Council of the
European Union

Brussels, 7 June 2023
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ADD 1

ESPACE 27	**ENER 335**
RECH 274	**AGRI 301**
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EU-GNSS 16	**CSDP/PSDC 440**
TRANS 229	**CFSP/PESC 804**
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MAR 84	**PECHE 231**
TELECOM 182	**FIN 599**

COVER NOTE

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Delegations will find attached document SWD(2023) 203 final.

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PART 2/2

COMMISSION STAFF WORKING DOCUMENT

European Radio Navigation Plan 2023

Contents

5 APPENDIX A: PNT Systems

5.1 Global Navigation Satellite Systems (GNSS)

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

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

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

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

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

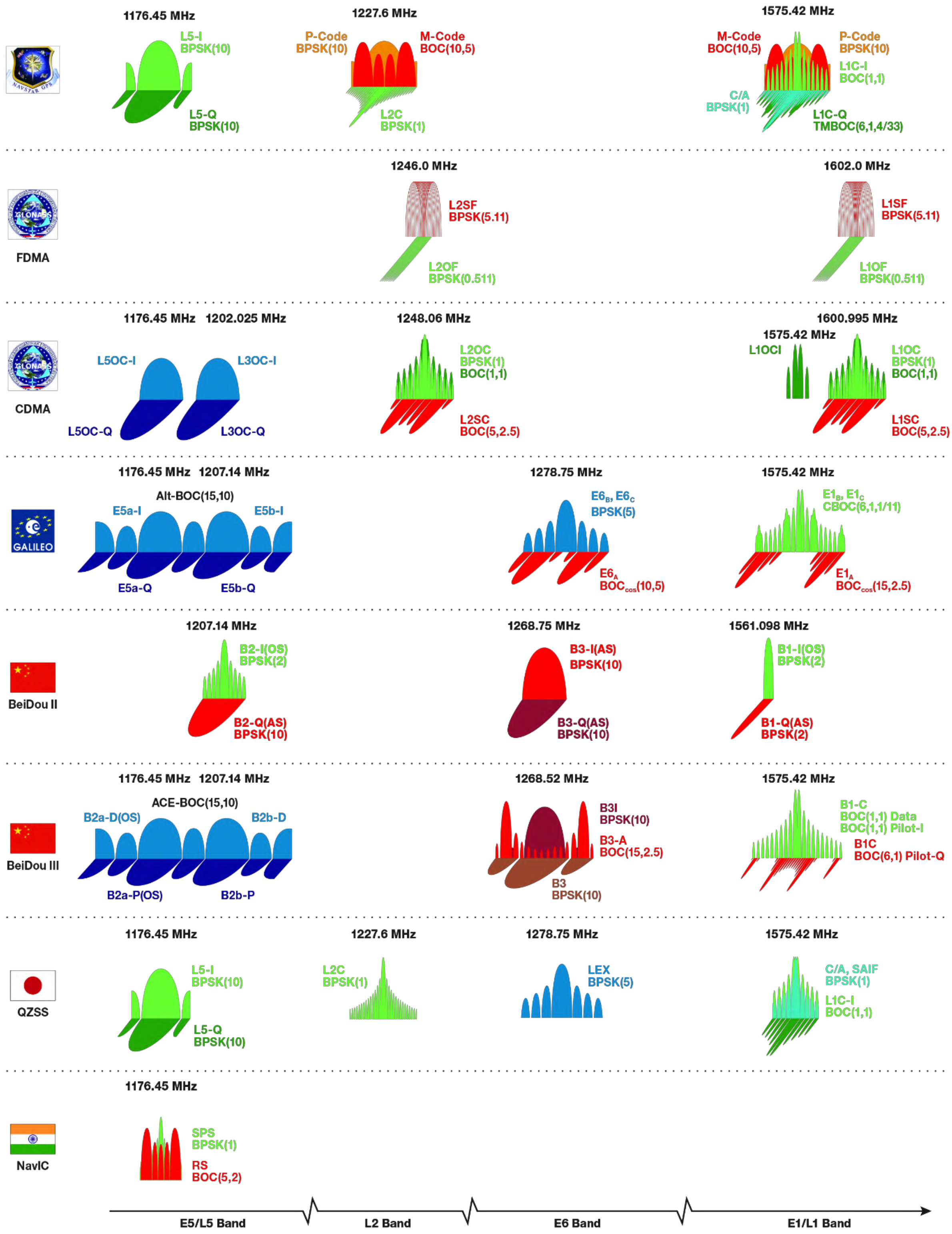


Figure 21 – GNSS frequencies (Credit: Navipedia)

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

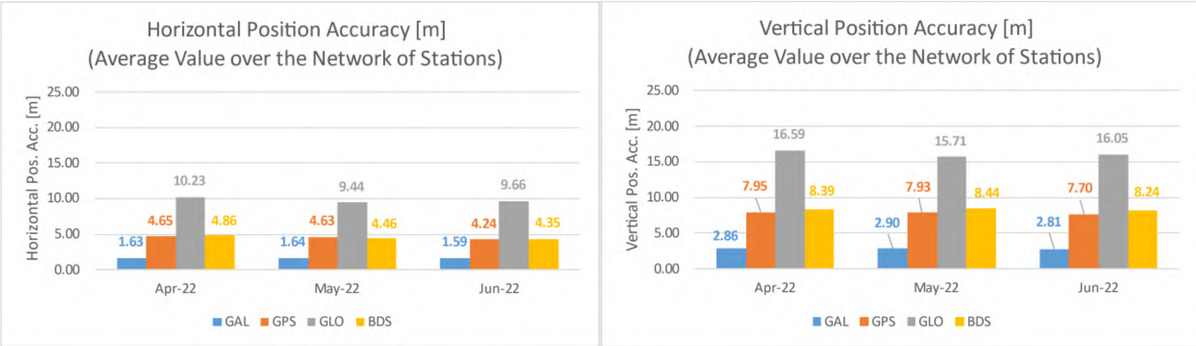


Figure 22 – GNSS horizontal and vertical accuracy performance (Credit: EUSPA)

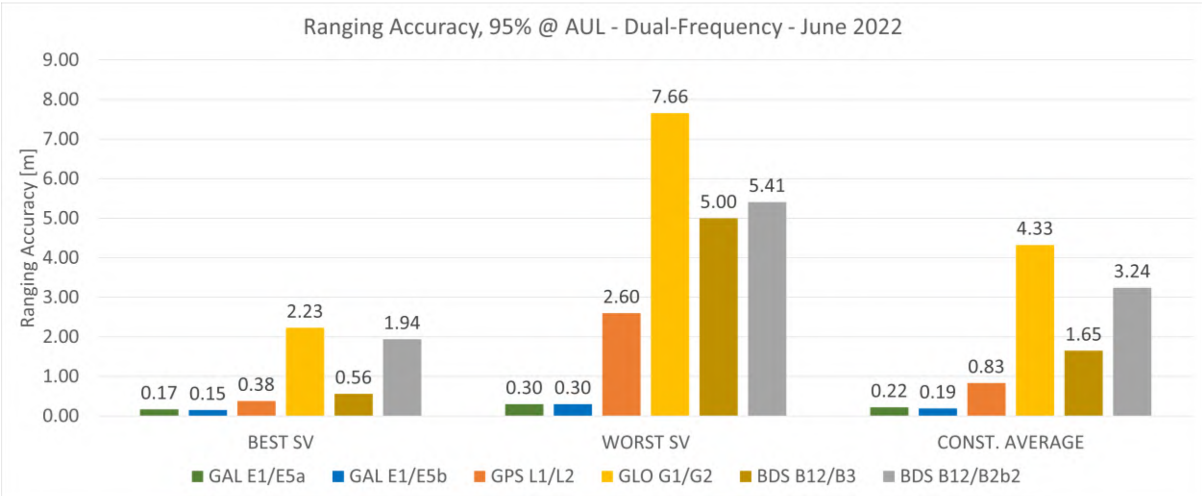


Figure 23 – GNSS ranging accuracy 95% for Galileo, GPS, GLONASS and BeiDou Dual Frequency users

5.1.1 Satellite Navigation Systems – Global coverage

5.1.1.1 Galileo

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

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

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

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

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

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

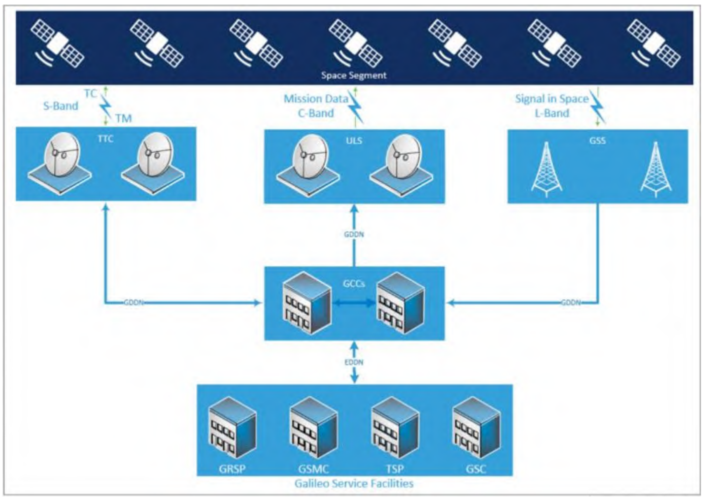


Figure 24 – High level scheme of the Galileo Ground Segment Architecture

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

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

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

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

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

in Maspalomas (Spain), Larnaca (Cyprus), Spitsbergen (Norway), Toulouse (France) and Santa Maria (Portugal). A fourth MEOLUT will be deployed in Reunion Island (France) in 2023.

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

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

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

5.1.1.1.1 *Galileo Services*

Galileo services are described in section 3.2.

5.1.1.1.2 *Main characteristics*

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

Table 7 – Principal characteristics of Galileo signals

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

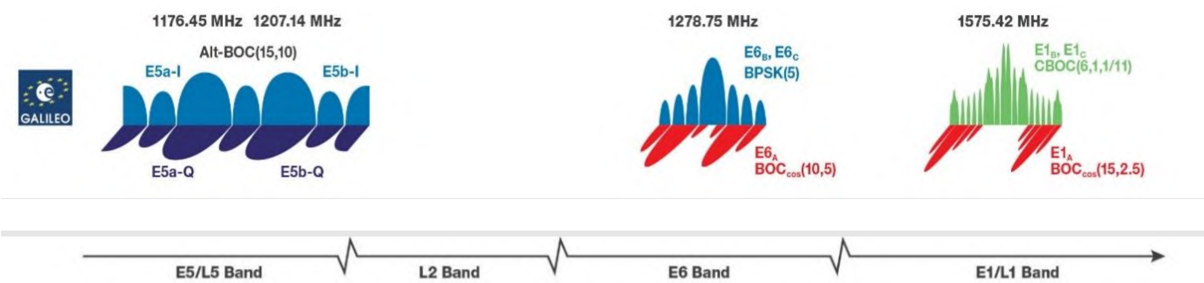


Figure 26 – Galileo signals (Credit: Navipedia)

5.1.1.1.3 Performance

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

Table 8 – Galileo Service Performance when fully deployed.

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

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

5.1.1.1.4 Status and modernisation plans

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

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

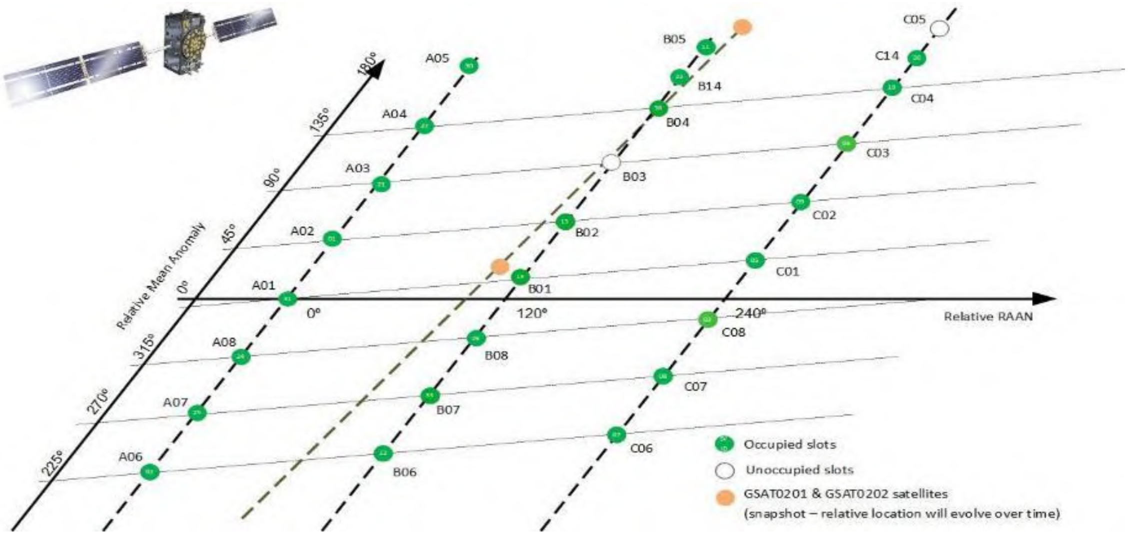


Figure 27 – Galileo Space Segment (status at the end of 2022)

