

Chapter 2

Overview of Galileo System

**Javier Pérez Bartolomé, Xavier Maufroid,
Ignacio Fernández Hernández, José A. López Salcedo
and Gonzalo Seco Granados**

Abstract This chapter provides an introduction to the Galileo program and architecture. It starts by presenting the program context, rationale and history, including the early definition phases and test beds and the GIOVE experimental satellites. It then presents an overview of the Galileo services. Later, an architectural overview is provided, including the Galileo segments: the Space Segment, the Ground Mission Segment, and the Ground Control Segment. The chapter also provides a description of Galileo's contribution to the Search And Rescue services through COSPAS/SARSAT, and finalizes with an overview of the user segment and highlighting interoperability and compatibility issues with other GNSS.

Galileo Program Context, History and Implementation Phases

Institutional Context of the Galileo Program

As the reader can imagine, the process of developing Galileo has not been easy. In exchange, the Galileo program is, apart from a satellite navigation system whose signals will be received worldwide, the evidence that different sovereign nations can collaborate for the benefit of the EU and the world. Galileo has pioneered the cooperation in EU space industries to develop a highly complex operational and globally distributed infrastructure.

The context of the European Union under which Galileo has been conceived and developed is a very important aspect that has driven the program significantly. Saying that Galileo has been developed by the twenty-seven Member States that

J.P. Bartolomé (✉) · X. Maufroid · I.F. Hernández
European Commission, DG Enterprise and Industry, Brussels, Belgium
e-mail: Javier.PEREZ-BARTOLOME@ec.europa.eu

J.A. López Salcedo · G.S. Granados
Universitat Autònoma de Barcelona, Barcelona, Spain

form the European Union would already be a simplification of the facts. Galileo is therefore different to any other system like GPS, GLONASS and Beidou, which are developed under a single nation (the United States of America, the Russian Federation and the People's Republic of China, respectively). Perhaps this does not represent a difference from the technical point of view or from a usage perspective, but it represents a big challenge for the program. The program management had to reconcile the views of many sovereign states, liaise with independent intergovernmental bodies, and deal with intricate decision processes.

The European Union is the main sponsor and the owner of Galileo, according to the current regulation (European Commission 2008). Whereas the program was financed jointly with ESA in the first stages, its full deployment has been financed with European Union budget funds. The European Commission, as the executive arm of the European Union, is the program manager. As any other undertakings of the European Union, the EU Member States are the ultimate stakeholders of the program and play a major role in the decision-making process. The European Commission reports to them regularly on the program developments through a dedicated forum called the GNSS Programmes Committee. Many European Member States also support the Galileo program through dedicated activities performed by their national space agencies, as the French Centre National d'Etudes Spatiales (CNES), the German Deutsches Zentrum für Luft-und Raumfahrt (DLR), the Italian Agenzia Spaziale Italiana (ASI) or the recently created National Space Agency in the UK, just to name some. Other national ministries, as the Transport or Defence ones, are also involved. More details about the EU functioning and its Member States can be found in European Commission (2007) .

The European Space Agency has the leading role in the technical direction of the program. After pioneering research in satellite navigation in Europe in the late 1990s and successfully demonstrating the program's technical feasibility over the first decade of the 21st century, ESA is currently responsible for the development, deployment, integration and operational validation of the Galileo system infrastructure.

As the European Commission's main activities are related to policymaking and EU budget administration, as part of its normal functioning it is assisted by Community Agencies which deal with more specific tasks. In case of the GNSS programs, the agency in charge of assisting the EC is the GSA (former GNSS Supervisory Authority, now European GNSS Agency). The role of the GSA and the EC have slightly evolved over the years, and at the time of writing the GSA is foreseen to be in charge of the Galileo service provision and exploitation, market development and security.

