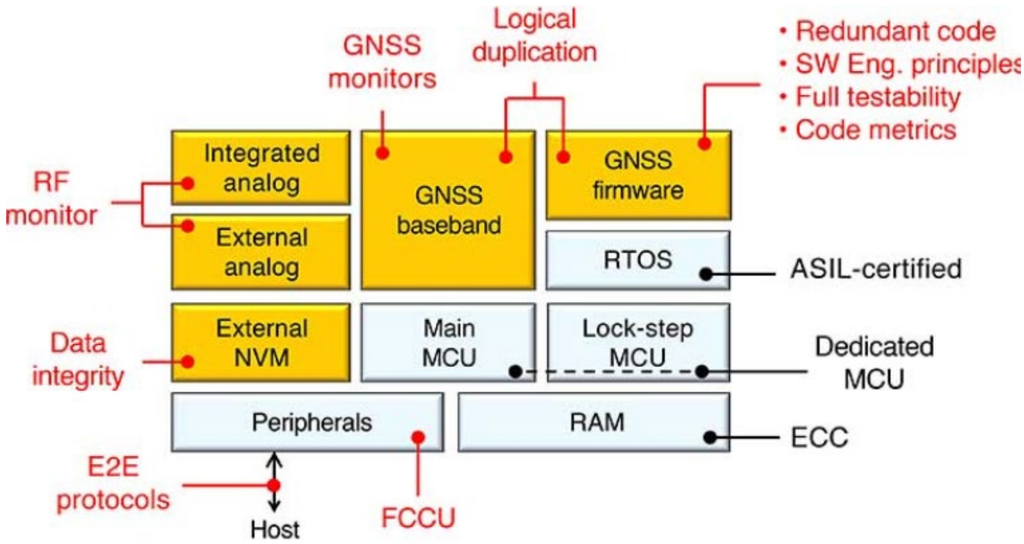


Figure 15.- Overview of Safe mechanism

Critical applications need to know how much faith they can place in their GNSS receiver's output at any given moment. Computed by the GNSS receiver in real-time, the protection level quantifies the reliability of the position information, improving data quality and keeping people and assets safe.

A GNSS receiver's protection level describes the maximum likely position error to a specified degree of confidence (see Figure 16). If, for example, a GNSS receiver determines its position with a 95% protection level of one meter, there is only a 5% chance that reported position is more than one meter away from its true position. Like the accuracy of a GNSS receiver's position information, the protection level constantly fluctuates, influenced by all the error sources that commonly affect GNSS solutions.

By continuously offering an upper bound on a GNSS receiver's expected error, the protection level lets applications adapt their performance to the quality of the information they receive and discard values that are deemed unreliable[27].

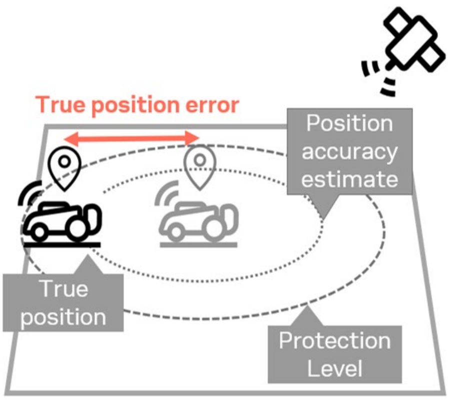


Figure 16.- Protection level and position error

[27] For more insight, see Protection level | u-blox. Last accessed March 29th 2024.

Lastly also security is becoming a paramount and a new standard for cybersecurity in automotive, the ISO/SAE 21434, is in development where for a GNSS receiver this means robustness versus jamming, spoofing and meaconing attacks.

Such GNSS receiver chipset are available e.g. from u-blow and ST Microelectronics (see Figure 17). However, their use is not yet very widespread due to enormous efforts for system integration and validation. With the additional need for more autonomy in vehicle driving such concepts will become more widely applicable.

Figure 17.- Functional safe GNSS receiver chip by u-blox

6.1.11 Chips and Modules

All modern GNSS receivers are realized as a mixed signal integrated circuit as described in chapter 3. Such highly integrated receivers have laid the foundation for mass market application in the last 15 years. Further integration was achieved in processor systems for mobile phones, mainly by adding a radio and using the vast processor structure for signal processing.

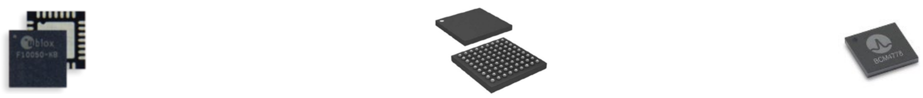


Figure 18.- u-blox F10 multi-constellation dual-frequency low power GNSS chip with footprint 4x4mm; ST Microelectronics automotive triple-band GNSS precise engine receiver with footprint 7x11mm; Broadcom low power dual-frequency GNSS receiver with footprint 2.4x2.7mm

However, for many applications and products such highly integrated concepts are not cost effective and not adequate to their economics, including long life cycles, product flexibility and robustness. Modules are the more adequate solutions in such cases and a broad range of GNSS modules can be found in the market. Initially modules served for high integration of the receiver system at a time when the chipset still count three individual circuits, the LNA (low noise amplifier), the radio and the baseband chip. The Swiss company u-blox was the leader in creating such modules and set the de-facto-industrial standard for the form factor.

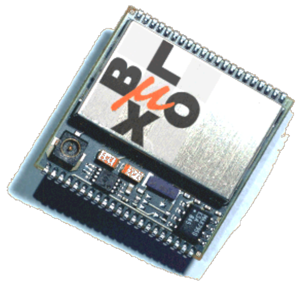


Figure 19.- One of the first GNSS receivers modules (2001) by u-blox with footprint 30x30mm

Today modules have taken the form and shape of integrated circuit: They employ a similar packaging technology while integrating miniature radio components.

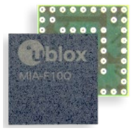


Figure 20.- Miniature GNSS receiver module with footprint 4.5x4.5mm

Still large form factors are required for more complex receivers that integrate inertial sensors or a redundant system.

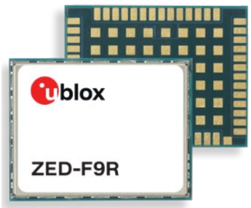


Figure 21.- u-blox F9 high precision dead reckoning module with footprint 16.8x21.8 mm

6.1.12 New constellations[28]

An influx of satellites in Low Earth Orbit (LEO) are driving innovation in PNT technology. Improved signal strength compared to GNSS can be obtained from LEO satellites merely due to their proximity to Earth. Therefore, even communication satellite transmissions are becoming appealing to navigation, as so-called Signals of Opportunity (SOP).

The proximity of LEO satellites to users is the driving factor behind these developments. A received signal gain is achieved due to lower path loss along the shorter distance to the user. Furthermore, a user will see a LEO satellite traverse the observer's sky faster than a MEO satellite. Resulting rapid changes in satellite to observer geometry are studied as beneficial to Precise Point Positioning (PPP) convergence time. However, the signal gain comes at the cost of the satellite footprint. A LEO satellite footprint is in the order of tens of kilometres whereas one MEO satellite is generally visible from half of the globe. This disadvantage has only been outweighed by manufacturing many more satellites at cheaper prices per unit. Thereby increasing the availability of LEO satellite signals.

[28] Receiver architectures for positioning with low earth orbit satellite signals: a survey (springeropen.com). Christina Pinell, Fabricio S. Prol, M. Zahidu, H. Bhuiyan and Jaan Praks. Last accessed March 29th 2024.