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

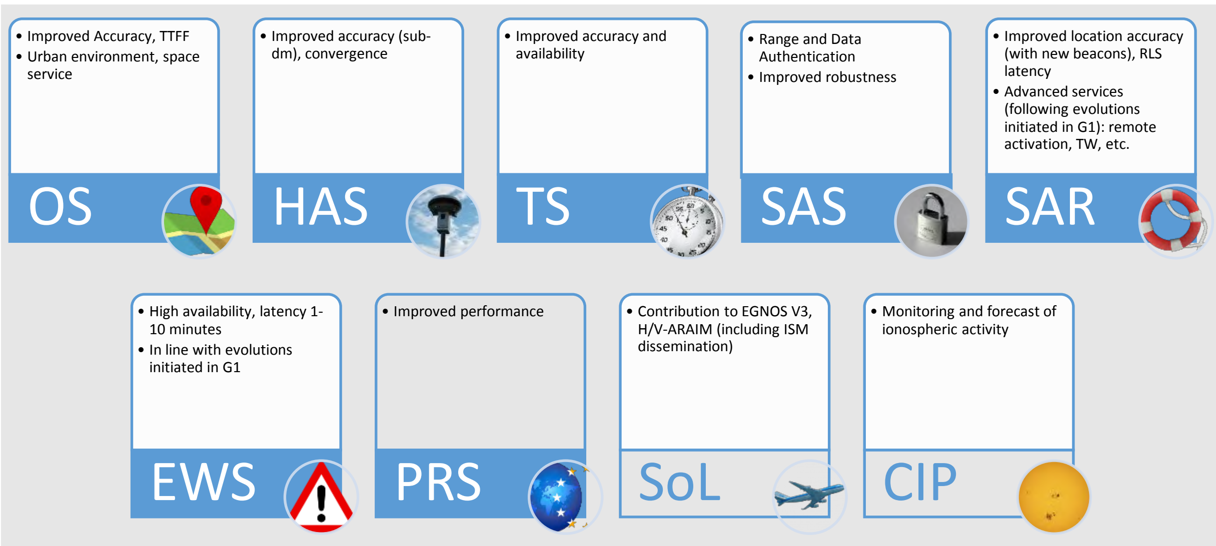


Figure 28 – Galileo Second Generation service improvements

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

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

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

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

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

5.1.1.2 GPS

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

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

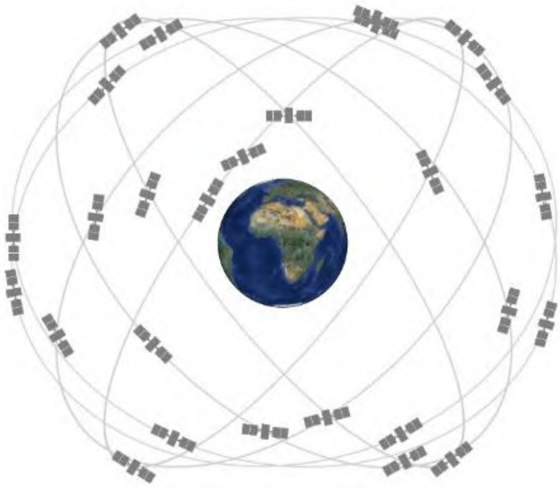
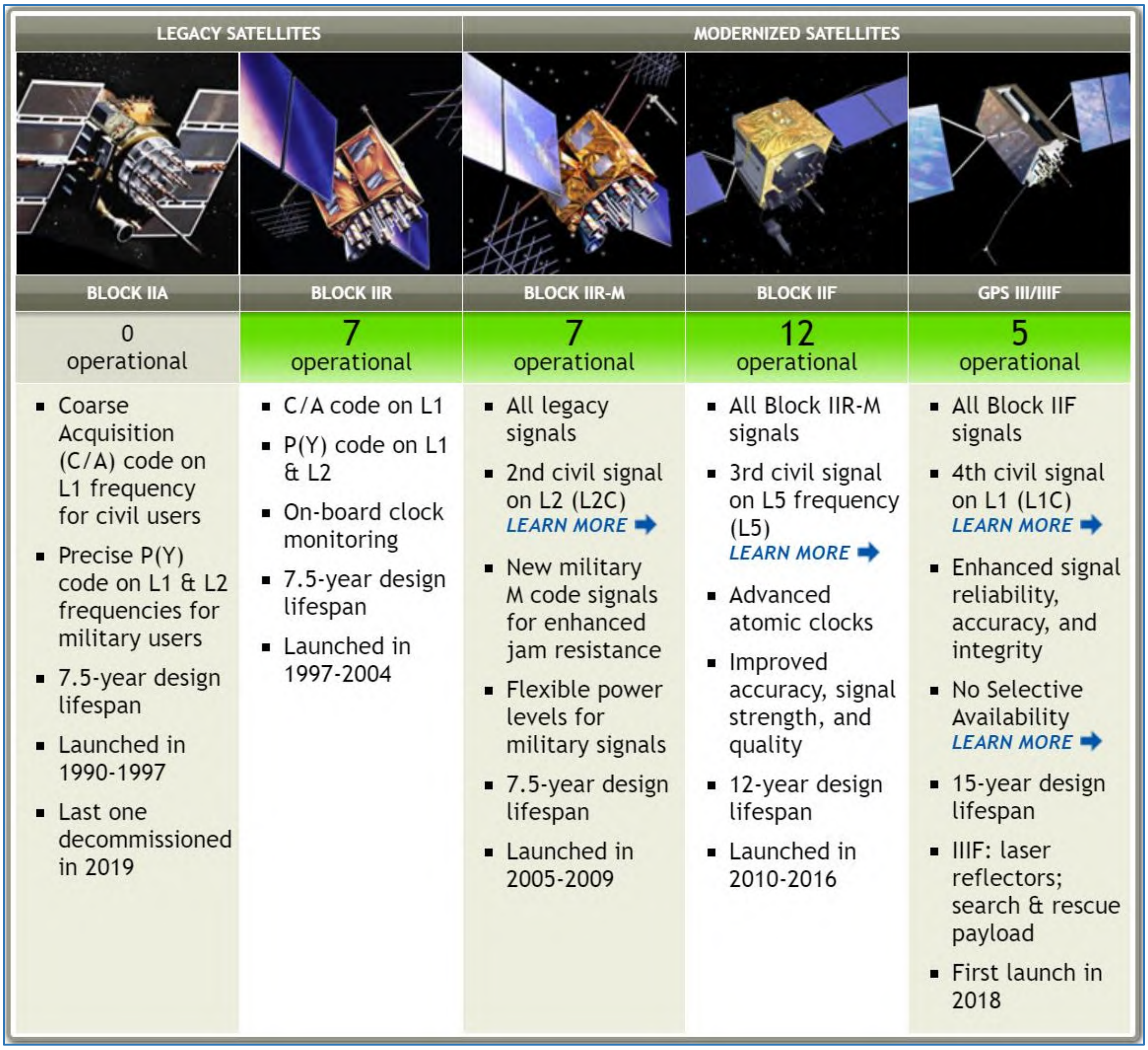


Figure 29 – GPS constellation (Credit: http://www.gps.gov)

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

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



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

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

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

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

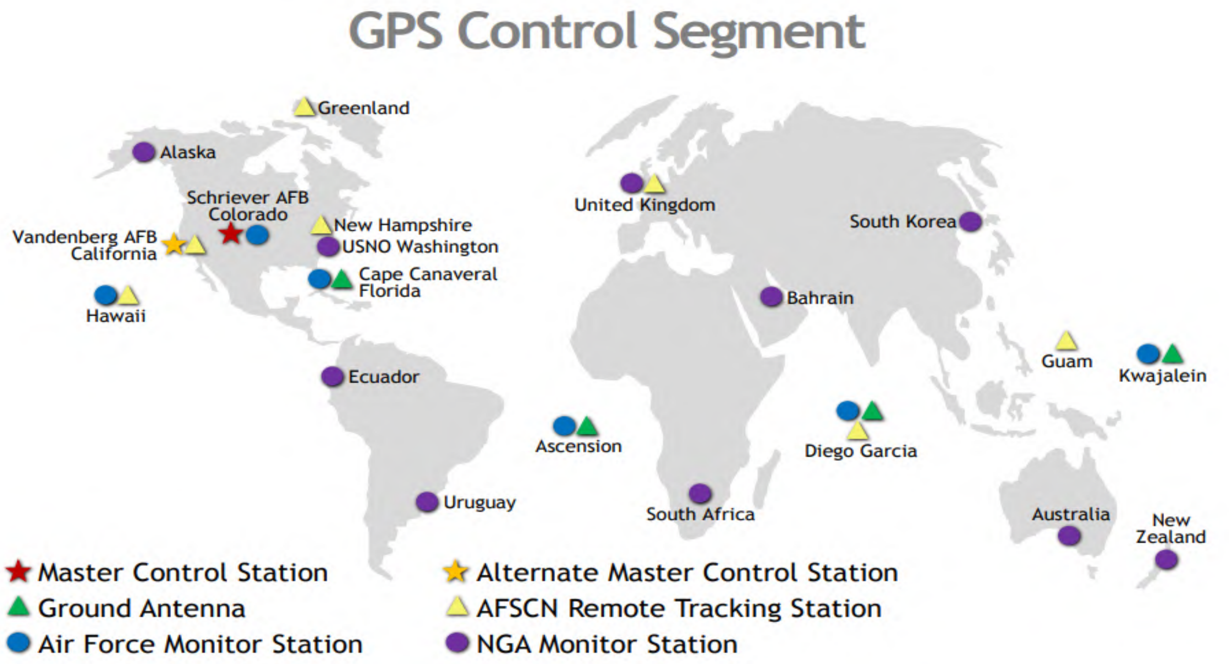


Figure 31 – GPS Control Segment (Credit: http://www.gps.gov)

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

5.1.1.2.1 GPS Services

There are two types of GPS Positioning Services:

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

5.1.1.2.2 Main characteristics

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

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

Table 9 – Principal characteristics of GPS signals

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

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

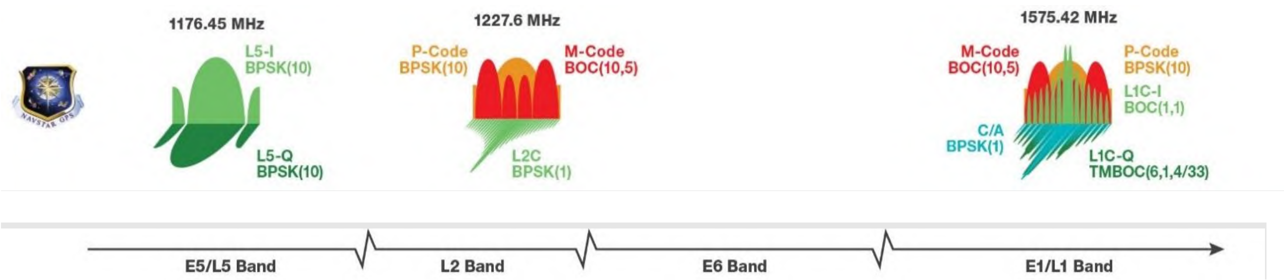


Figure 32 – GPS signals (Credit: Navipedia)

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

Table 10 – GPS SPS position and time accuracy standards

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

Time transfer error (95%) ≤ 40 ns (SIS only)	

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

Table 11 – GPS SPS specifications

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

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

5.1.1.2.3 Performance

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

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

5.1.1.2.4 Status and modernisation plans

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

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

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

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

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

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

5.1.1.3 BeiDou

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

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

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

Figure 33 – BeiDou constellation

5.1.1.3.1 BeiDou Services

BeiDou will have two types of services:

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

5.1.1.3.2 Main characteristics

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

Table 12 – Principal characteristics of BeiDou signals

B1				
Signal	B1-I(OS)	B1-Q(AS)	B1-C	B1
Frequency (MHz)	1561.098	1561.098	1575.42	1575.42

Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (2)	BPSK (2)	MBOC (6,1,1/11)	BOC (14,2)
B3				
Signal	B3-I(AS)	B3-Q(AS)	B3-A(AS)	B3(AS)
Frequency (MHz)	1268.52	1268.52	1268.52	1268.52
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (10)	BPSK (10)	BOC (15,2.5)	BPSK (10)
B2				
Signal	B2-I(OS)	B2-Q(AS)	B2a	B2b
Frequency (MHz)	1207.14	1207.14	1176.46	1207.14
Access Technique	CDMA	CDMA	CDMA	CDMA
Modulation	BPSK (2)	BPSK (10)	AltBOC (15,10)	AltBOC (15,10)

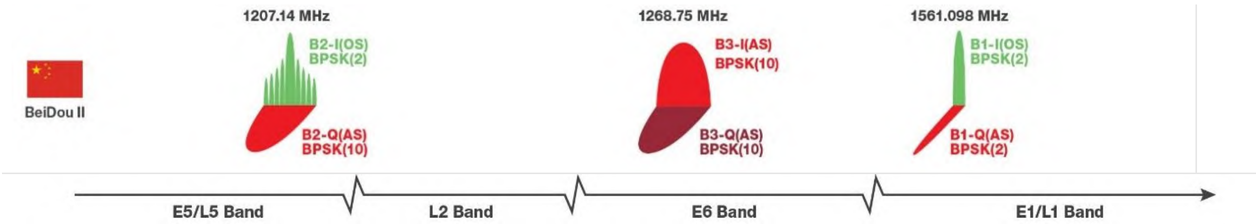


Figure 34 – BeiDou signals (Credit: Navipedia)

5.1.1.3.3 Performance

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

Table 13 – BeiDou performance

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

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

5.1.1.3.4 Status and modernisation plans

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

5.1.1.4 GLONASS

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

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

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

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

5.1.1.4.1 GLONASS Services

GLONASS has two types of services:

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

5.1.1.4.2 Main characteristics

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

Table 14 – Principal characteristics of GLONASS signals

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

	1248.625	1248.625		
Access Technique	FDMA	FDMA	CDMA	CDMA
Modulation	BPSK (0.511)	BPSK (5.11)	BPSK (1)	BOC (5,2.5)
Minimum received power [dBW]	-167	N.A.		
L3				
Signal	L3 OC			
Frequency (MHz)	1202.025			
Access Technique	CDMA			
Modulation	QPSK (10)			
L5				
Signal	L5 OC			
Frequency (MHz)	1176.45			
Access Technique	CDMA			
Modulation	QPSK (10)			

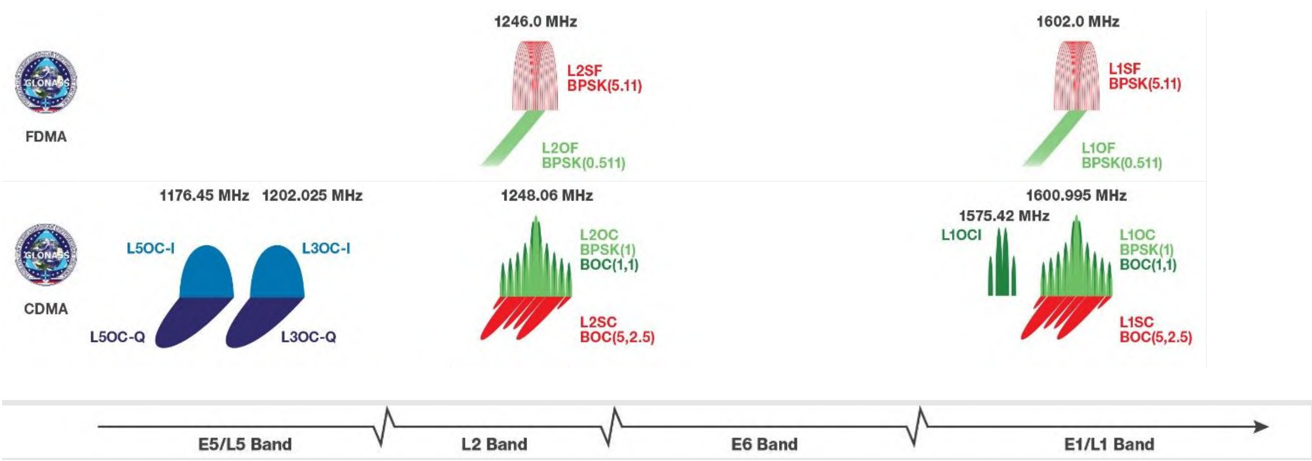


Figure 35 – GLONASS signals (Credit: Navipedia)