The Early Stages

In the early nineties, the European Union started to consider the development of its own satellite navigation system, first through the deployment of a regional infrastructure, called GNSS-1 at the time, and later by developing its own global system,

GNSS-2. A formal agreement was concluded on 18 June 1996 between the European Community, Eurocontrol and ESA for the development of GNSS-1, which would become European Geostationary Navigation Overlay Service (EGNOS), an SBAS or satellite-based augmentation system aimed at augmenting GPS to improve air navigation operations. GNSS-2 would later become Galileo. In 1995, at the time the GNSS-2 program was being outlined, GPS had just declared its Full Operational Capability, and the U.S. Government had already committed to provide the GPS signals to the civil user community (Kaplan and Hegarty 2006; Pace et al. 1995), although the selective availability, a functionality to intentionally degrade GPS position accuracy for unauthorized users, was still on. In this context, the European Commission's Communication "Towards a Trans-European Positioning and Navigation Network—including a European strategy for GNSS" (Kaplan and Hegarty 2006) issued in 1998 formally opened a serious debate for Europe to develop its own GNSS.

In 1999, the European Commission, with the support of the European Space Agency (ESA), prepared the Communication "Galileo—Involving Europe in a New Generation of Satellite Navigation services" (European Commission 1999) that was seminal to the GNSS program development in Europe. Three reasons for the EU to develop its own system were stated in this Communication:

- To increase control on satellite-based safety-critical navigation systems.
- To ensure a positioning service for European users in the long term, not subject to the risk of potential U.S. policy changes affecting GPS.
- To support EU industry competitiveness in the global market of satellite navigation and grant access to the system's technological developments.

The Communication presented the results of consultations with worldwide stakeholders to define how the EU satellite navigation system would look alike. Influenced by ESA GNSS-2 Comparative System Studies (ESA 1998) and EC GNSS-2 Forum (Fairbanks 1999), it proposed to develop a system very similar to GPS or GLONASS to minimize technical risk and provide the highest value for money. This included a signal structure compatible and interoperable with GPS as much as possible.

Once the political drive to build Galileo was clear, and its basic principles outlined, the EC and ESA embarked in the first studies to define the Galileo mission and system requirements that would ultimately determine the Galileo system and receiver technologies. The EC formed the Galileo Task Force (GTF) and launched the GALA project to define the future Galileo service levels and receiver functional concepts, and ESA launched the GalileoSat program to support the definition of ground and space infrastructure and study the signal design and transmission performance (Schweikert et al. 2000; De Gaudenzi et al. 2000).

In parallel, a considerable effort in international cooperation and research was carried out in the early 2000s to agree on the spectrum allocation, carrier frequencies selection, signal design, code selection and timing and geodetic references for Galileo, in order to make Galileo and GPS, the only operational system at the

time, as compatible and interoperable as possible. In the frame of the ONU International Telecommunications Union (ITU), these efforts eventually led to the allocation of the Galileo frequency plan in June 2000 by the World Radio Communications Conference held at Istanbul, granting protection until June 2006. Some years later, in 2004, the EU and the U.S. signed a Cooperation Agreement “On The Promotion, Provision And Use Of Galileo And GPS Satellite-Based Navigation Systems And Related Applications” (United States of America and European Community 2004) that set the framework to achieve full interoperability and radio frequency compatibility between both systems.

Galileo Early Technology Demonstrator

Several years of development and qualification of critical technologies have been necessary for the deployment of an operational system like Galileo. This is particularly true for the satellite on-board clocks. In the late 1990s, the European Space Agency started the development of the Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHMs) that would be integrated in the satellites and, in early 2000s, these two technologies were environmentally qualified on-ground.

Later on, ESA launched in 2002 the GSTB-V1 (Galileo System Test Bed 1) program aimed at developing an experimental ground mission segment for the validation of Galileo navigation and integrity determination algorithms and products based on raw GPS measurements collected by a global network of sensor stations.