6.1.12.1 Receivers for signals of opportunity SOP

Commonly LEO signals are used as so-called Signal of Opportunity (SOP). A satellite SOP is commonly measured as the Doppler shift of the signal's carrier frequency. Due to the large number of satellites per constellation, the communication and IoT constellations are the main source of satellite SOP for PNT. IoT services broadcast broadband signals, in contrast to narrowband signals for communication.

At the heart of the user segment is the receiver and its signal processing. Customized to a given system's signal, the receiver performs signal interception, error correction and PNT computation.

LEO on the other hand is not home to a GNSS constellation yet. Currently, LEO satellite signals are utilized in positioning as Signals of Opportunity (SOP). SOP in PNT refer to signals not being designed for positioning, that nonetheless provide a positioning opportunity.

The current state-of-the art LEO receiver architecture is a customized Software Defined Radio (SDR). The hardware may be composed out of COTS components which makes such a receiver feasible but not cost-effective. The measurements, namely the signal carrier's Doppler shift and phase, are obtained via the acquisition and tracking loops. Their implementation is customizable. The navigation filter processes the obtained parameters. A Kalman variant is suitable, as it is adjustable to modified loops.

Aiding GNSS with LEO satellites is offered as a service by the company called Satelles. The STL signal is designed for their own PNT solution, that complements the GNSS service in challenging environments. As such, it contains its own timing and frequency information, separate from GNSS.

The final important component to consider within the RF is the source of the frequency reference. Components may already contain internal reference oscillators, such as a Temperature Compensated Crystal Oscillator (TCXO). External references may be added though. They could provide higher accuracy and stability, at the cost of increased complexity and price.

In addition to the user segment, the satellite can provide timing and error estimates. These may be derived with the help of a GNSS on-board receiver, or with a Chip Scale Atomic Clock (CSAC). The obtained timing accuracy is relevant to the positioning solution in the user end because ranging is a timing navigation.

6.1.12.2 Receiver for Dedicated positioning signals

A suitable receiver architecture is a flexible SDR set-up with an additional correlation step in the acquisition process. Correlation is a significant difference to SOP, that brings with it increased precision.

Ultimately, a RF of large bandwidth and frequency range is needed, combined with a SDR, that enables adjustments to the receiver loops. Adjustments in the acquisition and tracking loops are required to tolerate faster changing Doppler than current GNSS. Ephemeris decoding is an additional step compared to SOP, and additional parameters compared to GNSS are required for correct orbit characterization leading to precision positioning solutions. Correlation and local replica components might be another addition for increased precision and authentication. Moreover, the details of the receiver architecture are dependent on the signal design. The signal design choices dictate all choices starting from the antenna to an algorithm implementation extracting positions from possible encryption. Due to the cost to performance ratio, utilizing LEO-SOP as such a back-up for GNSS signals in weak signal environments seems to be the most suitable receiver option. However, SDR architectures are not power and cost efficient. Such disadvantages must be traded off against the flexibility in adapting the RF path.

6.1.13 LEO satellites and consequences for GNSS receivers

Developments in LEO satellite signals with respect to PNT user receiver architectures. In conclusion:

- The order of magnitude in positioning accuracy with SOP is generally tens of meters when unassisted.
- The most common receiver architecture is a SDR set-up with signal customized EKF implementation.
- In SOP processing, positioning signal analysis is the most demanding task due to the challenges in acquisition and tracking of a LEO satellite with signal specific characteristics, that are not in the public domain.
- Software Defined Radios (SDR) are more expensive and power hungry than hard coded GNSS receivers topologies.
- Utilizing multiple channels for different signals is an option. However, multiple antennas may also be needed.
- The largest error source in SOP stems from the uncertainty of the satellite status, due to low precision of TLE files.
- Time keeping is critical in SOP. The precision of the user receiver clock is significant, especially when it is not disciplined by a precision clock such as in the GNSS system. Clock drift further degrades the possible positioning accuracy.
- Dedicated LEO-PNT receivers are unlikely to be a necessity, rather user will strive for GNSS inter-operability.
- Noteworthy challenges are tackling frequency attenuation versus size of receiver, multipath mitigation, encryption and LEO specific ephemeris.

Early stages will likely see a focus on GNSS inter-operability, therefore receivers with the same type of set-up as GNSS receivers. As frequency bands get increasingly crowded and positioning services more numerous, there might be a market for receivers with more specialized features. Here commercial receiver set-ups of paid company services are conceivable. However, for cost efficiency reasons mass market receivers will prevail.

6.2 Autonomous sensors

The growth of GNSS enabled PNT and growing dependence on GNSS has its origins in the development of radio navigation aids – DECCA, LORAN and OMEGA for example – in the 1950s and 1960s. GPS was developed as "one radio navigation aid to rule them all", the use of space-based transmitters giving global coverage with a single system. Terrestrial aids had their drawbacks. Propagation issues limited coverage and accuracy away from land masses. The civil aviation community opted for inertial navigation systems as a solution for the oceanic routes and the affordability of the inertial systems led to their widespread adoption.

Whereas radio receivers sense a man-made infrastructure of signals in GNSS and radio-navigation systems, sensors which detect natural phenomena and structures have the potential to be highly resilient. They include:

- Sensing magnetic north: (Compass)
- Sensing rotation and displacement. (Accelerometers and gyroscopes in an inertial navigation system.
- Measurement of the perceived position of stars or the sun. (Celestial navigation). This also includes a requirement for a precise clock.
- Measurement of position with respect to gravitational or magnetic anomalies.

All of these have the potential of providing "infrastructure free" PNT services. (Although signals of opportunity exploitation may not require dedicated infrastructure, it requires the parasitic use of someone else's infrastructure.)

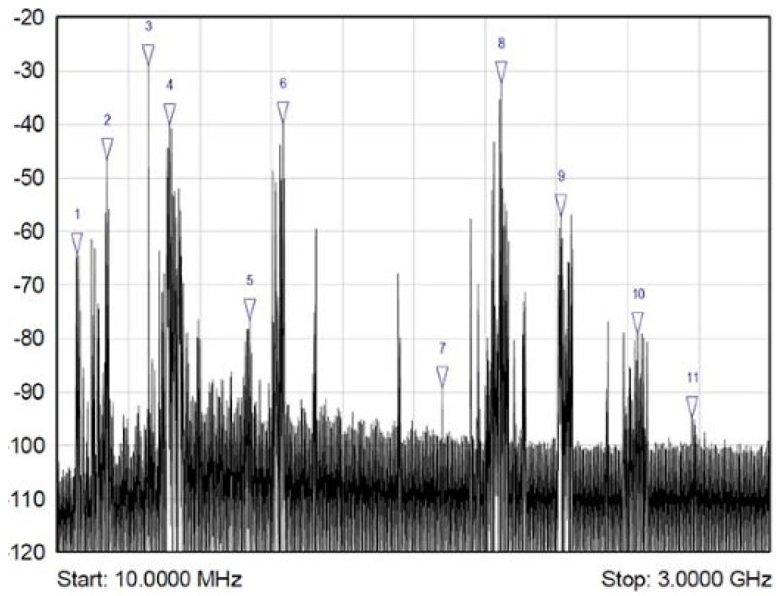
It should also be noted that using sensors to navigate is not totally infrastructure free. Celestial navigation requires a book of tables. Magnetic or gravitational anomaly navigation will require a map. Even the use of a compass requires knowledge of the current location of the magnetic pole. However, it is possible to make access to this information far more resilient than reliance on instantaneous communication.