5.1.1.4.3 Performance

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

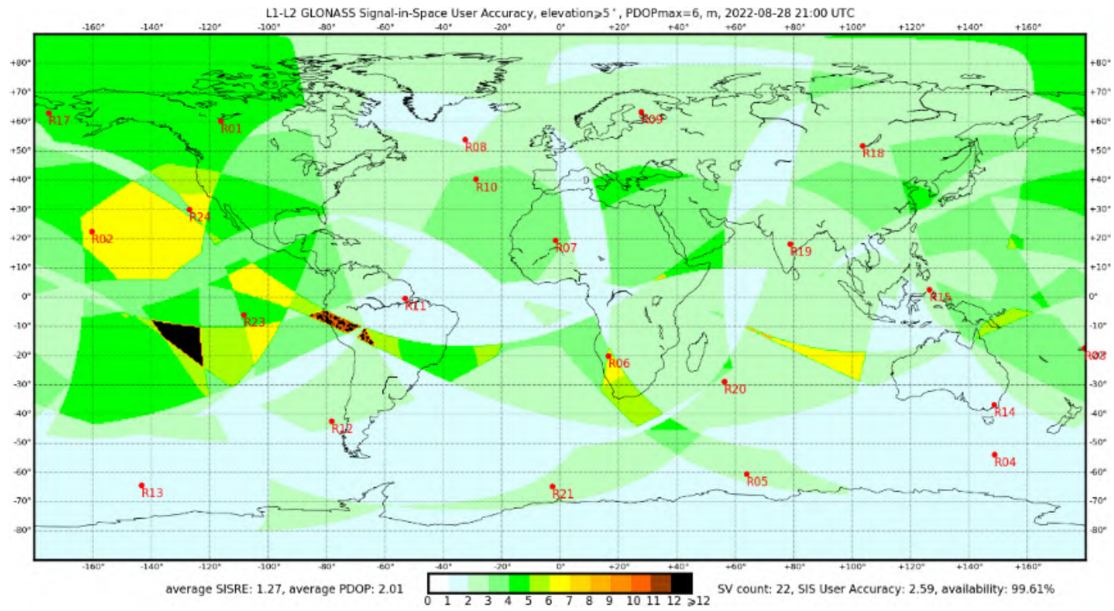


Figure 36 – GLONASS Signal-in-Space User Accuracy (SIS UA) performance

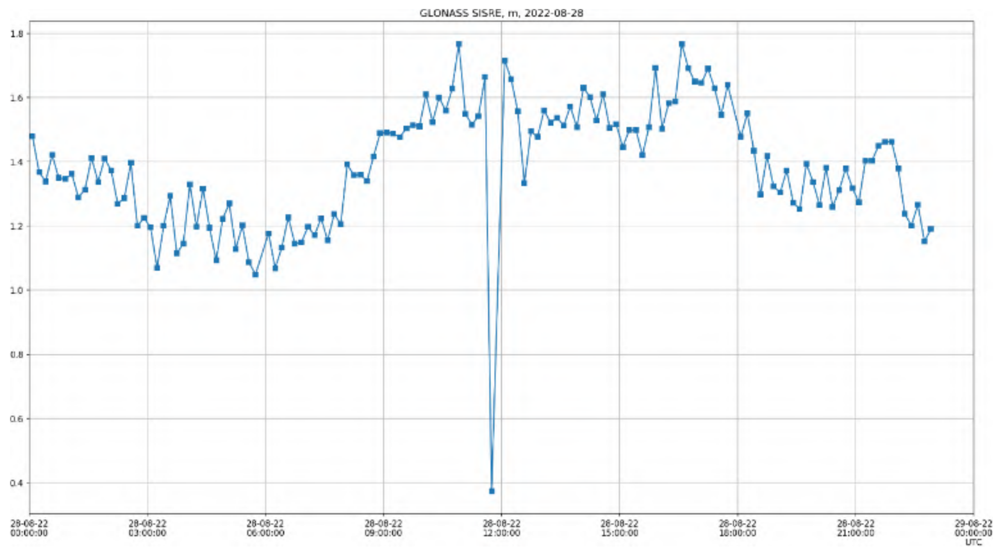


Figure 37 – GLONASS the Signal-in-Space Ranging Error (SISRE) performance

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

5.1.1.4.4 Status and modernisation plans

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

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

5.1.2 Satellite Navigation Systems – Regional coverage

5.1.2.1 QZSS

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

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

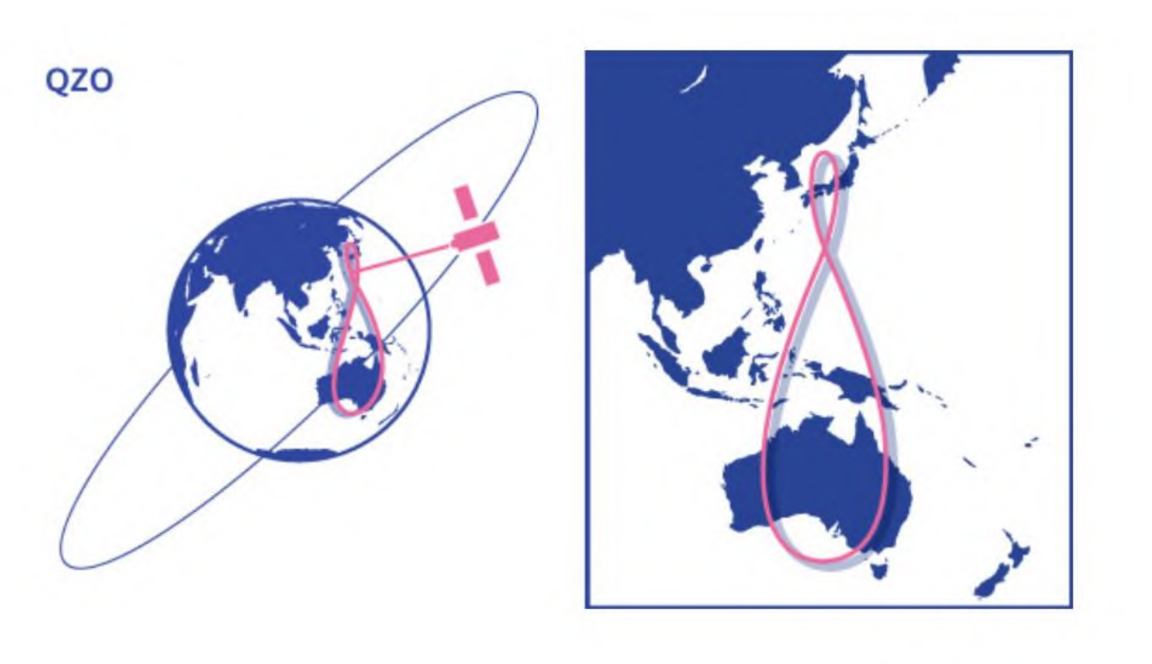


Figure 38 – QZSS constellation (source: QZSS National Space Policy Secretary)

5.1.2.1.1 QZSS Services

The QZSS provides three classes of public service:

- The **PNT service** complements the signals used by the GPS system, providing additional ranging signals. The service broadcasts at bands L1C/A, L1C, L2C, and L5C, the same as GPS.
- The **SLAS (Sub-metre Level Augmentation) service** provides GNSS augmentation for GPS and is interoperable with other GPS-SBAS systems. It transmits on L1 frequency.

- The **CLAS (Centimetre Level Augmentation) service** provides high-precision positioning compatible with the higher-precision E6 service of Galileo. The band is referred to as L6 or LEX, for 'experimental'.

5.1.2.1.2 Main characteristics

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

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

Table 15 – Principal characteristics of QZSS signals

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

Access Technique	CDMA
Modulation	BPSK
Minimum received power [dBW]	-155.7 (Block I) -156.8 (Block II)

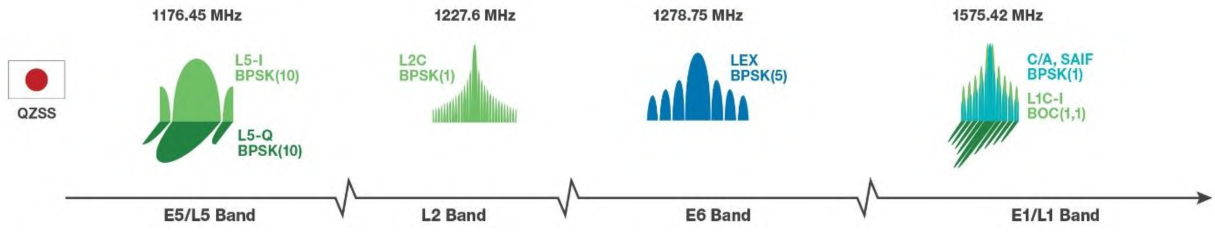


Figure 39 – QZSS signals (Credit: Navipedia)

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

5.1.2.1.3 Performance

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

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

Figure 40 – QZSS performance

5.1.2.1.4 Status and modernisation plans

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

Further information can be also found in Navipedia.

5.1.2.2 IRNSS (NavIC)

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

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

5.1.2.2.1 IRNSS Services

NavIC will provide two levels of service:

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

5.1.2.2.2 Main characteristics

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

Table 16 – Principal characteristics of IRNSS signals

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

Figure 41 – IRNSS signals (Credit: Navipedia)

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

5.1.2.2.3 Performance

Performance of IRNSS is described on technical reports available on the IRNSS Programme website. The User Ranging Accuracy of QZSS satellites over 2021 is displayed in Figure 40.

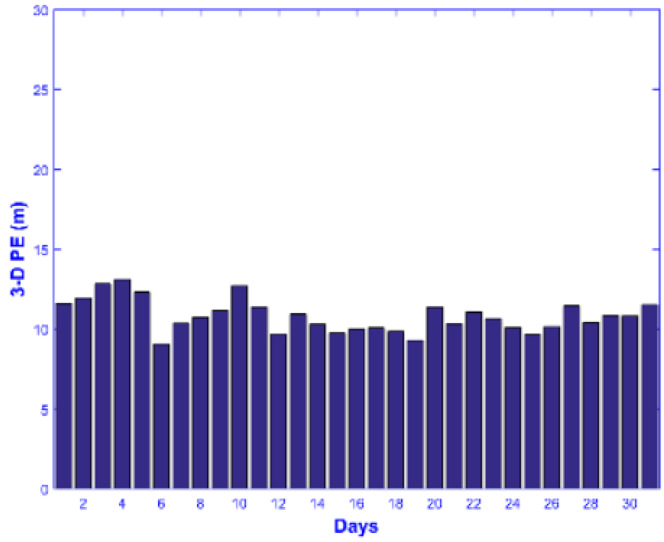


Figure 42 – IRNSS SISRE performance in December 2021 (Source: IRNSS Official report Q4 2021)

5.1.2.2.4 Status and modernisation plans

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

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

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

5.1.2.3 *Korean Positioning System (KPS)*

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

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

5.1.3 Augmentation Systems

5.1.3.1 *Space Based*

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

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

5.1.3.1.1 *Satellite-Based Augmentation Systems (SBAS)*

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

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

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

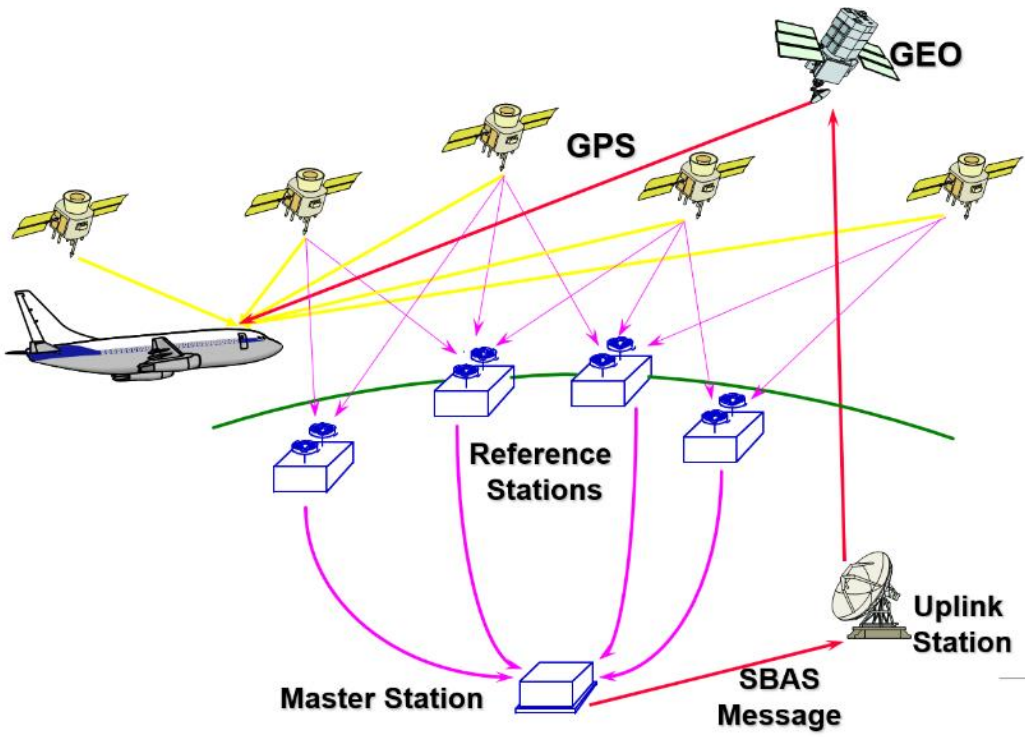


Figure 43 – SBAS Architecture (Source: ICAO)

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

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

- the **European Geostationary Navigation Overlay Service (EGNOS)** is the European augmentation system that improves the accuracy of positions derived from GPS (and Galileo in the future) signals and warns users about the reliability of the signals. EGNOS transmits differential correction data for public use and is certified for safety-of-life applications (operational services since 2011).
- the US Federal Aviation Administration (FAA) has developed the **Wide Area Augmentation System (WAAS)** which provides GPS corrections and is certified for civil aviation industry since 2003.
- The **MTSAT Satellite Augmentation System (MSAS)** is an SBAS that provides augmentation services to Japan since 2007.
- The **GPS Aided Geo Augmented Navigation or GPS and Geo Augmented Navigation system (GAGAN)** is an SBAS that supports flight navigation over Indian airspace since 2013.
- Since October 2014, the Korea Aerospace Research Institute (KARI) is the leading research organisation developing and building the Korea's own Satellite Based Augmentation System (SBAS), known as **Korea Augmentation Satellite System (KASS)** in compliance with ICAO Annex 10. It is expected to provide APV-1 safety-of-life service in 2024.

- The **ASECNA-SBAS (ANGA – Augmented NaviGation for Africa)** is the SBAS for Africa and Indian Ocean Development initiative. ANGA aims to provide SBAS services for NPA, APV-1 and CAT I operations in 2025. Full DFMC services are expected beyond 2028/2030 for CAT I Autoland operations and potentially further ones.
- The **Southern Positioning Augmentation System (SouthPAN)** is the Australia and New Zealand's operational SBAS with plans to reach full operational capability in 2025.
- Republic of China is developing an SBAS system, called **BeiDou Satellite-Based Augmentation system (BDSBAS)** to provide SBAS services in China and surrounding regions. BDSBAS is expected to provide services in 2025 and is integrated in the BeiDou system by using BDS-3 type satellites to broadcast SBAS L1/L5 signal, augmenting BeiDou and GPS.
- Russia is developing **System for Differential Corrections and Monitoring (SDCM)** to provide Russia with accuracy improvements and integrity monitoring for both the GLONASS and GPS navigation systems. SDCM will also provide Precise Point Positioning (PPP) services for L1/L3 GLONASS signals.

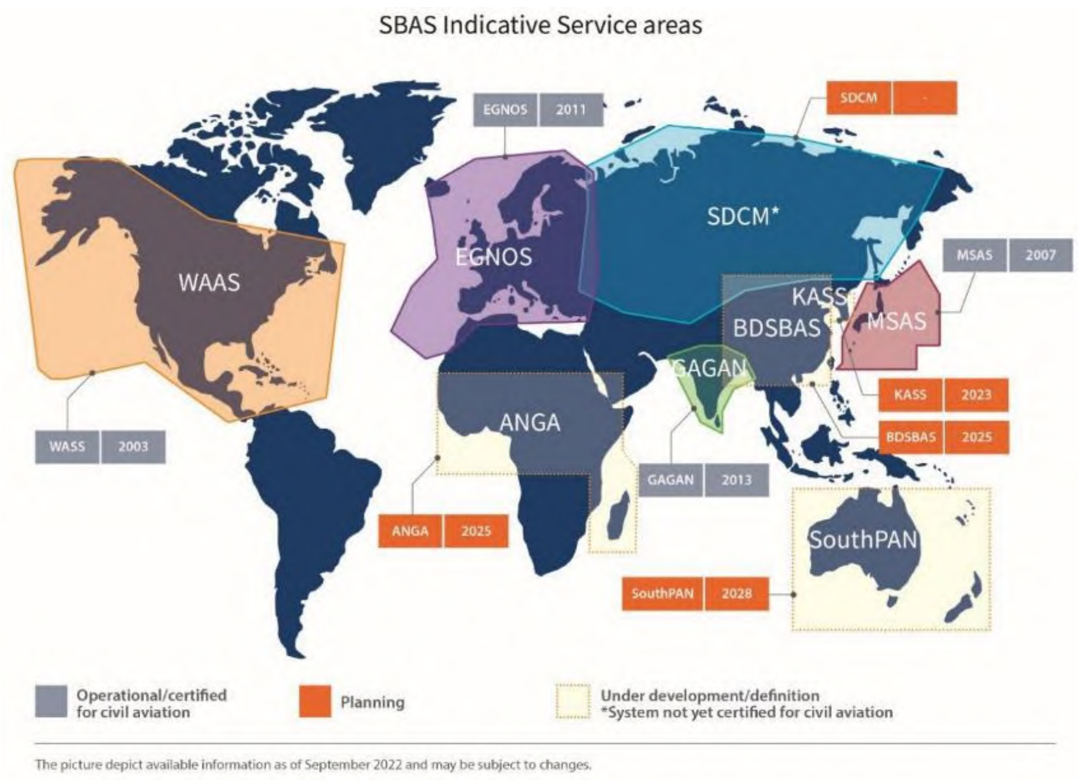


Figure 44 – SBAS systems and indicative service areas (Credit: EUSPA)

5.1.3.1.2 Precise Point Positioning (PPP)

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

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

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

5.1.3.2 Terrestrial

5.1.3.2.1 Ground Based Augmentation System (GBAS)

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

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

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

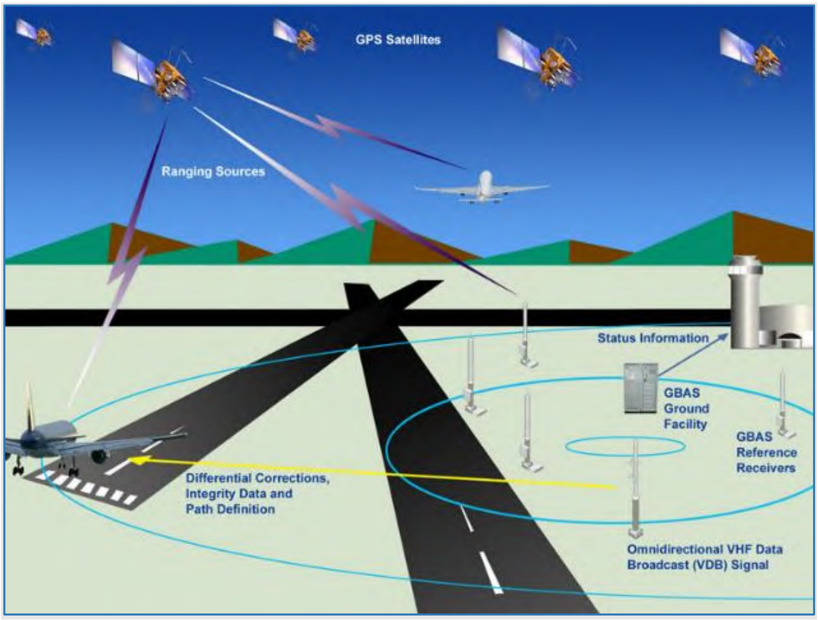


Figure 45 – GBAS Architecture (Credit: FAA)

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

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

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

5.1.3.2.2 Differential GNSS & Real Time Kinematics & Precise Point Positioning

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

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

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

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

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

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

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

5.1.3.3 Receiver Based

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

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

5.2 Conventional PNT Systems

5.2.1 NDB

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

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

5.2.1.1 Main characteristics

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

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

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

5.2.1.2 Status and rationalisation plans

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

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

More information can be found in Wikipedia - NDB.

5.2.2 VOR

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

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

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

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

5.2.2.1 Main characteristics

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

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

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

5.2.2.2 Status and rationalisation plans

VORs have been part of the ground infrastructure of aids to navigation for air traffic management during decades. However, due to its technical limitations, the appearance of GNSS, and the transformation towards performance-based navigation, we expect VORs to become less important in the following years. The European ATM Master Plan **plans to reduce the number of VORs to a**

Minimum Operational Network which would provide some **limited navigation capabilities in case of a temporary disruption of GNSS** as indicated in the PBN IR.

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

More information can be found in Wikipedia - VOR.

5.2.3 DME

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

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

5.2.3.1 Main characteristics

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

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

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

5.2.3.2 Status and optimisation plans

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

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

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

5.2.4 ILS

The **Instrument Landing System (ILS)** is a **precision approach and landing system** that provides aircraft with short range horizontal and vertical guidance just before and during landing and, at

certain fixed points, indicates the distance to the reference point of landing.

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

An ILS is composed of:

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

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

5.2.4.1 Main characteristics

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

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

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

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

- CAT I permits a DH of not lower than 200 ft and an RVR not less than 500 m.
- CAT II permits a DH of not lower than 100 ft and an RVR not less than 300 m.
- CAT IIIA permits a DH below 100 ft and an RVR not below 200 m.
- CAT IIIB permits a DH below 50 ft and an RVR not less than 50 m.
- CAT IIIC[1] is a full auto-land with roll out guidance along the runway centreline and no DH or RVR limitations apply. This Category is not currently available routinely.

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

5.2.4.2 Status and optimisation plans

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

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

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

5.2.5 TACAN

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

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

5.2.5.1 Main characteristics

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

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

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

5.2.5.2 Status and rationalisation plans

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

More information can be found in this Wikipedia – TACAN.

5.2.6 Loran

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

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

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

5.2.6.1 Loran-C / Chayka

Loran-C was the most extended version of Loran.

5.2.6.1.1 Main characteristics

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

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

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

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

Loran-C has no capacity limitations.

5.2.6.1.2 Status and rationalisation plans

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

5.2.6.2 eLoran

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

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

5.2.6.2.1 Main characteristics

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

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

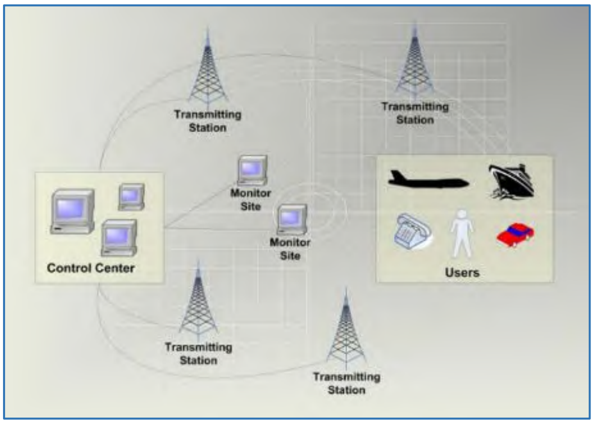


Figure 52 – eLoran system (Credit: eLoran Definition Document)

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

5.2.6.2.2 Status and modernisation plans

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

5.2.6.3 DLoran (Differential eLoran)

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

5.2.6.3.1 Main characteristics

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

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

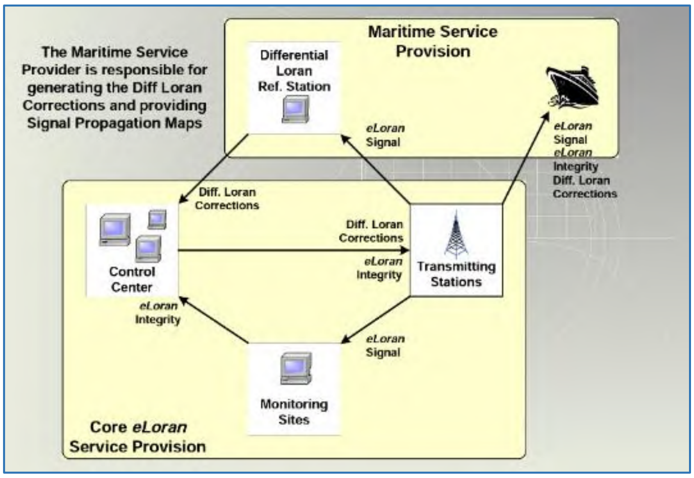


Figure 53 – Example of an DLoran service provision for maritime users (Credit: eLoran Definition Document)

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

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

5.2.6.3.2 Status and modernisation plans

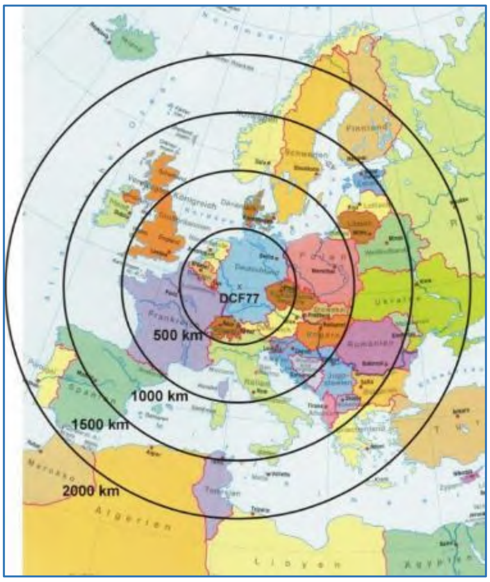
DLoran is a local augmentation system to eLoran. Since Loran-C and eLoran transmissions ceased in Europe in 2015, **DLoran services are not being provided**.

5.2.7 Longwave time and frequency distribution systems

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

5.2.7.1 Main characteristics

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



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

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

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

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

5.2.7.2 Status and modernisation plans

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

5.2.8 Atomic clocks

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

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

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

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

5.2.8.1 Main characteristics

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

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

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

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

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

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

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

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

5.2.8.2 The miniature chip scale atomic clock (CSAC)

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

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

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

5.2.8.3 Status and optimisation plans

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

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

5.3 Emerging Technologies

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

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

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

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

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

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

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

5.3.1 White Rabbit (WR)

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

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

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

5.3.1.1 Main characteristics

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

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

5.3.1.2 Status and optimisation plans

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

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

5.3.2 Computer network time distribution

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

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

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

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

5.3.2.1 Main characteristics

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

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

5.3.2.2 Status and optimisation plans

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

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

5.3.3 Pseudolites

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

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

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

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

5.3.3.1 Main characteristics

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

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

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

Test at JRC demonstrated the following performance:

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

5.3.3.2 Status and optimisation plans

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

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

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

- Limited outdoor range.
- Permission requirements.

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

5.3.4 5G and cellular networks based PNT

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

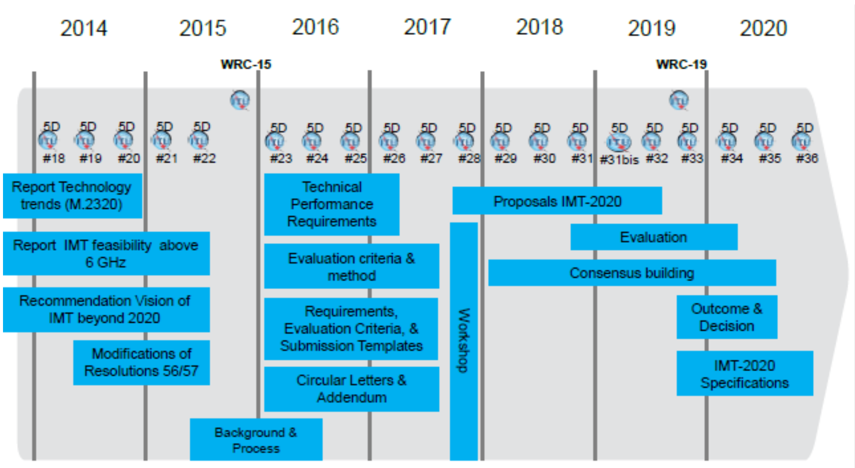


Figure 55 - Timeline and process for IMT-2020 (source: ITU-R)

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

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

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

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

5.3.4.1 Main characteristics

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

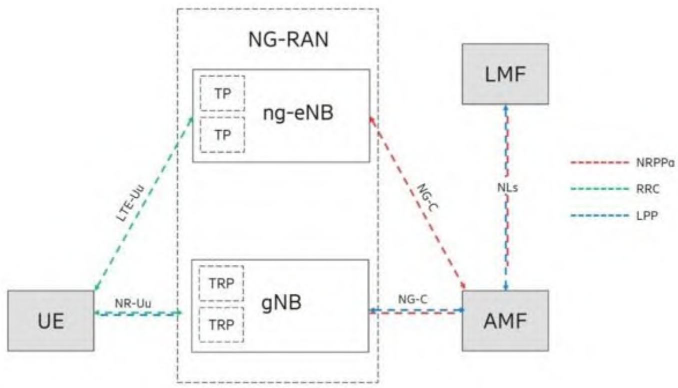


Figure 56 – 5G positioning architecture (Credit: Ericsson)

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

5.3.4.2 Status and optimisation plans

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

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

More and more 5G Test Beds, based on SA technology, are operational across the world. For example, at the MWC held in 2022, Qualcomm Technologies showcase precise positioning with the mmWave spectrum, for indoor and outdoor deployments such as smart factories. Rohde & Schwarz demonstrated a GNSS-backup system based on the 5G Broadcast[2] technology. The positioning reference signals are transmitted together with information about the location of the transmitters.

[2] 5G Broadcast is based on 3GPP technology that is used for cellular 4G and 5G networks reusing of already established broadcast deployments (e.g., Radio, TV, etc.). It enables mobile reception of audio-visual content using a highly efficient broadcast mode.

Such terrestrial infrastructure using 5G broadcasting towers act as a GNSS backup. This solution provides the same signal to a multitude of mobile and fixed receivers simultaneously like smartphones, tablets, cars, and wearables and achieve a metre-level accuracy. In addition, the content broadcasted by 5G transmitters can be enhanced with RTK and PPP corrections to bring the accuracy down to cm-level.

5.3.5 Ranging mode (R-Mode)

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

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

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

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

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

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

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

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

5.3.5.1 Main characteristics

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

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

5.3.5.2 Status and optimisation plans

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

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

R-Mode is currently dependent on GNSS for synchronisation. Future plans consider inclusion of atomic clocks for short term holdover and possibly alternative, backup time source though this implementation is challenging.

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

5.3.6 Visual navigation

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

5.3.6.1 Main characteristics

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

The identification and matching of the same features from image to image, disregarding light changes and camera dynamics is the biggest challenge for this navigation type. This can be a challenge for aviation. In the terrestrial and pedestrian scenario, the problem is simplified due to limited movement and rotation in the height axis and was demonstrated to provide reliable results. If a simple movement algorithm is used, we can de-facto use any well-lit feature or even repeated pattern. In the case of aviation, IMU information is essential.

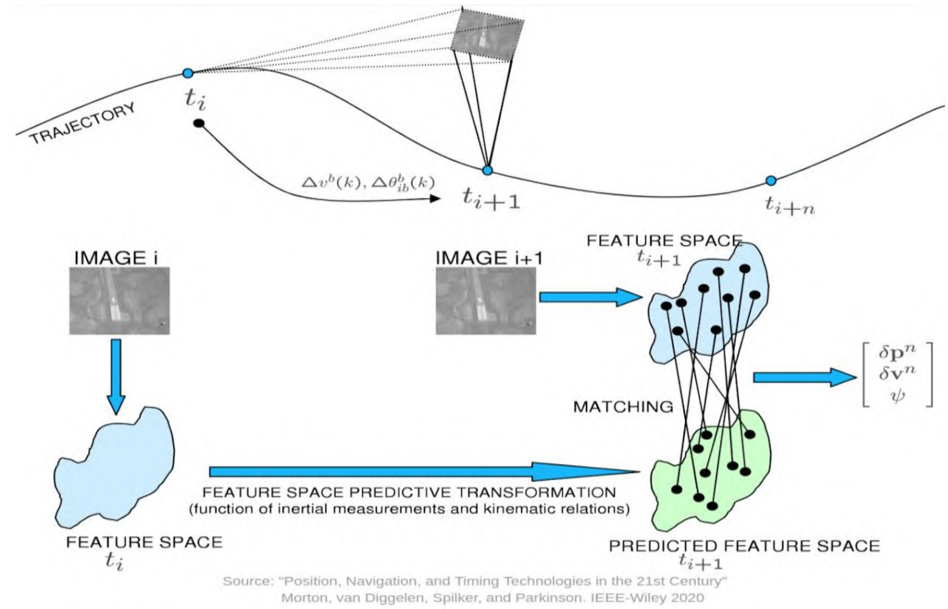


Figure 58 – Overview of image-aided sensor fusion with IMU (Credit: pnt21book.com)

LiDAR a method for determining distance to the object by measuring the time for the reflected light to return to the receiver. It is commonly used to create high-resolution models and maps. It **can** also **be used for navigation**, using one of two approaches:

- Featureless approach when the spatial distribution of measurements (point cloud) is used directly to compare with existing data. The algorithmic challenge here is the sub-selection of points for matching (identification of the overlay area). Selection is then used for the best match in the reference data and optimised (rotated) to minimise the cost function (fit error). The identification of the area to compare is critical to optimise the search. Initial known position and orientation are very useful.

- Feature-based approach when features are first identified and exacted from the data (point cloud). Navigation is then based on identifying them and using them for position estimation. Those features usually are much simpler features than descriptive man-made objects and tend to be points or simple geometric features. Once extracted the perceived movement between them and the scanner (user) can be used to estimate the movement, orientation, and position.

5.3.6.2 Status and optimisation plans

LiDAR-based navigation support mechanisation (integration) with odometer or IMU is possible. This is frequently used during Simultaneous localisation and mapping (SLAM) when collected data can be used to improve existing maps. LiDAR can be used for vehicle or pedestrian-based navigation. **Optical methods** have similar characteristics.

For both a recursive SLAM algorithm is very popular due to its speed and efficiency. The position is estimated as relative, yet if some of the features have known positions, object movement can also be mapped to the global reference frame. When the same location is re-visited (loop closed) the position accuracy can be estimated, and the previous estimation corrected if needed.

An alternate approach is the particle filter (PF) which uses a probabilistic approach to estimate the position, as the object is moving until the position can be provided with enough confidence.

There are several considerations for visual navigation:

- Large data volume is produced, hence firstly data is reduced, by identifying specific areas of interest, by sub-sampling. This also includes removing outages, such as moving vehicles or pedestrians. Secondly, most algorithms use iteration to arrive at the local minima.
- It is different to differentiate observation uncertainty in range and angle measurements. In the case of LiDAR, this depends on the angle and the surface reflected, for an image this is related to lenses and the light conditions.
- Integration with other sensors requires careful preparation including lever arm estimation and stability.

A space application of these principles is the star tracker and sun sensor. Both devices use **celestial navigation** to compare known views of the stairs using photocells or a camera. The method requires clear visibility of the stars, which is night sky for a terrestrial user, and is predominantly used by the space-borne platforms, offering both position and orientation when combined with IMU.

Technology is used in practically all space missions. Usually, a mission has both star and sun sensors. First, the latter is used for the coarse attitude determination, usually after spacecraft separation of the launcher. The star tracker is used for the fine attitude determination and IMU reading for the sensor fusion approach to obtain smooth orientation and position.

Sun sensor accuracy is 3 - 0.005 ° and star tracker of 0.01 - 0.0003 °. The sensor can be either tracker or scanner, suitable for rapidly rotating (spinning) spacecraft. The method requires pre-filtering to remove noise, such as stranded light or reflections, avoid being blinded by the sun or moon and require stabilisation of reading (for which IMU is used).

Due to the increased quality and decreased size of the components, the simplified technology is used for LEOs and investigated for the CubeSat missions. Apart from commercial offerings, an open source algorithm exist, used for the CubeSat platforms. Measurements are conducted in the celestial reference system, which would require transformation to GNSS ITRF or similar.