Sensors of interest for navigation include:

- Clocks: Atomic clock technology continues to evolve, including chip-scale atomic clocks and quantum clocks.
- Accelerometers and Gyros: Inertial navigation systems have already undergone a change in technology with the adoption of ring-laser gyro systems in the 1980s. New technologies including quantum and MEMs bring new capabilities. The fundamental differences in performance of these sensors (e.g. sensitivity, accuracy, stability, biases, drift and dynamics) herald the appearance of hybrid inertial systems using more than one sensor type.
- Quantum magnetometers are showing high levels of sensitivity. Their usefulness in navigation will not only depend on practical issues (such as SWaP and cost) but also on the complementary map-making activities. These in turn will require sensors – possibly space-borne.
- Quantum Gravimetry: The issues are similar to those impacting magnetometers.
- Imaging systems: Novel imaging systems (high resolution stereo camera, LIDAR) may have a role in navigation. The ability to interpret a star map is one application. Google Maps already contains a calibration feature which compares an image from the user's camera with a database of imagery. AI will continue to be developed for image interpretation, including for navigations. Quantum techniques are being developed for hyperspectral imaging and seeing through dispersive media. These techniques can be used for improved visual navigation.

6.3 Other RF sensors

There are plenty of opportunistic RF signals than may be used for PNT purposes. As shown in the figure below, this includes many different sources, from radio or digital TV broadcasting to Wi-Fi. By using a variety of techniques, almost any radio signal can be used for opportunistic navigation purposes. However, this will require complex hardware to perform well. Handling a wide range of frequencies needs a sophisticated receiver and a set of several antennas Moreover, when resilient PNT is a critical requirement, it can hardly be afforded to rely on signals that are not controlled or guaranteed.



Signal Marker	Frequency	Level	Identity
1	93.72 MHz	-64.36 dBm	FM radio broadcast
2	219.3 MHz	-46.67 dBm	DAB radio
3	392.72 MHz	-29.10 dBm	TETRA
4	482.42 MHz	-40.24 dBm	Digital TV
5	817.3 MHz	-76.67 dBm	LTE (EUDD band)
6	954.84 MHz	-39.91 dBm	GSM (E-GSM band)
7	1.6246 GHz	-89.28 dBm	Iridium
8	1.8698 GHz	-32.37 dBm	GSM (DCS1800 band)
9	2.1209 GHz	-57.23 dBm	WCDMA (IMT band)
10	2.4439 GHz	-79.22 dBm	Wi-Fi (2.4 GHz band)
11	2.6711 GHz	-94.81 dBm	LTE (IMT-E band)

Figure 22.- Signals of Opportunity (SoOP) available at the UK[29]

Wi-Fi, Bluetooth Low Energy (BLE) and UWB beacons are convincing options for indoor positioning. In fact, many smartphones have already available the required sensors (i.e. receivers) to use these signals. They can provide a useful complement to allow seamless indoor- outdoor positioning and navigation, although the short range of these signals limit their application in outdoors scenarios – not to mention global service -.

6.4 Sensor fusion and processing techniques

Sensor fusion is a basic technology in location and navigation. Based on measurements in a multi-sensor system the complete information about the navigation state space has to be estimated. The navigation state space (assuming rigid body dynamics) of the user is a high-dimensional vector space: **x** = [**p**, **v**, **q**, ω, t] with **p** position vector, **v** velocity vector, **q** attitude vector, ω rotational rate vector and t time. By use of sensor measurements, information about the state space is collected. Usually, the problem is overdetermined (more observations as unknowns). Therefore, an estimation process is necessary to determine a unique solution for the unknown state vector **x**. In performance-based navigation various requirements are posed on **x**: Accuracy, availability, continuity, integrity. A new requirement is resilience of the navigation system. Currently, no metrics exists for resilience in PNT.

Moreover, resilience has to be designed in by intent. Fusion can result in a decrease in availability if the solution is dependent on all sensors. Resilience of course can be improved by the addition of a resilient sensor. However, there is no "safety in numbers". Part of this is due to an almost Darwinian

[29] Signals of opportunity: Holy Grail or a waste of time? JONES, Michael. GPS World. February 2018. [Signals of opportunity: Holy Grail or a waste of time? - GPS World](). Last visited March 15th 2024.

process. If a highly resilient single sensor did exist, it would be adopted alone rather than part of a fusion of sensors. If a fusion of sensors is being used, the resilient sensor obviously does not exist!

6.4.1 Application specific sensor integrations

Always under development, in navigation systems, sensor integration is application specific for different user groups. It is important that sensors have complementary characteristics and error performance. The important point is that an integration kernel in all applications exists: GNSS, inertial and / or other sensors, and a Kalman filter or least squares estimator (special case of Kalman filter).

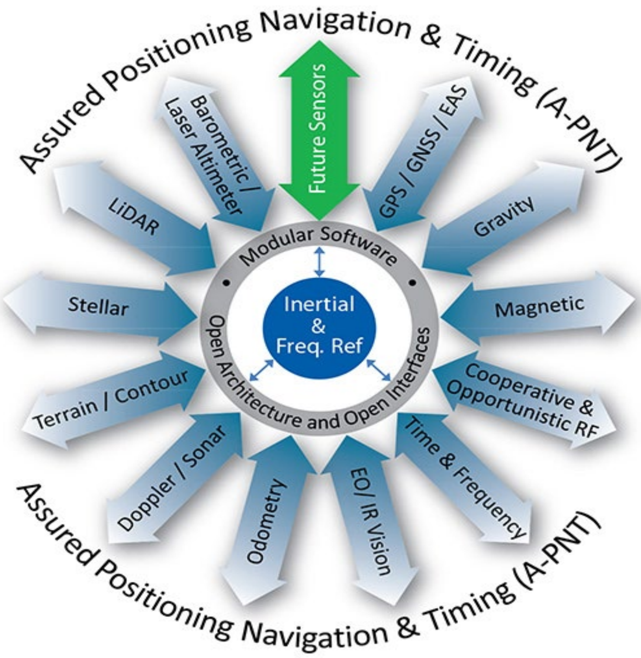


Figure 23.- Overview about potential navigation sensors (Source: Northrop Grumman[30])

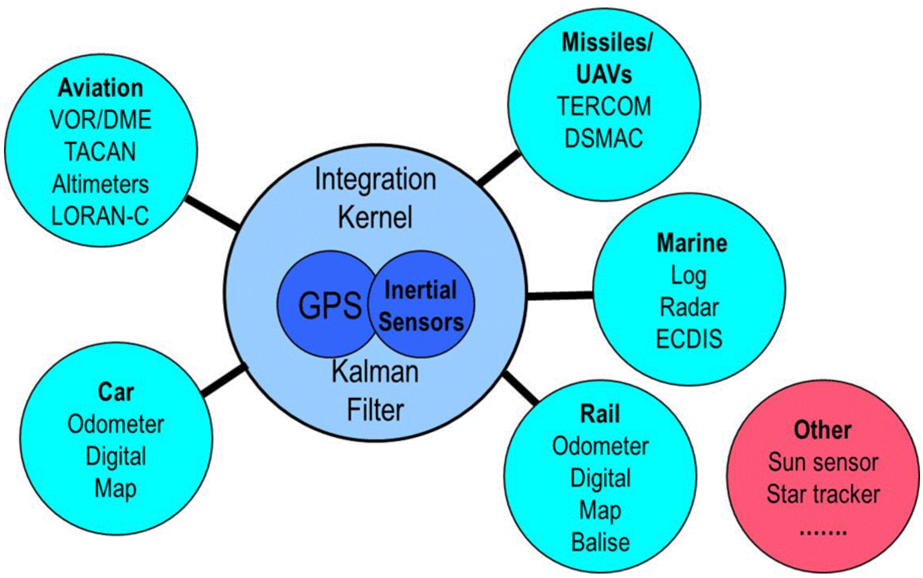


Figure 24.- Application specific multi-sensor integration

[30] Assured Positioning, Navigation and Timing (PNT) | Northrop Grumman. Last accessed March 29th 2024.

6.4.2 Kalman filter

The basic algorithmic concept in sensor fusion is the Kalman filter. Nowadays, several versions of the Kalman filter have been formulated: The classical linear version, the EKF Extended Kalman filter, non-linear), the Uncended Kalman filter (UKF) and the Partical Filter (PKF). In navigation, the classical linearized version of the Kalman filter is dominant. By inclusion of low-cost sensors, non-linear versions like the EKF and UKF gained more importance over the last years. In some applications, non-linear error dynamics is present. In these cases, it is also preferable to work with nonlinear Kalman filter versions.

Table 5.- Sketch of the linear Kalman filter

Linearized measurement equation: $\mathbf{z}_k = \mathbf{H}_k\,\mathbf{x}_k + \mathbf{v}_k \qquad \mathbf{v}_k \sim N(\mathbf{0}, \mathbf{R}_k)$
Linear dynamic model of error states: $\mathbf{x}_k = \mathbf{\Phi}_{k-1}\,\mathbf{x}_{k-1} + \mathbf{w}_k \qquad \mathbf{w}_k \sim N(0, \mathbf{Q}_k)$
Estimation of error state by aid of measurements: $\underline{\hat{\mathbf{x}}}_\mathbf{k} = \underline{\tilde{\mathbf{x}}}_\mathbf{k} + \underline{\mathbf{K}}_\mathbf{k}\left(\underline{\mathbf{z}}_\mathbf{k} - \underline{\mathbf{H}}_\mathbf{k}\,\underline{\tilde{\mathbf{x}}}_\mathbf{k}\right)$
Minimization of L^2 – norm (quadratic norm of the estimation errors): $\sum \hat{\varepsilon}_x^{\,2} = Minimum$

There are also special cases of the linear Kalman filter. Two limiting cases may be outlined:

- **Least-squares adjustment**: A transition of the Kalman filter into least-squares adjustment (Gauss) happens, if the state vector has no dynamics: $\mathbf{x}_k$ = const.
- **Wiener filter:** If the linear dynamic error model has a steady state solution in the limit (stable eigenvalues) $\mathbf{x}_k (k \to \infty) = \mathbf{x}_k(\infty)$ the Kalman gain $\mathbf{K}_k$ gets constant and the estimation equation is simplified.

In Kalman filtering the following extensions and trends are notable and may have an impact on future PNT data processing techniques:

- **Extended Kalman Filter (EKF)**
  - Dynamic system and measurement equation non-linear plus additive noise.
  - Covariance propagation and Kalman gain computation linear.
- **Uncented Kalman Filter (UKF)**
  - Construction of so-called sigma points.
  - Propagation of sigma points via non-linear system.
  - Covariance computation from spread of sigma points
- **Particle Filter (PKF)**
  - Sequential Monte Carlo simulation method.
  - A spread of the state vector is generated and propagated by non-linear system.
  - No assumption on statistical distributions required.

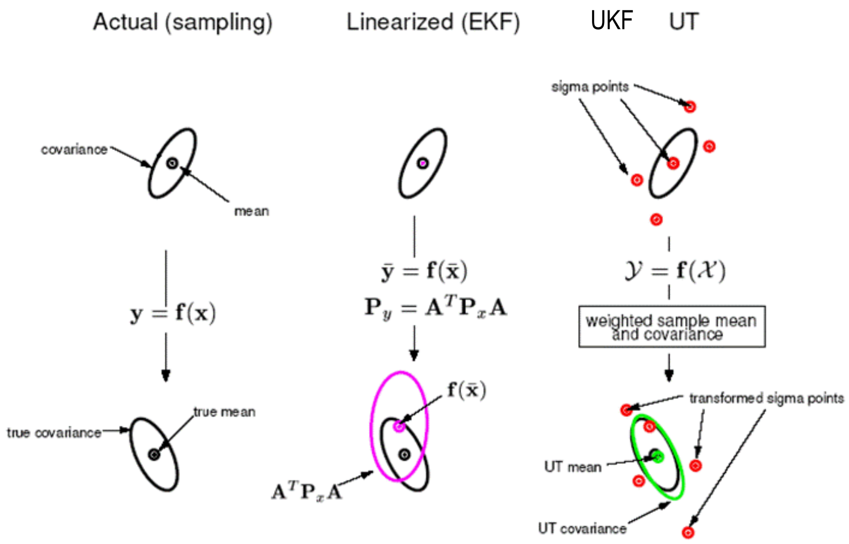


Figure 25.- Comparison of linearized EKF with UKF

In deterministic PNT error modelling no competitive algorithm for the optimal Kalman filter is available. Some sub-optimal filters like the α-β target tracker or observers are known. The impact on this classical process by artificial intelligence (AI) and machine learning (ML) is difficult to predict. An impact of AI and ML cannot be excluded.

6.4.3 L2-norm filters versus L1-norm filters

As outlined above the Kalman filter is derived by minimizing a quadratic norm of the estimation errors. In estimation theory a quadratic norm is called an L^2 – norm. This indicates that other norms are in principle possible. The L^2 – estimators have a weak point in case of outliers in the data. With L^2 – estimators it is difficult to stay robust against outliers. If an outlier is contained in the measurements, this estimator is distributing the effect over the entire unknowns. This leads to a biased estimation sometimes called smearing effect. In estimation theory, it is known that the application of the L^1 – norm is much more robust against outliers. In this case the norm to be minimized has the form: $\sum |\hat{\varepsilon}_x| = Minimum$. The algorithmic form for estimation is very similar to linear programming. Although known in theory in practical PNT – filters the L^1 – norm, possibility for outlier detection, does not play an important role. In geodetic network adjustment it is a standard. Therefore, we propose to re-consider L^1 – estimators in sensor fusion.

6.4.4 Coupling principles in sensor fusion

In the early times of Kalman filtering the number of computer instructions and operations were counted in order to assess the real-time processing requirement for the navigation computer. Because of these computational issues, sensor fusion initially was done in the simplest way on position level. With growing processing power it was possible to work on raw data level. In recent years, the Kalman filter is implemented on signal level where high-speed data processing has to be performed (non-linear Kalman filters with 100 Hz up-date cycle).

In GNSS/INS integration which is in most applications the integration kernel five ways of GPS/INS couplings (US terminology) are known: "Separate" (Reset of INS), "Loosely" (Position aiding), “Tightly” (Raw data aiding), “Ultra-Tightly" (GPS tracking loop aiding) and "Deeply " (GPS Signal aiding). Deep coupling was first developed for military purpose. Military concepts can be utilized for civil applications by reverse engineering. The development trend is the vector receiver which is up-dated directly by correlator outputs (I & Q samples). Additionally, up-dates with inertial data, dead reckoning speed measurements, etc. may be included. The deep coupling concept in the user segment leads to higher robustness against jamming and interference. For an inertial deeply coupled receiver a margin of up-to 18 dB anti-jam in the C/No may be obtained in comparison to an unaided receiver.