5.3.7 Mobile based navigation

Smartphone nowadays is the primary navigation source, replacing TomTom or Garmin's dedicated navigation devices, as well as the paper maps. In 2020 there was more than 4 billion GNSS enabled smartphones. Hence it is interesting that its GNSS capacity happen almost by accident. In 1999, the Federal Communications Commission (FCC) mandated positional requirement, as part of the E-911. The triangulation from the mobile tower network was not precise enough. Instead, a positioning using GPS chipset was suggested.

The **mobile phone is not intended as a GNSS/GPS receiver**. It has a simple inverted-F monopole, a linearly polarised antenna with low gain and noise suspension. It has low-quality clock and are prone to self-interference due to component placement. Why those are important? GNSS position is based on time difference between the satellite (so stable local oscillator is important) using very low power signal, frequently below the noise floor (hence good antennas are essential). By itself, **smartphones have low performance as GNSS receivers**.

Assisted GPS (A-GPS) eliminates those flaws by increasing sensitivity and the Time To First Fix (TTFF), with the assisted data reducing the frequency search space but not the delay space. This also changes the chipset architecture, which is based on massive parallel search capability. As the chipset main limiting factor is the chip memory size, to minimise all parallel hypotheses, the manufacturers are searching first on one GNSS constellation (typically GPS with short codes) and once acquired, the chipset will then do a fine-time narrow search for other GNSS longer codes. For Galileo, the chipset tracks the Galileo Data Component (E1B–OS-NMA) only at the beginning of the location request; once data is obtained, chipset starts tracking the pilot code. Technical details can be found in F. van Diggelen, A-GPS: Assisted GPS, GNSS, and SBAS. Artech House, 2009.

5.3.7.1 Main characteristics

GNSS capacity is provided by the A-GPS (A-GNSS) architecture. In addition, two recent advances are worth noting, both described from the Android perspective since the Apple approach is not well documented.

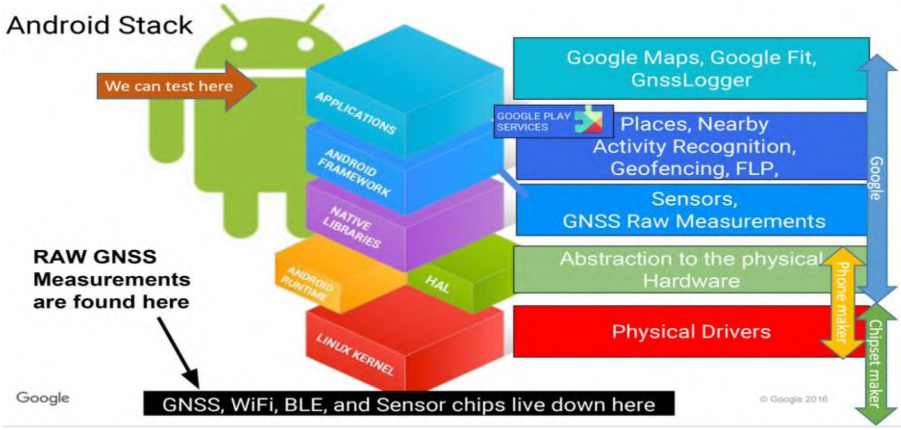


Figure 59 – Overview of the Android stakeholders' control of the stack, adopted after Google (Credit: Google)

Android Google Play services

The modern phone is a very complex ecosystem that contains multiple sensors, including inertial, WiFi and Bluetooth, and is run by the operating system. This is utilised by Android via Google Play services' Location Application Programming Interface (API) encapsulation. It does everything from geofencing and detecting activities to identifying places near you. Its most important element is the Fused Location Provider (FLP) which provides a smart location and battery saving. This offers the possibility to navigate indoors using the strength of the nearest WiFi access point (AP) and indoor maps to fingerprint (identify) your location. Combined with machine learning this is used by the Android Emergency Location Service (ELS). This service activates when an emergency call is placed and provides precise location to the emergency services, including elevation and correct floor. This service requires separate arrangements with phone operators and is enabled in some EU countries.

The RAW measurements

Since 2016 Android Location API provides direct access to the GNSS chipset (bypassing a few layers of the stack). Those **GNSS observations** are **known as RAW measurements**. The A-GPS-based phone's chipset acquires the observations before the time is precisely synchronised, leading to observations in a more raw format than those of the typical GNSS receivers.

Access to the RAW measurements opens the door to more advanced GNSS processing techniques that, until now, have been restricted to more professional GNSS receivers. New signals (E1/L1 and E5/L5 frequencies), differential observations and other advanced algorithms can be used. These underpin applications such as assured time, atmospheric monitoring, or interference detection.

Despite the **mobile phone** having **several limitations** such as not handling properly dynamics or multipath well, it can utilise **more advanced algorithms**, for example, differential solutions. A presentation during the EUSPA Raw Measurements Taskforce showed the post-processing results of data collected during slowly walking over the GOOGLE letters. Left to right, we see the simple RAW measurements algorithm, then a Kalman filter algorithm using pseudo ranges, this is similar to FLP. The last image shows the improvement with using the carrier phase, something that is not possible for FLP. It is worth noting that, at the current stage, it is difficult to outperform the FLP unless in an open environment.

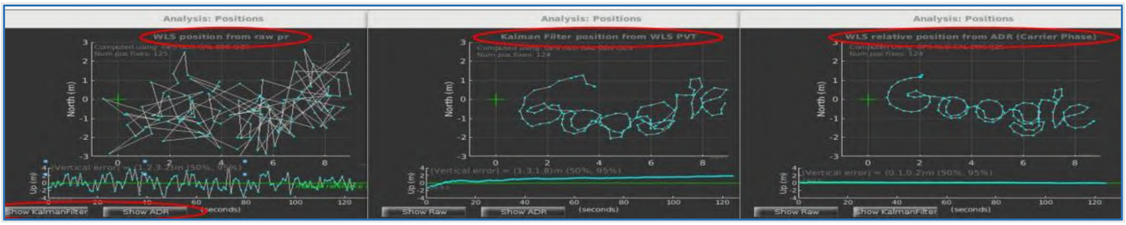


Figure 60 – Improving position using RAW measurements (Credit: Frank van Diggelen)

More details in the EUSPA White Paper on using GNSS Raw Measurements on Android devices.

5.3.7.2 Status and optimisation plans

A new algorithm proposed by Google and intended for pedestrian use aims to combat the multipath problem. It first estimates the user location; ideally identifying the street's side the user is on, based on the buildings' photo-realistic models. Then, it provides this information back to the chipset to improve the GNSS position directly. Data models cover all the European cities and most of the world. The algorithm is focused on Google's Pixel series (starting with the 5G version of model 5) with a planned roll-out to other Android handsets.

The API layer now communicates directly with the GNSS chipset by providing corrections and the Android stack is now a two-way communication channel. In short, **a mobile phone can be used as a modern GNSS receiver**.

5.3.8 IMU Dead-reckoning

Dead reckoning is the process of calculating position of a moving object by having a determined position and then incorporating estimates of speed, heading direction, and course elapsed time. While several technologies utilising this estimation exist, we will focus on the inertial systems, common in aviation and transport.

An **inertial measurement unit (IMU)** is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body. IMUs consist of three gyros and three accelerometers and usually includes magnetometers and determine three axis orientation of the moving body. To determine absolute position with respect to the reference frame the starting position, velocity and orientation of the body should be known. If the gyro accuracy is well below earth rotation (15 °/h) the attitude can be estimated based on gravity and earth rotation.

The cost of the hardware varies, depending on the quality of the components, as seen in Table 17. A low-cost microelectromechanical system (MEMS) used in mobile devices usually cannot be used on its own and requires sensor fusion - those tend to be GNSS, Bluetooth and WiFi – while the ring laser gyro (measuring light frequency difference in two directions) is the most performing and costly.

Table 17 – Overview of dead-reckoning systems

Type	Ring Laser Gyros	Fiber optic gyros	MEMS	Low-cost MEMS
Cost [euro]	100 000	20 000	< 2 000	< 1 000
Gyro drift	0.003 °/h	1 °/h	360 °/h	3 600 °/h

Type	Ring Laser Gyros	Fiber optic gyros	MEMS	Low-cost MEMS
1 m drift	~ 2 min	~ 30 s	~ 5 s	< 5 s

Note that the values reported in the table follow the constant speed dynamics.

5.3.8.1 Main characteristics

Inertial navigation works by **integrating sensor measurements** over time in a process known as drift. The high-end units can determine earth rotation and work independently yet most commonly those are used in combination with GNSS receivers.

As errors grow with time, the ideal approach is the combination of the IMU sensor measurements with GNSS position fixes in a Kalman Filter which steers the body position towards the good quality GNSS position fixes while having a high update rate in between. An example is the Inertial Navigation System (INS) which obtain the body's position, orientation, and velocity without the need for external references. This system can bridge short GNSS outages, aid RTK ambiguity resolution and assist with cycle slip detection and mitigation. In case of tightly coupled solution this also means that position can be obtained with less than three visible satellites.

Technical details about the IMU, mechanisation and sensor fusion can be also found in Principles of GNSS, inertial, and multisensor integrated navigation systems, P. Groves, Artech House, 2013.

5.3.8.2 Status and optimisation plans

With the first usable IMU produced in the 1950s and the technology matured around '80s, the development has since focused on miniaturisation and development of IMS - loosely, tightly and coupled as well as Kalman Filter. **IMUs are now widespread, with low-cost IMUs powering mobiles.** The current development is to decrease size, cost and increase performance using new materials. The Quantum section describes the development of a new very promising hardware approach.

5.3.9 Magnetic navigation

The usage of magnetic maps for navigation dates to the missile navigation in the 1960s where **changes in terrain were used to identify user position**, by comparing the continuous readings with the recorded morphological map. To be useful for navigation, those observations need to be stable over time and provide enough difference to distinguish one area from the other.

5.3.9.1 Main characteristics

Magnetic navigation is one of the oldest forms of navigation. The earth's magnetic core was used to determine north and maintain constant azimuth. The modern approach focuses on anomalies instead, as those are stable over time. The magnetic reading is the superposition of all magnetic sources, that is Earth's core, Earth's crustal field and man-made and space weather effects.

The **Earth's core** (95 - 99% of the whole magnetic force), while well described by existing models and measurable from space, has large spatial wavelengths and a time-varying nature, which makes it not suitable for map-based navigation. The **Earth's Crustal Magnetic Field** (1 - 5% of the total magnetic effect) is very stable and shows local differences. This magnetic field differs across the globe and extends under the oceans, covering the whole Earth's surface. **Man-made effects** can be split into static and time-varying. Only the first is useful for navigation, and many long man-made features can be useful for determining location. In this context **space, weather effects** introduce the equivalent of the measurement noise.

Magnetic anomalies (i.e., local variation in the Earth's magnetic field) are difficult to measure. In addition, magnetic measurements need to be propagated upwards for higher altitudes as the power of the magnetic field follows inverse square law.

Magnetic force is measured by two types of **instruments**. The scalar one is measuring field intensity and the vector one, such as fluxgate magnetometers, is measuring three orthogonal components. While the latter is less accurate it can remove common errors (due to man or space-borne effects) and provide additional spatial information. Unfortunately, gradient maps are less common than anomaly ones.

The position is the probabilistic estimation which requires initial a-priori information. With this approach a single static position creates multiple possible positions. When user moves, the estimation is updated using the particle filter (PF) to converge, with time, to a single correct position.

5.3.9.2 Status and optimisation plans

Practical results for magnetic navigation indicate that while **indoor accuracy is below metre** and can be even dm level, **outdoor performance** varies from **metres to hundreds of metres**, which then requires a fusion with other sensors. Similarly, flight demonstration using magnetic reading and IMU was shown to be efficient being the main limitation the flight elevation (few to ten metres of accuracy below 1 km altitude, yet at an altitude of 10 km accuracy degrades to hundreds of metres). Precise accurate maps of anomalies at or below the flight altitude are essential.

Magnetic technology is **rapidly maturing**. Commercial companies offer location and navigation services, limited to specific areas, by utilising magnetic data with other sensors (WiFi and Bluetooth and pre-mapped locations). Other companies propose it for rail applications to determine track and current train location while other uses include maritime with a Radar Absolute Positioning which uses the features extracted from radar reading, matched to radar charts to identify user position. All **these technologies require sensor fusion**.

5.3.10 Low Earth Orbit (LEO)

Low Earth Orbit (LEO) systems are constituted of hundreds or possibly thousands of satellites transmitting from an operational altitude between 400 and 1 500 km (avoiding atmospheric drag and solar effects). Until recently, this altitude was predominantly used by Earth Observation (EO) and communication satellites (SatCom) with a constellation not exceeding 100 satellites.
LEO orbit offers **low latency** and **high received signal strength** (30dB larger than from MEO orbit) at a low transmission power. Those characteristics make it interesting to mega-constellations aiming to provide wideband internet. The broadband providers aim to utilise high-frequency Ku-band, which should be able to offer data speed up to 8 - 20 Gbps.

Such close orbital positioning to the earth's surface **also has disadvantages**, as the typical satellite footprint (which is the ground area that can be covered by the transmitting antennas) is much smaller (9 LEOs are required to cover the footprint of one MEO). Also, the satellite's relative speed to the ground is much higher. LEO's orbital period is around 100 minutes compared with MEO's of around 12 hours. This means that full earth coverage requires much larger constellations.

The table below is a non-exhaustive selection of LEO services. Given the relatively modest ITU filling cost and the priority advantage (over filings registered later), there is a tendency to file systems even if their operational plans are not yet fully developed so the list below is based on the perceived closeness of constellations to the market and communication mega-constellations. One significant omission from this table is the EO satellites.

Table 18 – Overview of LEO constellations

System	Number of satellites	Satellites in service (Aug 2022)	Altitude [km]
Iridium	66	66	780
Kuiper	3 236	0	590-630
Starlink	4 409	2 268	540-570
OneWeb	4 000	354	1 200
Kepler	6 LEO + 24 MEO	0	7 600 + 29 600
Centispace	120	2	975
XonaSpace	300	1	975

Please note that the values in the table are subject to rapid change.

5.3.10.1 Main characteristics

LEOs constellations provide multiple services including secure communication and broadband connectivity for smart devices and connected vehicles. They do **not include a dedicated navigation payload (except Iridium)** and hence today they can only provide augmentation data to GNSS signals or their signals can be used indirectly for navigation using the Signal of Opportunity (SoO) approach and the doppler navigation.

Currently the only available means of providing position and navigation from a LEO constellation is using **Doppler navigation** whose main weakness is the orbit detection and time synchronisation of fixes (which is partially offset by the calculation method). The increased numbers of LEO satellites can improve positional accuracy (using the SoO Doppler approach) but not the time provision.

Iridium provides a dedicated navigation signal which also provides time synchronisation. In 2016, Satelles Time and Location (STL) was formed as a consortium formed by Iridium, Satelles Inc and Boeing to provide global navigation services. The system infrastructure is mostly space segment with ground segment limited to a single control station (with hot backup active within 10 minutes) located in the US and several passive ground monitoring stations. STL signals-in-space are broadcast on the L1 (1616 – 1626 MH) frequency.

Iridium is designed for just one satellite in the user's view. Each of the 66 Iridium satellites has 48 spot beams. To provide secure and anti-spoofing capabilities, each beam transmits the navigation message with an individual code, which changes every second. Since there is full control over the STL beams, the navigation message can be limited to specific areas (which prevents signal to be received in the areas of no subscribers). The complex, overlapping beam patterns of the satellites combined with signal authentication techniques allow STL to deliver a **trusted time** (synchronised to UTC) **and location capability secure and independent from GNSS**.

STL signals are received on Earth's surface around 1 000 times (30 dB) stronger than GNSS, which allow for **indoor** reception. The satellites do not carry atomic clocks on board. Instead, they are constantly calibrated using a ground station and the inter-satellite capabilities of the Iridium constellation. Subscribers need to pay a service fee.

5.3.10.2 Status and optimisation plans

Only **STL** is a deployed and mature technology for PNT. It can provide reliable time provision, with an accuracy of 100 - 150 nsec, fixed to UTC(k). The **position** is more difficult to obtain, and the current solution is to use the Doppler effect which provides accuracy around 10 m for static users. Once a fix is obtained (which requires up to 20 minutes of convergence if starting at unknown position), the position can be obtained even with a single satellite, but as much reduced accuracy, up to tens of metres. STL can also include assistance data in real-time for satellite clocks, orbits, and message payloads. The rapid geometry changes are expected to improve the multipath mitigation, as its effect over a few minutes will average out.