6.4.5 Integrity (generalized A-RAIM concept)

Receiver Autonomous Integrity Monitoring (RAIM) is an important topic in sensor fusion. Classical RAIM was developed in 1990ties and is now required for all GNSS receivers in performance-based avionics. Classical RAIM assumed a GPS only case. RAIM works with redundant satellites: Five satellites are required to detect (FD, fault detection) one malfunctioning satellite in the set. A sixth satellite is required to identify and exclude the malfunctioning satellite (FDE, fault detection and exclusion). Because of the Galileo development, it got essential to investigate the combination of two constellations (GPS + Galileo) in the RAIM concept. It turned out that by combining two independent constellations a more carful probabilistic weighting is necessary. The result was a concept of higher complexity: A-RAIM (Advanced RAIM). A-RAIM has two basic elements:

- *GNSS specific constellation performance parameters:* Bounding of fault-free clock and ephemeris distributions, prior probability of satellite faults, and prior probability of constellation faults.
- *Integrity support message for A-RAIM users*: The GNSS service provider or the aviation authority provides an information flow with nominal basic constellation data (User Range Accuracy URA, nominal Bias b_{max}, p_{sat}, p_{const}). With the emerging LEO-PNT constellations, which shall provide PNT for autonomy, the question is now on the table on how to integrate one or more LEO-PNTs and additional sensors into the A-RAIM concept.

Standford University did already an initial investigation of the problem. In a paper[31], mega constellations were considered for A-RAIM. A result was that an extremely high number of sub-sets has to be computed and compared to each other (with maximum separation algorithm). An additional problem is that with LEOs the satellite fault probability gets high (≈ 10^{-2} or 10^{-3}) whereas the constellation fault probability gets lower (≈ 10^{-7}). For comparison the values for Galileo are p_{sat} = 10^{-5} and p_{const} = 10^{-4}. For GPS the values are considerably lower.

Further developments in A-RAIM by including LEO-PNT is surely a future area of development. The inclusion of Precise Point Positioning (PPP) in A-RAIM is also important.

6.4.6 Resilience

In the PNT world, everybody talks about resilience. The problem is that resilience engineering in PNT is underdeveloped in comparison to other technology disciplines. Resilience means much more than pure redundancy concepts. A general definition of resilience was developed by the INCOSE (International Council on System Engineering)[32]:

Resilience:

1) "Resilience is the ability (of a system) to provide required capability in the face of adversity"
2) "Adversity is any condition that may degrade the desired capability of a system" (environmental sources, normal failures, human sources – malicious or accidental)

This general definition should be adapted to the PNT field. PNT capabilities are formulated in higher dimensions in minimum by the four parameters (accuracy, availability, continuity, integrity). In performance-based navigation the user requirements are formulated on these parameters. If an adversity happens one or all parameters could lose the capability or change to a new state. Usually,

[31] Advanced RAIM for Mega-Constellations | Technical Program - ION ITM 2024. Blanch, Juan et al. January 2023. Last accessed March 29th 2024.
[32] Resiliency in Systems Engineering (incose.org). Last accessed March 29th 2024.

this state has degraded performance. After a certain time, the lost capability could be re-established again.

The important point is to determine the resilience of a PNT system by applying a metric to each of the four capability parameters.

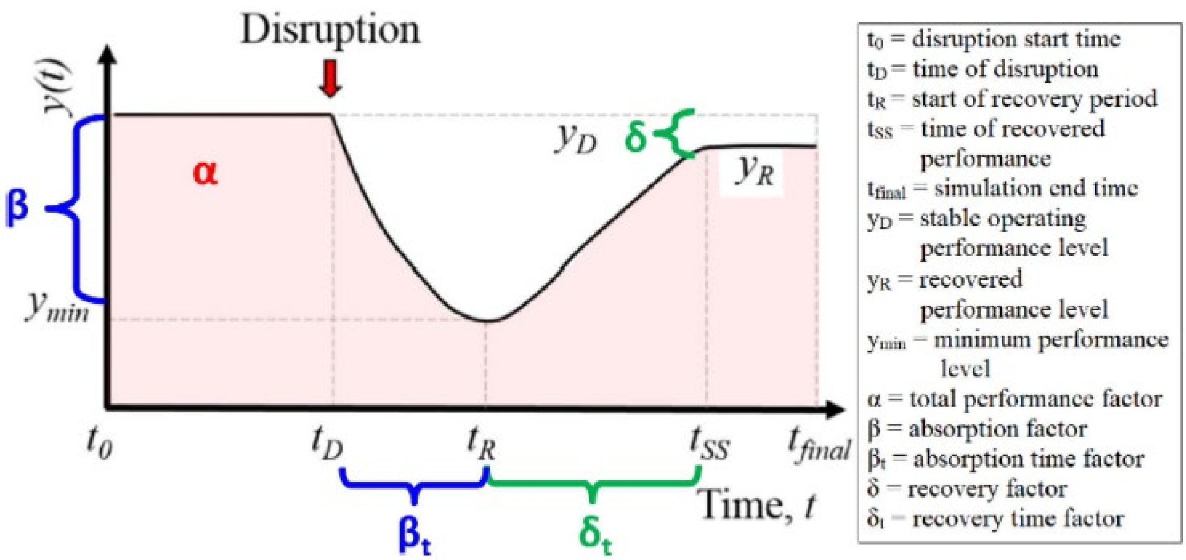


Figure 26.- Comprehensive resilience metric capacities[33]

The resilience metric for the performance capability is proposed as follows:

$$R = \underbrace{w_\alpha \alpha}_{\text{Total performance capacity}} + \underbrace{w_\beta \beta \beta_t}_{\text{Absorption capacity}} + \underbrace{w_\delta \delta \delta_t}_{\text{Recovery capacity}}$$

Table 6.- Resilience metric component equations

Variable	Description	Equation
$w_\alpha, w_\beta, w_\delta$	Capacity weights	constant
α	Total performance factor	$\frac{\sum_{t=t0}^{t_{final}} y(t)}{y_D(t_{final} - t_0)}$
β	Absorption factor	$\frac{y_{min}}{y_D}$
β_t	Absorption time factor	$\frac{t_R - t_D}{t_{ss} - t_D}$
δ	Recovery factor	$\frac{y_R}{y_D}$
δ_t	Recovery time factor	$\frac{t_{ss} - t_R}{t_{ss} - t_D}$

The short description shows that it is possible to formulate metrics for a PNT system in the parameters accuracy, availability, continuity, integrity (and may be others). A transfer of the general system engineering concepts for resilience to PNT systems is not easy but possible. ESA is encouraged to do a step in this direction.

[33] A framework for the quantitative assessment of performance-based system resilience. *Rel. Eng. Syst. Saf.*, vol. 158, pp 73-84. H. T. Tran, M. Balchanos, J. C. Domerçant, and D. N. Mavris. 2017.

7 Integrated systems

7.1 System integration considerations

GPS/GNSS is an excellent example of a sensor/system/service which users almost exclusively experience as part of a complex integrated system. Early receivers gave position in “lat-long” and the user had to plot position on a (compatible) chart. Now position, the map and even guidance from “A to B”is part of the smartphone user-experience.

Behind the scenes is a story of technology maturation and product evolution. For many years the Google Android operating system has given application developers access to raw GPS data, not just position. Access to pseudo range, pseudo range rate and automatic gain control settings have given developers the opportunity to develop new applications and services. The GNSS chipset has evolved from being a provider of position to a provider of pseudo ranges. This unlocks the use of GSM and Wi-Fi signals in a tightly integrated solution.