To overcome the main limitations of using LEO for full PNT (as opposed to time-only provision), namely for orbit determination and time synchronisation, the use of GNSS receivers on board is desirable to estimate both the position and time of the transmission (but then the service is no longer independent from GNSS). This approach, known as the **fused LEO PNT**, is the focus of the **Xona Space** whose Pulsar PNT service claims metre-level accuracy. The first satellite was launched as part of SpaceX's rideshare mission in 2022 and the service is expected operational in late 2023. The actual performance is not yet known.

Kepler is a concept for a fully tailored PNT system using a mix of LEO and MEO satellites. As such, this is completely different from other LEO systems discussed before, as this is a PNT-tailored system instead of a partial optimisation/reuse of an LEO infrastructure designed originally for a different scope, e.g., communication or broadband internet access. Kepler establishes the synchronisation by direct measurements with optical links and can operate entirely independently or in cooperation with Galileo.

Finally, an alternative option is to perform Doppler ranging for any signal transmitted by LEO satellites **or** use those signals as Signals of Opportunity. Both approaches are independent of the system owner, as anyone can use those observations. However, there are limitations since Doppler depends on a large number of visible satellites while SoO on the dedicated ground segment (base station).

5.3.11 Quantum Technologies

Among the new and emerging technologies which can provide substantial advantages to PNT applications, those leveraging **quantum physics effects are particularly promising**. In most cases, however, several years of development are still required for novel quantum technologies to really have the expected impact on PNT applications.

5.3.11.1 Quantum Clocks

5.3.11.1.1 Main characteristics

Continuous progress on atomic clocks is expected to greatly benefit satellite-based positioning systems:

- For the **ground infrastructure**, clocks based on cold atom interferometry can be taken into consideration to substitute the existing ensembles of Caesium clocks and active hydrogen masers which are universally employed to generate the system time. Although cold-atom clocks have reached a rather mature development stage and some commercial products are starting to become available, their use is still largely limited to the scientific community.
- For the **space infrastructure**, better clocks in satellites will improve the signal-in-space user-range-error, but constraints linked to their use in space are presently restricting the possible candidates to ion-based clocks, pulsed optically-pumped clocks, and in the longer term optical atomic clocks based on nonlinear effects such as two-photon absorption and modulation transfer spectroscopy.

Laboratory-scale optical atomic clocks are already in use and will undoubtedly contribute to the implementation of a metrological timescale: although GNSS systems do not need an autonomous realisation of such a time scale, they will likely take advantage of it via time transfer protocols based on carrier-phase two-way satellite time and frequency transfer or coherent optical links in free-space or via optical fiber.

Figure 61 – A commercial cold-atom clock (left) and a prototype of an optical frequency standard based on two-photon transition in Rb (right). Note that in the latter the frequency comb necessary to translate the optical stabilised frequency into a microwave signal is not included [Strangfeld 2021]

5.3.11.1.2 Status and optimisation plans

In the longer term, **novel GNSS architectures may emerge for optical-scale time generation and distribution** to fully take advantage of the stability properties of optical atomic clocks interconnected via optical inter-satellite and ground-to-satellite links.

To give an example, **a future system could be entirely based on space-based infrastructure**, with no need of world-wide distributed sensor or upload stations, which are necessary for present-day GNSS. The space-based infrastructure could include MEO and LEO satellites, equipped respectively with cavity-stabilised lasers and optical atomic clocks, suitably interconnected with optical links to provide ps-level global synchronisation and µm-level accuracy range measurements. In principle, the only ground infrastructure needed is a receiving optical station to keep the system time aligned with the universal coordinated time UTC. The **Kepler** project shows how optical atomic clocks can enable future GNSS architectures with a ~**100-fold improvement in the signal-in-space**.

However, it should be considered that because of ionosphere, troposphere, and multi-path-interference disturbances, a better SIS does not immediately translate in better positioning accuracy for the final user. Complementary techniques such as precise point positioning or real time kinematics must be substantially upgraded if optical-scale GNSS time generation and distribution is to effectively benefit the final users. In addition, a very complex miniaturisation process will be required for optical atomic clocks to reach the chip-scale dimensions and battery-compatible power requirements if they were to be used in high-end man-portable equipment.

5.3.11.2 Quantum Inertial Navigation Systems

5.3.11.2.1 Main characteristics

Quantum physics principles are being exploited also for navigation, with the rationale that harnessing fundamentally **inalterable atomic properties will improve the drift performance of inertial measurement units**. Research has focussed on:

- **Nuclear Magnetic Resonance (NMR)** gyros exploiting nuclear spin and first developed in the 60s', but the competition from ring laser gyros and fiber optics gyros hindered their commercial appeal. Only recently, new devices have been disclosed which exploit miniaturisation technologies for compact navigation grade systems at a competitive cost.
- **Spin-Exchange Relaxation Free (SERF)** gyros, much less investigated, based on the electronic spin of alkali metals (first proposed in 2005) and those leveraging the spin of nitrogen-vacancies in diamonds (in the last decade), both still mainly the object of academic research.
- **Cold Atom Interference (CAI)** gyros, today the most promising systems for autonomous navigation, exploit the fundamental stability of atomic mass to guarantee immunity from drifts, thus eliminating any need for periodic recalibrations. In addition, CAI-based systems measure absolute values of acceleration and rotation rate and not variations with respect to reference values. These advantages come at the cost of high cost, size, weight, and power footprint, since complex enabling technologies are required (vacuum systems, lasers and optical systems, control electronics, etc.), whose progress constitutes a key factor for the development of field-deployable CAI-based inertial sensors.

Table 19 provides a comparison among these quantum gyroscopes and with the conventional ones MEMS and ESG. **Micro Electro-Mechanical Systems (MEMS)** gyros are widely applied in consumer applications but are unlikely to reach the drift requirements needed for autonomous navigation. The performance of mechanical floated gyroscopes and of optical gyroscopes is approaching the limit determined by the underlying physical principles, and any improvement will involve a high extra cost. The **Electrically Suspended Gyroscopes (ESG)** are also considered consist of a two-degree-of-freedom gyro where the spinning rotor ball is supported in a vacuum by an electric field. Atomic gyroscopes (NMR, SERF, and CAI) are projected to become competitive with conventional navigation-grade for the next-generation inertial navigation systems.

Table 19 – Comparisons of gyroscopes based on different physical principles [data taken from Zhang 2016]

Grade	Type	Drift (°/h)	Size (mm³)	Cost (USD)
Tactical	MEMS	1 000 – 0.1	< 100	< 100
Navigation	NMR	10^{-2}	10 - 10^{4}	10^{3} - 10^{4}
	Ring Laser	10^{-2} – 10^{-3}	~ 10^{5}	10^{4} - 10^{5}
	Fiber Optics	10^{-2} – 10^{-3}	10^{5} - 10^{6}	10^{4} - 10^{5}
Strategic	Mechanical floated	10^{-3} – 10^{-4}	10^{6} - 10^{7}	10^{5} - 10^{6}
	ESG	10^{-4} – 10^{-5}	10^{7} - 10^{8}	10^{6} - 10^{7}
	SERF	~ 10^{-4}	10^{6} - 10^{7}	< 10^{5}
	CAI	> 10^{-5}	~ 10^{9}	10^{5} -10^{6}

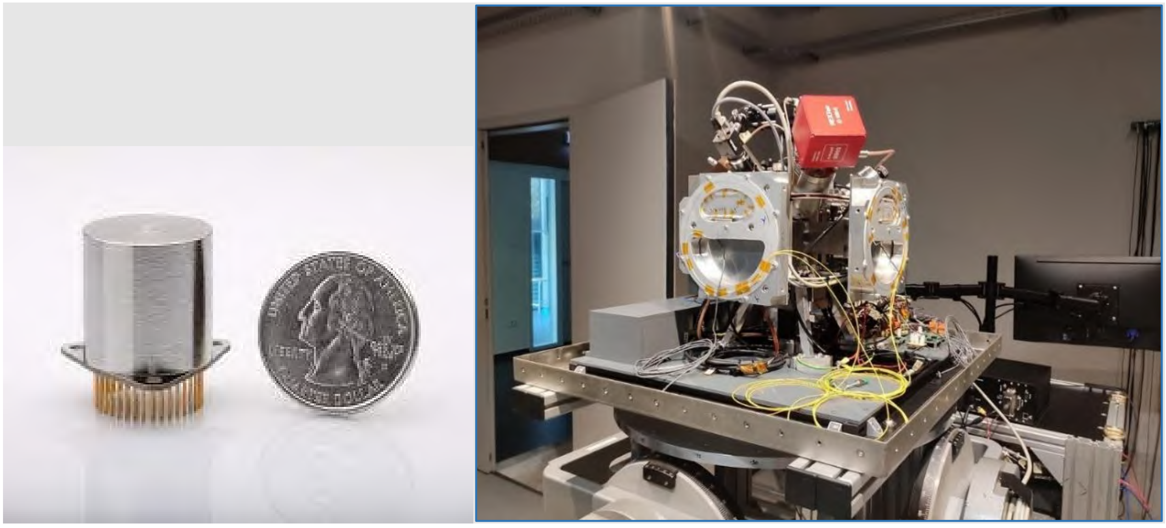


Figure 62 – NMR gyro for tactical applications prototype by Northrop Grumman (left) and a laboratory-based IMU based on the hybridisation of fiber optics gyroscopes and CAI accelerometers developed by IXblue (right)

5.3.11.2.2 Status and optimisation plans

The **path towards a portable CAI-based six-axis IMU** fast, robust, and compact enough to be employed **for inertial navigation** requires negotiating several trade-offs and overcoming several technological challenges, which are likely to call for **several years of sustained efforts**. To take effective advantage from absence of drift embedded in its working principle, reliable and robust technologies able to support long term autonomous operation in harsh environments must be developed and implemented.

Also, it should be noted that a CAI-based IMU unavoidably present dead-time intervals during which atom cooling takes place and will therefore need to operate in a hybrid fashion comprehending also classical devices. An alternative approach could be the use of CAI systems to provide plug-in calibration to fast and sensitive accelerometer and gyroscopes based on other working principles.

Single-axis cold-atom gravimeters used to measure slowly varying gravitational fields along a single axis are already commercially available (TRL=9, i.e., actual system proven in operational environment), while several prototypes of CAI-based accelerometers and gyroscopes have been developed, demonstrating a TRL between 3 (experimental proof of concept) and 4 (technology validated in lab).

As a final note, it should be reminded that atomic sensors to be used for inertial navigation are likely to be considered dual-use items and subject to ITAR export restrictions, as already happens for the high-performance systems based on optical or mechanical effects.

5.3.11.3 References

The reader interested in a deeper analysis is referred to the following references:

- G. Giorgi et al., *Advanced technologies for satellite navigation and geodesy*, Advances in Space Research 64, 2019.
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2019.

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- M. Travagnin, *Cold atom interferometry for inertial navigation sensors - Technology assessment: space and defence applications*, JRC122785, EUR 30492 EN, 2020.
- M.J. Wright et al., *Cold Atom Inertial Sensors for Navigation Applications*, Frontiers in Physics, submitted on 14 July 2022.

5.3.12 Pulsars' PNT

A Pulsar (from **pulsa**ting **r**adio source) is a highly magnetised and fast rotating **neutron star**, that emits beams of electromagnetic radiation out of its magnetic poles. The electromagnetic radiation can be observed only when a cone of emission is pointing toward Earth. As Neutron stars are very compact objects with short, regular rotational periods, **the interval between pulses is very precise** and ranges from milliseconds to seconds for an individual pulsar. The electromagnetic signal (in particular in the radio, optical and X bands) emitted by the pulsars can be detected by the specialised equipment and each pulsar can be identified based on the light curve reconstructed from the emitted signal. In particular, the X-ray signal emitted by the stars can be detected by the specialised equipment and each star can be identified based on the nature of the signal emitted. Hence pulsars are not only the source of precise timing but can also be used for navigation on a galactic scale. This idea was first proposed in '74 by G.S. Downs.

5.3.12.1 Main characteristics

Pulsars were firstly considered for the **time provision** (millisecond pulsars offer time stability comparable with the atomic clocks). This idea already has a practical implementation, with the first terrestrial pulsar clock installed in Gdansk, Poland in 2011 to commemorate 400 anniversary of Johannes Hevelius' birth. Since then, several other devices were installed, practically testing the concept of the Pulsar Time Scale, intended as a combination of long-term pulsar observations with the ultra-stable local clocks. Indeed, even the simple combination of an atomic clock and corrections computed from Pulsars observation generate very stable time scale independent from other inputs.

While not every pulsar can be used for precise timing, mostly due to frequency, they are all very stable (some have been monitored since the '70s). Interestingly sources that are less bright are more stable. Each pulsar has a unique transmission profile, in particular the repetition period of the pulses, allowing to identify it. This led to their consideration for navigation, firstly by G.S. Downs.

The main argument was that they are visible from anywhere within the galaxy, and several pulsars (that can be distinguished based on their frequency, much like lighthouses) can form a set of beacons, whose pointing direction is known.

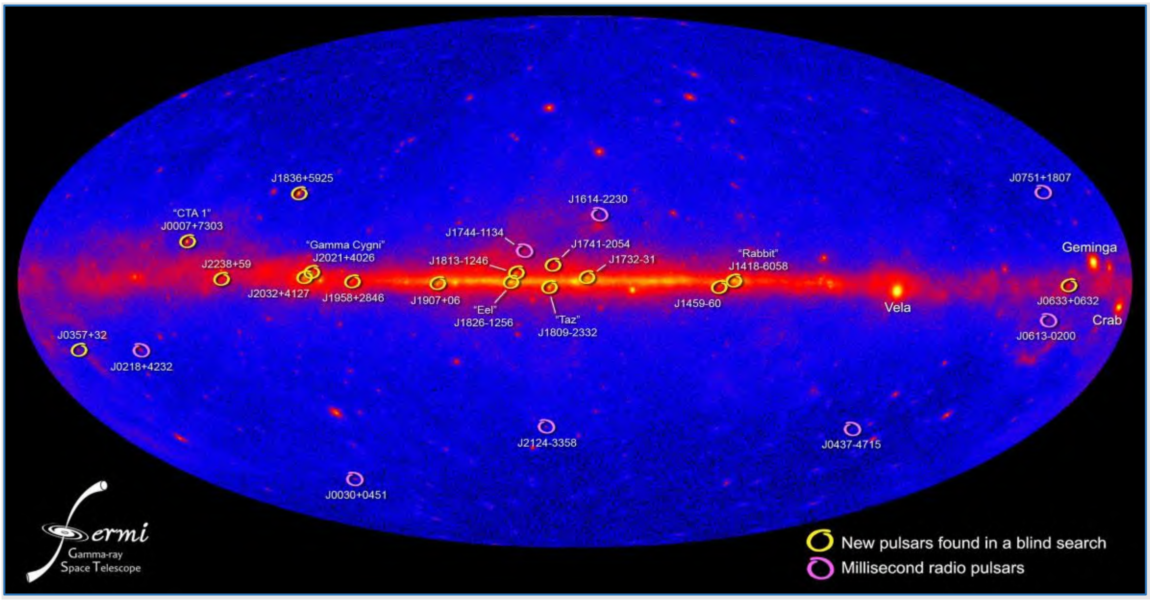

Figure 63 – Known pulsars, plotted along the Galactic Longitude and Latitude (Credit: NASA public domain)

Since then, multiple space missions have observed and identified thousands of X-ray sources, with several of them actively monitored. In addition, other space radio signals were identified such as Gamma-Ray Bursts (GRB) which are recommended for the position and velocity with Bright X-ray sources and Fast Radio bursts (FRB) recommended for relative navigation. Radio band pulsars are also used actively for studies on gravitational waves.

5.3.12.2 Status and optimisation plans

Most of the relevant research output is from NASA and ESA, developing capacity and algorithms. Two **navigation methods** for spacecrafts are proposed:

- Absolute navigation involves just one satellite trying to position itself with regards to an inertial reference point, such as the Solar System Barycentre (SSB). This would require a sporadic connection between the satellite and the ground control for updating the pulsar ephemeris that might occasionally change because of pulsar glitches (time span of years) or other timing irregularities.
- Relative navigation involves multiple spacecraft observing the same sources using only observations on the involved spacecraft Differential observations between two spacecraft flying in formation, with a known distance, were also proposed.

The **main interest of pulsars' navigation is for deep space systems** and interplanetary travel. Most of the existing space navigation systems operate using telemetry and X-ray pulsar-based navigation and timing (XNAV) could significantly reduce the cost and offer flexibility due to increased accuracy. The most appealing aspect is the wide availability of the signals and lack of maintenance (navigation only requires infrequent ephemeris updates of each identified pulsar). X-ray sensors are very resistant to noise in other frequencies, which is very useful for in-space applications. Only pulsars transmitting in those frequencies are considered for navigation, even though other frequency ranges are under study.