This evolution has been driven by user demand. When considering future PNT technology the key question will be what benefits new “upstream” systems will bring to the users of systems which are already complex and highly integrated.

Thus, the challenge of working out what benefits a new system or technology might bring a user is problematic on many fronts:

- The integration process may be complex and opaque. If AI is adopted by some of the underpinning services it will be difficult to predict system performance or user experience.
- The impact of a particular sensor/system on the user is highly dependent on the use/use case. For example, users with no interest in resilience will gain little benefit from resilience.
- The performance of complex systems is difficult to model or predict. Adding new sensors and systems will undoubtedly have unforeseen consequences.
- More is often better but there is also a “lowest common denominator”. Adding satellites and constellations has greatly improved GNSS accuracy and availability. However, characteristics such as resilience will only be improved by adding more resilient systems.
- Resilience in particular is poorly understood.

Market forces have encouraged the integration of many systems on an opportunistic basis. The work of Focal Point Positioning Ltd in the UK – for example - illustrates how sophisticated developers have become. The task in hand for governments and institutions such as ESA is a new one. The question to be addressed is, “What additional systems and sensors will be required to give the overall system the desired performance for specific classes of user.”

This places a significant burden on those studying future infrastructure requirements. The impact of adding new systems to a large community of users of already using complex integrated systems is difficult to assess.

Furthermore, PNT services rarely standalone from other commercial services.

In most cases, PNT has to be combined with other systems or technologies to satisfy the user needs, for instance:

- In the case of mass consumer LBS, the need may be as simple as delivering personalized advertisements at the point of location or gaming.
- For autonomous driving, combination with multiple other technologies, e.g. V2X communications, visual detection, will be required.
- Advanced air mobility application will require communications and surveillance systems, possibly including some capabilities for non-cooperative traffic.

- In logistics and multi-modal transport applications, IoT technologies will play a pivotal role.

PNT sensors and solutions integration within the overall system required to deliver the solution at user level will, up to a certain extent, condition the architecture of the PNT solution itself. For instance, vehicle PNT information required to allow autonomous driving in urban areas could be generated at a centralized infrastructure and then distributed to the end-user vehicles using ubiquitous 6G networks, rather than computed at the vehicle itself.

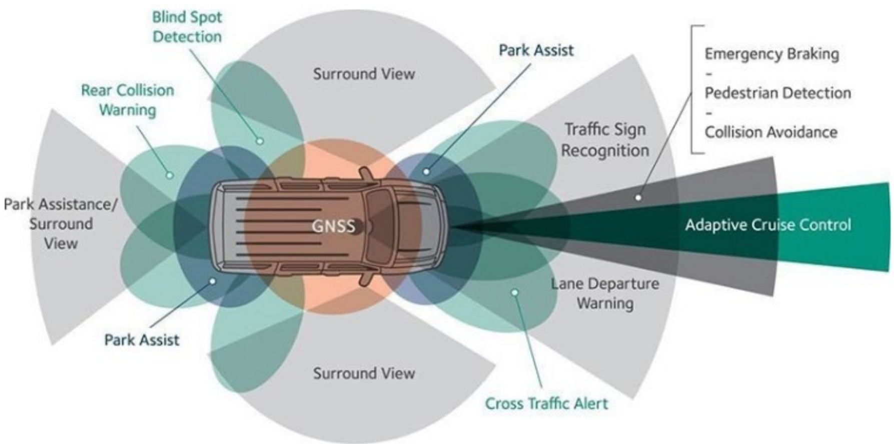


Figure 27.- Sensor suite for autonomous driving goes beyond pure PNT.

SWaP-C considerations will also determine the way in which PNT sensor and device architecture concepts evolve. For instance, Integrated Modular Avionics (IMA) architectures will not consider different processors for different functions, say communications and navigation, but rather implement a distributed processing architecture over an AFDX network, where SDR receivers will run indistinctly on the available computer nodes. ECU consolidation in the automotive industry will also follow this path.

In the low-end, but dominant, segment of the market, PNT sensors, and in particular GNSS, will mostly be part of integrated systems, or system-of-systems, including communication elements. This will lead to a higher integration of GNSS and RF communications devices, even at chip or other components level.

In summary, more often than not, use cases will require integrated systems combining PNT solutions with other sensors, processors, actuators or communication devices. In the vastly interconnected world of 2035, this will increase the exposure of PNT systems and sensors to a broad range of risks and threats. Under these conditions, some aspects of the end-user solution will only be testable and demonstrable at a higher level of system integration, e.g. safety, security or end-to-end performance.

7.2 Security and Safety

Future PNT systems at user level will possibly be more software intensive and less hardware dependent. Open architectures and standards will be required to allow the ease and straight forward integration of new autonomous sensors or RF navigation signals, even for security applications – consider, for instance, the US DoD efforts to implement modular open systems approaches (MOSA) with the aim of decrease the time and cost needed to integrate and field new PNT capabilities[34] –. This will tend to weaken the cybersecurity of the future systems.

[34] Technology Assessment. Defense Navigation Capabilities. US Government Accounting Office (GAO). May 2021. GAO-21-320SP, Defense Navigation Capabilities: DOD is Developing Positioning, Navigation, and Timing Technologies to Complement GPS. Last visited: March 14th 2024.

Besides, the integration of PNT with other solutions in a vastly interconnected environment increases the vulnerabilities of the system, and makes it harder to protect it against cyberthreats. New threats on the GNSS systems will come more from the cybersecurity front than from the physical RF environment, although of course these will not disappear. Under these conditions, encryption and authentication are key features to guarantee the security of future PNT solutions. Quantum technologies will also have a role in this respect.

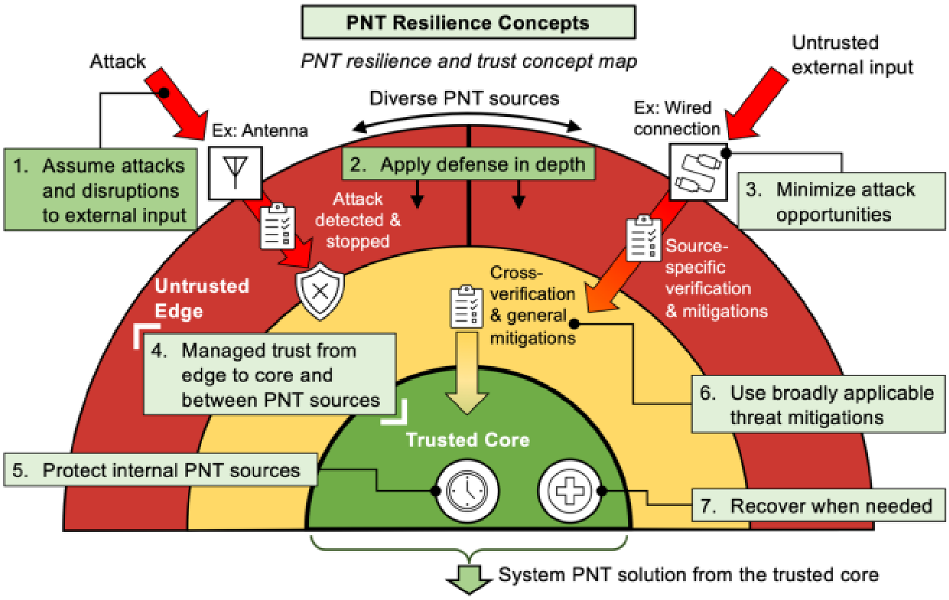


Figure 28.- Conceptual representation of trust in a PNT UE system and PNT resilience concepts. The managed trust concept relies upon verification and isolation methods.[35]

As concerns safety considerations, the certification of PNT solutions will, in many cases, depend on issues at a higher level of system integration. For instance, SAE Level 4 autonomous driving features will have to be certified at vehicle level, even if the on-board PNT system meets the most stringent requirements for road applications.