A 2004 ESA study found that observation of a single pulsar, estimating distance, requires a moderate antenna size (10 m^2) and signal integration time of about an hour. It also concluded that X-ray pulsar-based navigation and timing (XNAV) could offer 1 000 km accuracy for space missions. As the full system would require multiple antennas for synchronous multi-pulsar observations the total weight of the system was deemed too heavy for the spacecraft.

Since then, several hardware tests and demonstrations were completed. In 2016, China launched X-Ray Pulsar Navigation (XPNAV-1) experimental demonstration mission that demonstrated µsec-level timing resolution and measurement to a single pulsar. The hardware is still to be miniaturised and the signal processing calculations are still computationally intensive. A recent ESA study, with University of Padova, calculated accuracy increases down to a sub-km also reducing the payload size, weight, and power (SWAP, estimated to be 10 kg mass on 30x30x30 cm volume and 10 W power consumption).

Other ESA studies for interplanetary navigation are under way, reducing the number of antennas to one at the expense of more complicated spacecraft operations to acquire sequentially the Pulsar signals. Researchers also forecast that Pulsar measurements in the RF range could be used in the future for navigation on Earth, especially for certain use cases where the size of antenna might not be a problem. Further details can be found at *Use of pulsars for ship navigation: an alternative to the sextant*.

5.3.13 Summary of Strengths, Weaknesses, Opportunities and Threats

EMERGING TECHNOLOGIES	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
White Rabbit	- Proven and tested technology, that is easy to implement and manage. - Provided both by small and large EU companies.	- Require backbone infrastructure and uninterrupted fibre end to end. - Infrastructure might need to be upgraded.	- Innovation on the existing technology - EU is the leading provider.	- Commercial use of the existing scientific network is not agreed yet.
Computer Network Time Dist.	- Network does not need to be homogeneous and existing infrastructure can be used most of the time.	- Backbone links error budget will require commercial internet (guaranteed amount of bandwidth) not the best effort one. - Microwave links might be jammed.	- Number of connections naturally increases with the emerging markets such as IoT, smart city or transport.	- Network should be not extrapolated but interpolated (designed to support expansion). - Network error budget might need to be over-conservative.
Pseudolites	- Dedicated and encrypted signals designed for high accuracy positioning indoor and outdoor using low power levels. - Some technologies are multipath resistant with dedicated beamforming VRay antennas. - Broadcast system has no capacity limitations. - Resilient to local and system failures, some technologies are certified for safety of life applications.	- Accuracy is geometry-based, based on the placement of the transceivers, so height estimation is less reliable. - Number of units do not scale well with area and network must be deployed around vicinity of desired service area. - UTC time require external synchronisation.	- Deployment is easy, and the maintenance cost is low. - Established commercial use.	- Utilised frequency can be used by anyone without restriction (WiFi) or require dedicated permits. - Terrestrial components can be physically attacked and need power.
5G & Cellular Networks	- Based on the existing infrastructure, providing full PNT.	- Currently all position information are based on sensor fusion with GNSS.	- Mass market.	- PNT aspect is not well developed in platform proposal.
R-Mode	- Uses existing radio infrastructure. - Enables positioning, timing and integrity checks.	- Coverage is limited to coastal waters and geometry forced by the coastline can be challenging. - No support of high-accuracy applications. - System and service are under development and GNSS independent synchronization is challenging.	- Can fill the gap of the terrestrial component of the maritime PNT system. - Based on common world-wide maritime coastal radio services; scalable too be available world-wide along major shipping routes.	- Depends on availability of existing radio infrastructure . - Standardization needs to be finished within the next 5 to 10 years.

Figure 64 – Summary of Strengths, Weaknesses, Opportunities and Threats for the Emerging Technologies

EMERGING TECHNOLOGIES (cont.)		STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
	Image based navigation	- Tested Technology.	- Dedicated hardware calibration required.	- Very promising in sensor fusion.	- Current solutions are market specfic.
	Mobile based Navigation	- It is ubiquitous service already available en the mobile devices.	- Performance is not homogeneous and depends on the handset. - Technology is developed by different company than handset manufacturer.	- It is mass market and was tested in various commercial conditions.	- It is developed by commercial company (Google, Apple) as value-added offering.
	Dead-reckoning & IMU	- Passive world wide navigation, all attitude and all weather. - Reliable and easy to operate with fast reaction.	- Mechanical noise and error increase exponentially. - Lower cost solutions dependent on availability and quality of the additional information.	- Some of the applications can be addressed by low cost hardware. - Immune to spoofing. - Cost related to the unit performance.	- Cost of high end units. - GNSS required in sensor fusion for global position.
	Environmental maps	- Does not require infrastructure.	- Quality of underlying maps. - Some technologies require sky visibility.	- Difficult to spoof. - Off-The-Shelf hardware.	- Quality of underlying maps is not coherent. - Simultaneous localization and mapping (SLAM) is not efficient in updating data/users do not want to share data.
	Low Earth Orbit (LEO)	- Does not require infrastructure. - Signal 30dB higher than MEO, time delay is comparable with terrestrial infrastructure.	- Large number of satellites needed and large Doppler of constellation. - Apart from Iridium no dedicated PNT signal is used.	- Quick roll-out of updates as satellites have limited lifespan for new LEOs. - With so many signals further Signal of Opportunity (SoO) approaches might be developed.	- PNT service might be too expensive to deploy on top of communication service. - Proposed number of satellites might create problem in the future. - Orbit estimations are not precise enough.
	Quantum Technologies	- Based on fundamental inalterable physical properties.	- Complex enabling technologies are required.	- Improvement in a wide range of performances.	- High cost, acceptance by final users.
	Pulsars' PNT	- Can be used everywhere in the space and only require periodically updated almanacs.	- Require precise holdover clock and precise aligned antennas for each tracked pulsar (each direction).	- Full PNT for the space missions. - Time for Earth operations.	- Hardware cost and size. - Demonstration tests not conducted.

Figure 65 – (Cont.) Summary of Strengths, Weaknesses, Opportunities and Threats for the Emerging Technologies

6 APPENDIX B: Resilient PNT services

As it is shown in the **Error! Reference source not found.**, Position, Navigation and Timing services are vital for the EU society and economy, enabling precise timing and location information for critical Infrastructure, the professional and mass market and safety of life and liability critical applications.

Disruptions or failures in PNT services can have severe consequences, including financial losses and safety risks, stressing the importance of having resilient PNT services. Inaccurate timing information can cause disruptions in power grids, financial markets, and communication networks; similarly, incorrect location information can lead to accidents in transportation and logistics systems.

Considering that the protection level should vary depending on the criticality of the application, **resilient PNT** requires detection of threats, appropriate response mechanisms and rapid service recovery. It necessitates the development of new hardware (e.g., antennas), software (new algorithms), and alternative systems.

The EU vision advocates for a System of PNT systems to achieve resilient PNT requiring several elements:

- **Redundancy**: PNT services should have redundant systems and backup mechanisms to ensure continuity in the event of failures or disruptions.
- **Diversity**: PNT services should use multiple sources of data and signals to increase reliability.
- **Monitoring, testing and maintenance**: Regular monitoring, testing and maintenance of PNT systems are crucial to detect, identify and address any issues before they lead to a failure.
- **Security/Cybersecurity**: PNT systems should be designed with robust security/cybersecurity measures to protect against deliberate attacks and ensure the integrity of the information.
- **Common position and time reference frame:** to prevent the accumulation of errors when combining PNT services, since individual PNT services provide time and position in potentially different reference frames and timing systems.
- **Standards and regulations**: PNT standardization and regulation can help to ensure that they are designed, deployed, and operated to meet specific performance and reliability requirements, such as:
  - Standards / guidelines **to assess the performance of PNT services**, including test cases and test procedures.
  - Standards / guidelines with **minimum performance requirements** for application domains (e.g., aviation, maritime, timing applications, etc.).
  - Standards / guidelines (testing and minimum performance) for **interference and spoofing detection and mitigation techniques.**
- **Education and awareness** of users and designers about the importance of PNT services together with their potential risks and threats.

By considering all the elements described above, PNT services will become more resilient and their users will mitigate the risks of disruptions and failures and guarantee the continuity of their operations.

7 APPENDIX C: Regulations and Standards

The following table summarises the list of activities identified in section 3.4 to facilitate the uptake of EGNSS in the different market segments:

Table 20 –Summary of activities to uptake EGNSS (mainly Regulations & Standards)

Market Segment	System	Item	Organisation	Title	Timeline	Comment
All	GNSS	Standard		Interference and spoofing detection and mitigation techniques	asap	Growing threat from interference and spoofing
Manned Aviation	EGNOS	Standard	EUROCAE	Minimum Operational Performance Standard for Satellite-Based Augmentation System Airborne Equipment	2023	ED-259A including test procedures
Manned Aviation	EGNOS	Standard	EUROCAE	Minimum Operational Performance Standard for Satellite-Based Augmentation System Airborne Equipment	2024	ED-259B including H-ARAIM and institutional scenarios
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 Amendment 93	2023	Amendment to ICAO Annex 10 including DFMC SBAS SARPs and Galileo.
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 updated version	2024	Amendment to ICAO Annex 10 including ARAIM.
Manned Aviation	Galileo / EGNOS	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 updated version	2026	Amendment to ICAO Annex 10 including Authentication.
Manned Aviation	Galileo	Standard	ICAO	ICAO Standard and Recommended Practices (SARPs), Annex 10 of the Chicago Convention, Volume 1 revied version	2029	Amendment to ICAO Annex 10 introducing DFMC GBAS with multi-constellation capability and possibly

Market Segment	System	Item	Organisation	Title	Timeline	Comment
						multi-frequency.
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Aircraft System Performance Specification for Required Navigation Performance for Area Navigation	June 2022	ED-75E
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Operational Performance Standard for distance measuring equipment (DME/N and DME/P) (ground equipment)	2023	ED-57A
Manned Aviation	DME (for resilient PNT)	Standard	EUROCAE	Minimum Aircraft System Performance Specification (MASPS) for DME Infrastructure supporting PBN positioning	2023	New document
Unmanned Aviation	Galileo / EGNOS	Guidelines	EUROCAE	ED-301 Guidelines for the Use of Multi-GNSS Solutions for UAS Specific Category – Low Risk Operations SAIL I and II	Aug. 2022	Covers the use of GNSS for low-risk drone operations
Unmanned Aviation	Galileo / EGNOS	Guidelines	EUROCAE	Guidelines for the use of multi-GNSS solutions for UAS: Medium Risk	2024	Covers the use of GNSS for medium-risk drone operations
Maritime	EGNOS	Standard	IEC	Test standard for shipborne SBAS (L1) Receiver Equipment	2023	IEC 61108-7
Maritime	EGNOS	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including SBAS (L1)	2023-2024	1y after SBAS test standard The update of the regulation shall include the reference to IEC 61108-7, IEC 61108-1, IMO MSC 401, IMO MSC 112

Market Segment	System	Item	Organisation	Title	Timeline	Comment
Maritime	Galileo	Standard	IMO	Update of performance standard for shipborne Galileo Receiver Equipment	2023-2024	Update of IMO MSC 233 Draft proposal submitted for info. to IMO NCSR 10
Maritime	Galileo	Standard	IEC	Update of test standard for Shipborne Galileo Receiver Equipment	2025-2026	Update of IEC 61108-3
Maritime	Galileo	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including Galileo	2025-2026	Update IMO MSC resolution and IEC 61108-3 issue 2.0
Maritime	EGNOS	Standard	IMO	Performance standard for shipborne DFMC SBAS + ARAIM Receiver Equipment	2025	Proposal to be submitted in MSC 107 in May 2023
Maritime	EGNOS	Standard	IEC	Test standard for shipborne DFMC SBAS + ARAIM Receiver Equipment	2027	2y after the DFMC SBAS + ARAIM performance standard
Maritime	EGNOS	Regulation	EU	Update of Reg 2022/1157 on design, construction and performance requirements and testing standards for marine equipment including DFMC SBAS + ARAIM	2027-2028	1y after DFMC SBAS + ARAIM test standard
Inland waterways	Galileo / EGNOS	Regulation	EU	Update of European Standard for River Information Services, ES-RIS 2021/1	Every 2y	Specific provisions on PNT and GNSS may be covered.
Inland waterways	Galileo / EGNOS	Preparatory Action	EU	EU Space Data for autonomous vessels in Inland waterways	2023-2025	It will assess how EU Space Data from Galileo, EGNOS and Copernicus can be key enablers of the digital transformation.

Market Segment	System	Item	Organisation	Title	Timeline	Comment
Rail	Galileo / EGNOS	Standard	ERA	Technical Specification for Interoperability	2022-2028/2029	Standard to meet essential requirements and ensure interoperability of the EU railway system.
Road	EGNOS	Standard	ETSI 3GPP	Update of 3GPP standard	2024	Evolve 3GPP standards to be compliant to MOPS messages for DFMC GNSS signal dissemination through Mobile Network.
Road	Galileo	Standard	ETSI/CEN	Test Standard for GNSS + HAIS	2024	Set of standardised (and ideally certified) GNSS + HAIS related tests and data bases that would be used for service certification.
Road	Galileo / EGNOS	Standard	ISO	Intelligent transport systems — Low-speed automated driving system (LSADS) service — Part 2: Gap analysis	2023-2024	
Road	Galileo / EGNOS	Standard	ISO	Intelligent transport systems — Seamless positioning for multimodal transportation in ITS stations — Part 1: General information and use case definition	2024-2025	
Road	Galileo / EGNOS	Standard	ISO	Electronic fee collection — Localisation augmentation communication for autonomous systems	2024-2025	
Timing	Galileo	Standard	CEN/CENELEC JTC5	Standards for Galileo Time Receiver	2024-2025	

8 APPENDIX D: EU PNT major stakeholders

European Commission (EC)

The European Commission represents the general interest of the European Union and is the driving force in proposing legislation to European Parliament and Council, administering, and implementing EU policies, enforcing EU law jointly with the Court of Justice, and negotiating in the international arena. Within the European GNSS programmes, the European Commission has the **overall responsibility** for the implementation of the EU Space Programme, including in the field of security. The European Commission shall **determine the priorities and long-term evolution** of the Programme, in line with the user requirements, and shall **supervise** its implementation.

The Directorate-General for Defence Industry and Space (DEFIS) leads the European Commission's activities in the Defence Industry and Space sector. The European Commission shall ensure a clear division of tasks and responsibilities between the various entities involved in the Programme and shall coordinate the activities of those entities. The European Commission shall also ensure that all the entrusted entities involved in the implementation of the Programme protect the interest of the European Union, guarantee the sound management of the European Union's funds and comply with the Financial Regulation.

The European Commission departments and executive agencies are based in Brussels (Belgium) and Luxembourg.

European Union Agency for the Space Programme (EUSPA)

EUSPA is the operational European Union Agency for the Space Programme, with the headquarters in Prague. Its core mission is to implement the EU Space Programme and to provide reliable, safe, and secure space-related services, maximising their socio-economic benefits for European society and business.

Related to Galileo and EGNOS activities, EUSPA core tasks are to ensure the **security accreditation** of those systems and to undertake **communication**, **market development** and promotion activities as regards their services. EUSPA entrusted tasks consist of **managing the exploitation of EGNOS and Galileo** and implement activities related to the **development of downstream applications** based on the data and services provided by Galileo and EGNOS.

EUSPA is based in Prague (Czech Republic).

European Space Agency (ESA)

The European Space Agency (ESA) is an international organisation with 22 Member States and formal cooperation agreements with all Member States of the European Union that are not ESA members. ESA's purpose is to provide for, and to promote, for exclusively peaceful purposes, cooperation among European States in space research and technology and their space applications, with a view to being used for scientific purposes and for operational space applications systems.

As regards Galileo and EGNOS, ESA has been entrusted with the tasks of **systems evolution and design and development** of parts of the ground segment, and of satellites, including testing and validation and **upstream research and development** activities in ESA's fields of expertise.

In parallel to the work of ESA on Galileo and EGNOS, ESA is running several R&D programmes aimed to prepare the technology of the main systems and its applications. The main two programmes of ESA on this area related to PNT are the European GNSS Evolution Programme (EGEP) and the Navigation Innovation and Support Programme (NAVISP).

ESA Head Quarters are based in Paris (France).

European Aviation Safety Agency (EASA)

Formed by 31 Member States (the 27 Member States of the European Union plus Switzerland, Norway, Iceland and Liechtenstein), the European Aviation Safety Agency (EASA) is **an agency of the European Union** which has been given specific **regulatory and executive tasks in** the field of **aviation safety**.

EASA **mission** is to promote the **highest common standards of safety and environmental protection** in civil aviation. EASA develops common safety and environmental rules at European level and assist the European Commission with measures for the implementation of these rules and by providing the necessary technical, scientific, and administrative support to carry out its tasks. EASA monitors as well the implementation of standards through inspections in the Member States and provides the necessary technical expertise, training, and research.

EASA is based in Cologne (Germany).

EUROCONTROL

EUROCONTROL is pan-European, civil-military international organisation dedicated to **supporting European aviation**, working for seamless, pan-European air traffic management. It has 41 Member States with a vital **European expertise on air traffic management (ATM),** both leading and supporting ATM improvements across Europe. Among their activities EUROCONTROL supports the European Commission, EASA, and National Supervisory Authorities in their regulatory activities, including for the implementation of GNSS technologies.

EUROCONTROL is based in Brussels (Belgium).

SESAR Joint Undertaking (SESAR JU)

The SESAR Joint Undertaking (SJU) was established as a public-private partnership under Council Regulation (EC) 219/2007. The Council Regulation (EU) 2021/2085 marked the official launch of the SESAR 3 Joint Undertaking (SESAR 3 JU) bringing together the **EU, Eurocontrol, and more than 50 aviation organisations** (civil and military, Air Navigation Service Providers, airports, equipment manufacturers, authorities and the scientific community).

The **SJU is responsible for the modernisation of the European ATM system** by coordinating all ATM relevant research and innovation efforts in the EU. The SJU is responsible for the implementation of the European ATM Master Plan and for carrying out specific activities aiming at developing the new generation ATM system capable of ensuring a safety, green and fluid European air transport over the next thirty years. SESAR 3 Joint Undertaking will invest more than EUR 1.6 billion between 2022 and 2030 to accelerate, through research and innovation, the delivery of an inclusive, resilient, and sustainable Digital European Sky.

The SESAR Joint Undertaking is based in Brussels (Belgium).

European Maritime Safety Agency (EMSA)

The European Maritime Safety Agency (EMSA) provides technical assistance and support to the European Commission and Member States, Iceland and Norway in the **development and implementation of EU legislation on maritime safety**, pollution by ships, oil and gas installations, oil pollution response, ship and port security, vessel monitoring and long range identification and tracking of vessels.

EMSA **ensures the verification and monitoring of the implementation of EU legislation and standards**. The Agency provides technical assistance and scientific advice on matters regarding ship safety standards, and supports as well capacity building by providing expertise, training and research, cooperation, and tools. EMSA also participates in disseminating best practices and promoting sustainable shipping including implementation and enforcement of existing or proposed international and EU legislation and **collaborating with many industry stakeholders and public bodies**, in close cooperation with the European Commission and the Member States.

EMSA is based in Lisbon (Portugal).

European Union Agency for Railways (ERA)

The mission of the European Union Agency for Railways (ERA) is 'moving Europe towards a sustainable and safe railway system without frontiers'. To achieve this, **ERA contributes, on technical matters, to the implementation of the European Union legislation** aiming at improving the competitive position of the railway sector by **enhancing the level of interoperability of rail systems**, developing a common approach to safety on the European railway system and contributing to creating a Single European Railway Area without frontiers, **guaranteeing a high level of safety**.

Train navigation and positioning systems based on satellite applications are future components of the Control, Command and Signalling rail subsystem. Accordingly, ERA is setting the rules for their approval, in cooperation with trials run by railway operators and the system development, which is taking place under the aegis of Shift2Rail Join Undertaking, to which ERA is associated, as the first European rail initiative to seek both research & innovation and market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions.

ERA is based in Valenciennes and Lille (both in France).

European Maritime Radionavigation Forum (EMRF)

The European Maritime Radionavigation Forum (EMRF) **represents the maritime interests in Europe** and **provide expert input to European Policy** on safety of navigation and related matters.

The EMRF gathers different bodies, from maritime administrations to ship owners' organisations, to focus on the coordination of **European maritime interests in the field of radionavigation systems** for development within Europe. In particular, for global navigation satellite systems there are different activities within EMRF to address the use of GNSS, especially the improvements in position and related procedures which Galileo and EGNOS can bring into the maritime domain.

One of its main aims is to promote the **maritime requirements for the safety assessment and certification of future satellite systems**, their augmentation systems and back up, and to develop material to achieve recognition and operational approval of those systems as part of the IMO World-Wide Radionavigation System.

Member States

At the core of the EU are its 27 Member States and their citizens. The unique feature of the EU is that although the Member States all remain sovereign and independent states, they pool together some of their sovereignty in areas where this has an added value.

The role of Member States in PNT includes the support and participation in the development and implementation of regulation, policies and actions related to PNT, the coordination with other Member States and the EU institutions and the contribution to the development of new PNT technologies and applications.

Member States are involved in PTN from different perspectives:

- Key users of Galileo PRS and authorities for SAR.
- National Space Agencies which are key for the European GNSS Programmes.
- National Spectrum Agencies which manage the Radio-Frequency spectrum, ensuring coordination and intervene in RFI incidents.
- Ministries of Transportation which support and oversight the use of Safety of Life applications of GNSS in different domains such as aviation and maritime.

Finally, Member States support emergency management in case of a major RFI incident or GNSS outages, being key in the coordination among impacted stakeholders.

Other stakeholders

The following stakeholders are also relevant for PNT services:

- European Defence Agency (EDA).
- International Civil Aviation Organisation (ICAO).
- International Maritime Organisation (IMO).
- International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA).

9 APPENDIX E: EU reference frames

GNSS positioning is underpinned by the Terrestrial Reference System (TRS, with mathematical and physical foundations for its definition and properties) and the Terrestrial Reference Frame (TRF, a numerical realisation of the TRS). The most widely used is the International Terrestrial Reference Frame (ITRF) which is critical for the continuous monitoring of the earth's tectonic plate movement (1.5 cm / year for most of Europe) or mean sea level using Continuous Operating Reference Stations (CORS), which permanently locate GNSS receivers.

For centuries, each country has maintained its local grid and mapping transformation (i.e., the best fit of country 2D maps into a global ellipsoid), intended to reduce the transformation errors through the varied scale factor. Those national grids have been physically established using trigonometric points. Currently, **countries' mapping services** are moving away from the classical approach and **are widely using Network RTK**, maintained via a network of CORS and hence based on GNSS.

This trend of using GNSS as a global reference is expected to propagate to all aspects of PNT, especially given the expected increase in future PNT high-accuracy services. As the scale factor approach is prone to man-made blunders, even mapping and terrestrial engineering works are moving from national grids to GNSS-delivered local grids (usually using Helmert transformation).

This appendix lists the most important TRFs from the European perspective as well as provide simple best practice guideline on their use.

Reference Frames

The International Terrestrial Reference System (ITRS) was developed by the geodetic community under the auspices of the International Earth Rotation and Reference Systems Service (IERS). Its most accurate realisation is the **International Terrestrial Reference Frame (ITRF)**, which is in reality a series of improved versions of ITRF. The latest version is ITRF2020 though some earlier ITRF (usually not earlier that ITRF2000) could be still in use. Transformation between the frames is possible if the definition and epochs of both frames are known. While earlier frames changed up to the dm level since ITRF94 (since ITRF2005 for the heigh component) differences are on the mm level. The biggest effect, addressed by the epoch of establishment, is the tectonic plate movement.

Galileo uses **Galileo Terrestrial Reference Frame (GTRF)**, realised by the Galileo Geodetic Service Provider and since 2018 managed by the Galileo Service Operator (GSOp). The latest GTRF solution (GTRF19v01) is aligned with respect to the ITRF2014 with mm accuracy. Other GNSS systems also adopted reference to ITRF, and all are currently referenced to ITRF2014.

The **ETRS89 (European Terrestrial Reference System of 1989)** is based on ITRF89, epoch 1989.0 and monitored by a network of about 250 permanent GNSS tracking stations known as the EUREF Permanent Network. As ETRS89 is kept fixed at epoch 1989.0, the ETRS89 and the ITRS are diverging due to the European continental drift (approximately 2.5 cm per year). In early 2023, the difference exceeded 80 cm.

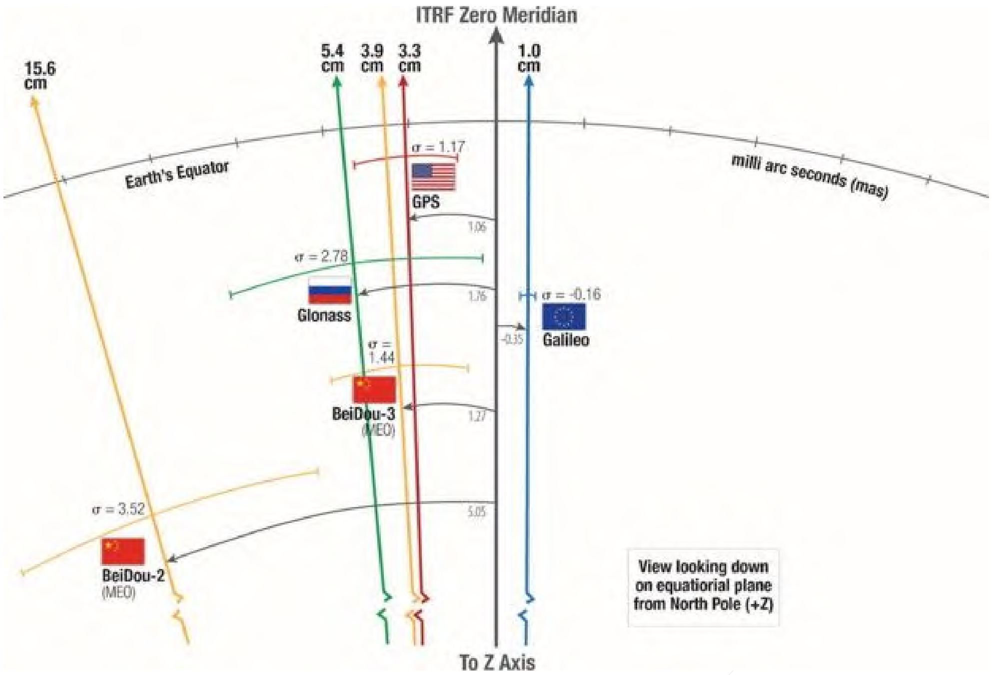

Figure 66 - Comparison of a prime meridian, as realised by GNSS TRF, with respect to the IGS14 zero meridian (Credit: https://www.sciencedirect.com/science/article/pii/S0273117720308292)

More information about the reference frames, transformations and IGS products can be found in:

- P. Teunissen and O. Montenbruck, *Springer handbook of global navigation satellite systems*. Springer International Publishing, 2017.
- Y. J. Morton, F. S. T. Van Diggelen, J. J. Spilker, and B. W. Parkinson, Eds., *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications*, First edition. Hoboken: Wiley/IEEE Press, 2021

Best practice

Based on the above, as a rule of thumb, **all coordinates should be referred to a specific ITRF**, at the specific epoch of establishment. For most continental Europe ETRS89 is the perfect replacement. In certain areas of increased tectonic activity, such as Greece, transformation requires known site velocities. This excludes any discontinuity due to earthquakes (points need to be re-established).

In the case of a GNSS-based system, it is worth noting that NRTK and PPP reference frames tend to differ. In Europe, most of the NRTK CORS are defined in ETRF89 and so are the final coordinates. For PPP the terrestrial reference frame will be defined by the datum of the corrections, usually the latest ITRF. Similarly, EGNOS reference frame is determined by the geodetic coordinates of the EGNOS stations (EGNO Ranging and Integrity monitoring Stations) which are established in ITRF2000.

In the case of terrestrial systems, only small-scale deployments (below 10 km^2) and indoors should use local grid implementation, as long as coordinates are linked to ETRF (ITRF including epoch of transformation). The GNSS-delivered local grids via Helmert transformation are suggested.

For the larger deployment, ETRF/ITRF should be used directly. It is worth noting that the use of the global coordinates is not intuitive (latitude/longitude distance varies with longitude and the Cartesian XYZ height component is difficult to read) so local coordinates will probably be used for visualisation (but not for the underlying system).

10 APPENDIX F: ACRONYMS

The next table provides the list of acronyms:

ABAS	Aircraft Based Augmentation System	ESA	European Space Agency
ACAS	Assisted CAS	ETCS	European Railway Traffic Management System
ADS-B	Automatic Dependant Surveillance Broadcast	ETSI	European Telecommunication Standard Institute
AIS	Automatic Identification System	EUSPA	European Union Agency for the Space Programme
ARAIM	Advanced Receiver Autonomous Integrity Monitoring	FAA	Federal Aviation Authority
ASF	Additional Secondary Factor	FCC	Federal Communications Commission
ATC	Air Traffic Control	FDMA	Frequency Division Multiple Access
ATM	Air Traffic Management	FOC	Full Operation Capability
AtoN	Aids-to-Navigation	G2G	Galileo 2nd Generation
BVLOS	Beyond Visual Line of Sight	GBAS	Ground Based Augmentation System
CAS	Commercial Authentication Service	GEO	Geostationary Earth Orbit
CBA	Cost Benefit Analysis	GIS	Geographical Information System
CDMA	Code Division Multiple Access	GIVE	Grid Ionospheric Vertical Error
CER	Community of European Railway	GLA	General Lighthouse Authorities of the UK and Ireland
CNI	Critical National Infrastructure	GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
CNS	Communication, Navigation and Surveillance	GMDSS	Global Maritime Distress and Safety System
COG	Course Over Ground	GNSS	Global Navigation Satellite System
DFMC	Dual-Frequency Multi-Constellation	GPS	Global Positioning System
DGNSS / DGPS	Differential Global Navigation Satellite System / Global Positioning System	GSC	GNSS Service Centre
DOP	Dilution of Precision	GSS	Galileo Sensor Station
EASA	European Aviation Safety Authority	HAL	Horizon Alert Limit
EC	European Commission	HAS	High Accuracy Service
EDAS	EGNOS Data Access Service	HMI	Hazardously Misleading Information
EGNOS	European Geostationary Navigation Overlay Service	HPL	Horizontal Protection Level
EMRF	European Maritime Radio Navigation Forum	IALA	International Association of Marine Aids to Navigation and
ERA	European Railway Agency	ICAO	International Civil Aviation Organization
ERNP	European Radionavigation Plan	ICG	International Committee on GNSS
ERTMS	European Railway Traffic Management	IEC	International Electrotechnical

	System		Commission
IGS	International GNSS Service	RNP	Required Navigation Performance
IMO	International Maritime Organization	RPAS	Remotely Piloted Aircraft System
IMU	Inertial Measurement Unit	RTCA	Radio Technical Commission for Aeronautics
IoT	Internet of Things	RTCM	Radio Technical Commission Maritime
ISM	Integrity Support Message	RTK	Real Time Kinematic
ITS	Intelligent Transportation Systems	SAR	Search and Rescue
ITU	International Telecommunication Union	SARPS	Standard & Recommended Practices
JRC	Joint Research Centre	SAS	Signal Authentication Service
LBS	Location Based Service	SBAS	Satellite Based Augmentation Systems
LEO	Low-Earth Orbit	SDD	Service Definition Document
LIDAR	Light Detection and Ranging	SES	Single European Sky
MEO	Medium Earth Orbit	SESAR	Single European Sky ATM Research
MFMC	Multi-Frequency Multi-Constellation	SOG	Speed Over Ground
MOPS	Minimum Operational Performance Standard	SIS	Signal In Space
MSF	Maritime Safety Committee	SoL / SOL	Safety Of Life
MSI	Maritime Safety Information Service	SOLAS	Safety Of Life At Sea
NLOS	Non-line of Sight	SPP	Single Point Positioning
NMI	National metrology institute	SSR	State Space Representation
OS	Open Service	STL	Satellite Time and Location
OSNMA	Open Service Navigation Message Authentication	TEC	Total Electron Content
PBN	Performance Based Navigation	TOA	Time of Arrival
PNT	Position, Navigation, and Timing	TSI	Technical Specification for Interoperability
PPP	Precise Point Positioning	TTA	Time To Alarm
PRS	Public Regulated Service	TTFF	Time To First Fix
PVT	Position Velocity and Time	UAM	Urban Air Mobility
QZSS	Quasi Zenith Satellite System	UAS	Unmanned Aircraft System
RAIM	Receiver Autonomous Integrity Monitoring	UTC	Universal Coordinated Time
RF	Radio Frequency	VAL	Vertical Alert Limit
RFI	Radio Frequency Interference	VDES	VHF Data Exchange System
RIMS	Reference Integrity Monitoring Stations	WAAS	Wide Area Augmentation System
RLS	Return Link Service	WWRNS	World-Wide Radionavigation System