The development of safety certification standards for PNT solutions will ease the deployment of these technologies in multiple application fields and, in many cases, will be a key market enabler. A lot can be learnt from previous cases as, for instance, EGNOS certification for Civil Aviation. The SBAS component of the overall system-of-systems achieved certification by 2011, but this milestone just opened a long process by which air-navigation service providers were bound to develop and publish new instrumental approach procedures based on this system. Then, the aircraft have to be fitted with compatible receivers and operators have to receive the corresponding certification before EGNOS could actually be used in airport approaches. Anticipating a clear roadmap to end-to-end certification of the future PNT systems for safety critical applications will be crucial to speed up the penetration of alternative and complementary technologies to GNSS.

In this respect, the availability of test beds for safety certification can be critical for the development of assured PNT solutions in the future, whether satellite based or not. Bearing in mind the long process from system implementation to final certification, having access to appropriate validation and operational experimentation test beds from the outset will greatly ease the path to the entry into service of new safety critical services.

[35] Resilient Positioning, Navigation, and Timing (PNT) Reference Architecture. Version 1.0. US Department of Homeland Security Science and Technology. June 2022. [Resilient Positioning, Navigation, and Timing (PNT) Reference Architecture (dhs.gov)](). Last visited: March 14th 2024.

Moreover, the certification of some of the expected future algorithms and data processing technologies may be cumbersome; in particular, but not just, Artificial Intelligence (AI). To trust the results obtained by an algorithm, the user needs to know that it is reliable and can be accounted for, and that it will introduce no uncertainty. The certification authorities need assurances that AI cannot be tampered with and that the system itself is secure. They need to be able to look inside AI systems, to understand the rationale behind the algorithmic outcome, and even ask it questions as to how it came to its results.

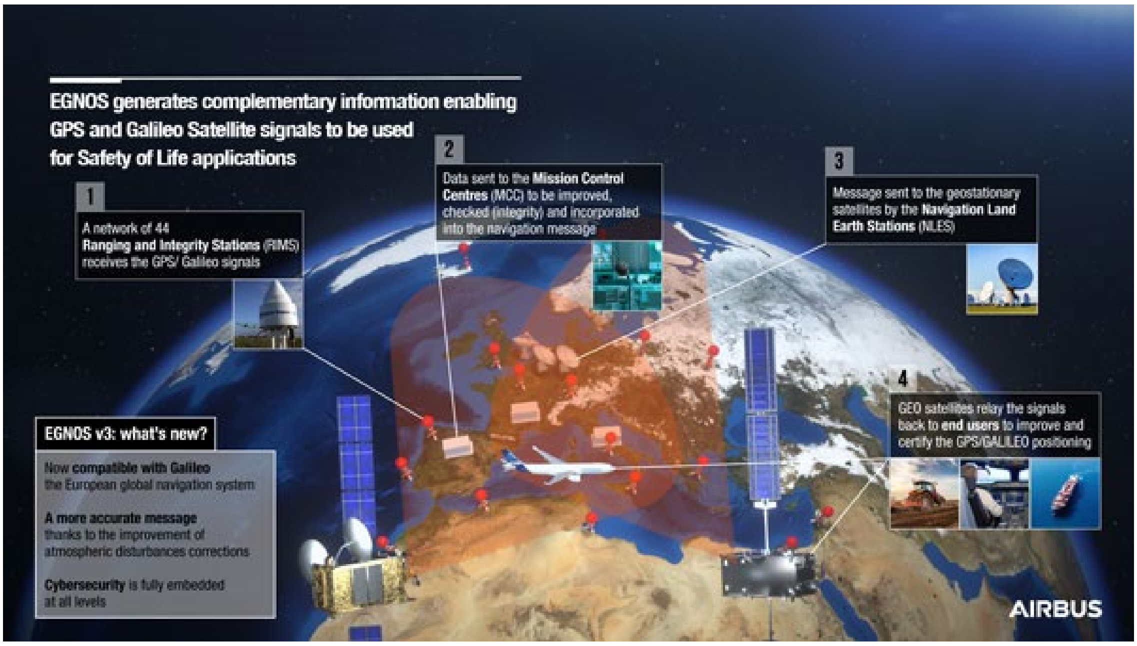


Figure 29.- Future safety critical PNT services like EGNOS V3 will require end-to-end system certification for which appropriate test and validation facilities will play a pivotal role.

8 Applications and services

8.1 Upcoming applications

Accurate, reliable and continuous PNT will be a prerequisite for many “killer” applications in 2035. However, PNT technologies alone will rarely be enough. PNT technology will be bundled with others to satisfy the end-user’s needs.

In most of the cases, communications will be involved one way or another. 5G/6G networks will be key to make feasible most of those applications and will be a complementary – or alternative – technology to satellite-based PNT. But it also runs the other way round: network optimization to improve network efficiency and communication capacity will require more accurate localization and synchronization. Examples are network management, resource management for device to device (D2D) communications, radio reconfigurable spectrum, vehicular ad-hoc networks, etc.

However, other technologies will also come into the bundle: VR/AR, caching, blockchain, video processing, tactile Internet, wearable devices and, of course, AI. All together, they will enable applications through a vast range of domains, for instance:

- Industry Internet: full automation will be provided by 6G with its ultra-massive connectivity capability and ultra reliability, which means that automatic control of processes, devices, and systems, aided by precise and seamless positioning both indoor and outdoor that will ease the implementation of VR/AR remote control of factory operations.
- Fully autonomous driving, at least up to SAE Level 3 (whether or not Level 4 can be achieved by mid-30’s is arguable).
- Autonomous vehicles of many sorts, including logistics delivery or lawn movers
- Super-smart cities, that can run intelligently and autonomously by collecting and analysing massive quantities of data – including PNT – from a wide variety of industries, from urban planning to garbage collection.

In all cases, high-end PNT applications will require improved performances in terms of accuracy, reliability, availability, integrity or time-to-first-fix. This will in turn push the growth of complementary PNT services, like assisted-GPS or RTK, that will also benefit from the development of other technologies (e.g. 5G/6G).

8.2 Upcoming services

As with applications, advanced PNT services may be offered bundled with other complementary services that add value to the end-user. For instance, safe GNSS ionospheric corrections can be distributed as part of a pay-as-you-drive AD solution. As a matter of fact, assured-PNT services can be a trigger for other E2E services across different domains.

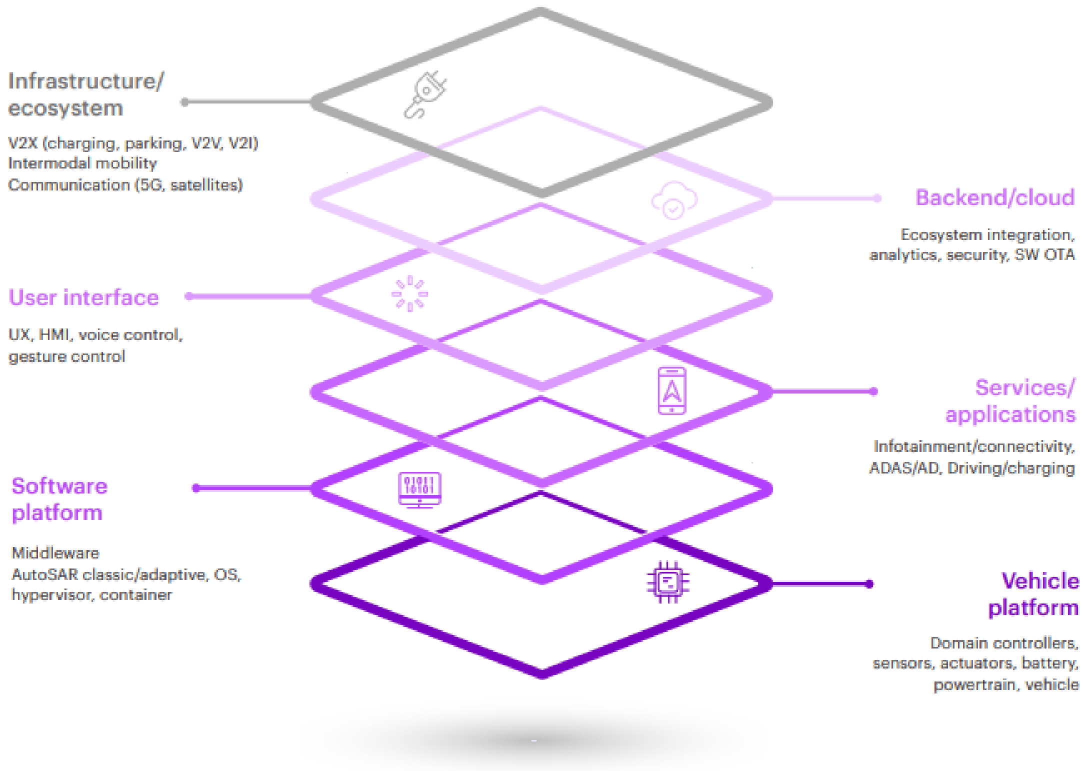
Services bundling has the potential to disrupt the structure of the value chain in the PNT market by attracting new players to the arena, in a similar way as happened in the telecom market with the bundling of fixed communications, mobile, TV and data services.

The architecture of the future services will include global, regional and local components. Service providers will have to decide at which level do they want to compete, but global services are likely to remain largely public, even though some commercial players may step into the game.

On the contrary, assured PNT services may evolve in the direction of local or regional solutions and be delivered by private organizations that undertake to develop the required additional infrastructure in those areas where the demand is higher, e.g. urban areas in developed countries. However, it is hard to imagine a pure-play service provider and, once again, service bundling will be the likely game.

8.3 Threats and opportunities in the downstream market

The fact that in most cases PNT solutions will have to be bundled with other technologies to satisfy the real needs of the end-user will certainly condition the pace at which future PNT-based applications and service will grow. Consider the case of autonomous driving. Figure 30 illustrates the technology stack for an electric autonomously driven vehicle. For the vehicle to perform up to the user expectations, PNT is just a piece of the puzzle. To start with, the vehicle platform will have to be provided with a complex suite of sensors that will allow it not just to position itself or navigate through the planned route, but to share the road with other non-cooperative man-driven vehicles, pedestrians or other more or less unexpected obstacles. But even if all the other vehicles would be equipped with cooperative systems, the autonomous operation would depend on having available a suitable vehicle-to-vehicle interconnection network that could support the multiple data exchanges required to navigate in for instance an urban environment. To achieve this connectivity, 5G/6G networks would have to perform up to their promise.



Legend: vehicle-to-everything (V2X); vehicle-to-vehicle (V2V); vehicle-to-infrastructure (V2I); user experience (UX); human machine interface (HMI); automotive open system architecture (AutoSAR); software over-the-air (SW OTA); advanced driver assistance systems & autonomous driving (ADAS/AD).

Figure 30.- Autonomously driven vehicle technology stack[36]

The problem is that the implementation of the complete stack will only run as fast as the slowest link in the chain. This threatens to delay the explosion of some of the PNT applications and services.

However, the opposite is also true: an accelerated market penetration of some of the technologies in the stack may speed up the growth of the assured PNT systems. For instance, the use of IoT in logistic services will be a catalyst to increase the penetration of PNT devices in this market segment.

[36] Moving into the software-defined vehicle fast lane. Accenture. 2022. [Moving into the software-defined vehicle fast lane | Accenture](). Last visited: March 15th 2024.

Or in other market segment, the growth of autonomous shipping will push for the implementation of an alternative PNT means in high seas, where global GNSS are the only available option.

Keeping a permanent watch on the evolution of other complementary technologies in the application and service stack will allow the industry to detect threats and opportunities and to anticipate a response to those.

9 Conclusions and recommendations

There is a clear case for investing in future PNT systems. Beyond the economic dependence on GNSS, growing security and defence concerns and a questionable access to some of the existing systems in the future make it advisable to consider the development of alternative and complementary resilient systems.

PNT services are threatened by attacks that endanger its security and safety, ranging from jamming, spoofing and meaconing, to cybersecurity risks. ESA should continuously review risks to the PNT environment, both physical as well as geo-political and regulatory changes

Although the development of mass applications such as autonomous driving will depend on the availability of a host of other technologies, the demand for higher accuracy and integrity, higher robustness against interference, jamming and spoofing, higher availability and more resilient PNT services will require closing the performance gaps in L-Band MEO-PNT in the direction of assured PNT. Within this context, the deployment of a LEO PNT constellation, whether independent or piggyback on a satcom constellation like IRIS2, cannot be overlooked. The design of this constellation must consider the potential implications on the user segment, especially as concerns the mass market that, in the end, provides the economic justification for the investments required.

Future alternative PNT systems, whether space or ground based, must be designed and implemented avoiding interdependencies to the present GNSS (e.g. using GNSS as the time reference for other ground networks). This, besides the known vulnerabilities of radionavigation systems, advices to foster the development of autonomous navigation sensors – inertial, magnetic or gravity field sensors, visual sensors combined with high resolution digital maps, etc – as well as clocks. Clocks performances will have to improve to resolutions in the order of picoseconds, to improve the resilience and accuracy of the systems.

Assured PNT will not necessarily have a homogeneous performance globally. Local performances will depend on the willingness of the actors contributing to the system-of-systems to deploy capabilities on their area of concern. Assured PNT may be more a regional issue than a global issue and therefore, it would be of interest to investigate regional solutions, interoperable with other regional solutions.

It is also worthwhile to explore further the possibility of exploiting Signals of Opportunity. A realm of systems will be available in the future that opens new avenues to provide a valuable complement to dedicated PNT infrastructure.

ESA should also help the development of new processing technologies, e.g. based on machine learning or AI. This is particularly important in the likely scenario of increasing complexity of the PNT systems and of the integrated systems that require PNT functionalities to render their services. However, insight into the reliability of such technologies is fundamental for their applicability.

Although mass market applications and services will drive the demand for future PNT systems, high end applications and services cannot be ignored, as they will represent a critical segment to be served in areas like precise agriculture, grid synchronization, air navigation, autonomous shipping or security and defence. A question to be carefully considered is that of future convergence of both ends of the market at the level of user receivers, and what could be the impact of such convergence on the design of future PNT systems.

ESA should also pursue the development of the technologies and systems required to extent the GNSS service volume. This will be crucial to the space ambitions of Europe, and to avoid lagging behind other space powers in the exploration of the Moon and Mars.