In 2003, the European Space Agency began the development of two test satellites, GIOVE-A and GIOVE-B (Galileo In-Orbit Validation Element), as part of the GSTB-V2 (Galileo System Test Bed 2) program.

The GIOVE-A satellite was built by SSTL and launched in December 2005. The satellite launch mass was about 600 kg for a total power of 700 W. The satellite was designed to transmit simultaneously 2 out of the 3 frequencies allocated to Galileo and included 2 cold redundant RAFS with a stability of 10 ns per day. A major Galileo program milestone was achieved on the 12th January 2006, when GIOVE-A transmitted for the first time a Galileo-like signal in space (SIS) towards the Earth from orbit, several months in advance of the ITU filing protection expiration date.

The GIOVE-B satellite was built by a consortium led by Astrium GmbH and was launched in April 2008. The satellite launch mass was about 530 kg for a total power of 1100 W. The satellite included 1 PHM and 2 RAFS. It was also the first satellite to transmit the Multiplexed Binary Offset Carrier modulation (MBOC), the latest signal waveform agreed between the European Union and the United States.

Both satellites were initially designed for a lifetime of about 2 years but thanks to very good performances at the end of their lifetime, their missions were extended. GIOVE-A satellite lasted more than 6 years in-orbit before being finally decommissioned on 30 June 2012. GIOVE-B was decommissioned on 23 July 2012 (Fig. 2.1).



Fig. 2.1 GIOVE-A (*left*) and GIOVE-B (*right*), artist's impression, courtesy of ESA

Galileo Implementation Phases

During the early definition phase, a staggered approach was adopted for the development, deployment, integration and validation of the Galileo system infrastructure. Two major implementation phases were considered, namely:

1. The In-Orbit Validation phase (IOV),
whose main goal was the end-to-end validation of the Galileo service concept based on a mini constellation with four operational Galileo spacecraft and a limited ground system configuration.
2. The Full Operational Capability phase (FOC),
intended to complete the deployment of the Galileo constellation and ground infrastructure and achieve full operational validation and service performance.

More details on the satellites and ground infrastructure of Galileo IOV and FOC phases are provided in the following sections on the Galileo segments.

Galileo Services

Like other GNSS systems such as GPS or GLONASS, the Galileo navigation concept relies on the measurement of the time of arrival (TOA) of electromagnetic signals transmitted from Medium Earth Orbiting (MEO) satellites. As the signals are synchronously transmitted by the satellites, the minimum number of independent measurements (i.e. transmitters) required to compute a 3D position is four, to account for the three-dimensional position unknowns plus the unknown offset of the receiver clock, which is not supposed to be synchronized with the GNSS and affects all measurements equally.

In addition to the time of arrival of the synchronized signals, the receiver needs to know the position of the transmitters at the exact time the signals were

transmitted, in order to compute a position. More details on GNSS navigation principles and the related equations can be found in most satellite navigation references in the literature, such as (Kaplan and Hegarty 2006; Misra and Enge 2011 or Spilker and Parkinson 1996).

In order to maximize the potential user base and the potential benefits that Galileo could offer, Galileo has been developed to provide different services, all based on the TOA positioning method as described above, and some of them with additional features, such as signal encryption, digital signature authentication or search and rescue services. The Galileo services are briefly introduced hereafter:

- **Open Service:** The Open Service (OS) provides positioning and timing information worldwide through ranging signals and data broadcast by the Galileo constellation. The detailed definition of the Galileo OS signals is publicly available and can be found in European Union 2010. The OS will be accessible free of charge by any user equipped with a Galileo compatible navigation receiver. It will be provided in the E1 and E5 bands, and it will be comparable to the service offered by GPS open civil signals L1C/A, L2C or L5.
- **Public Regulated Service:** The Public Regulated Service (PRS) provides positioning and timing information worldwide through ranging signals and PRS data broadcast by the Galileo constellation. The access to the PRS will be restricted to government-authorised users, for sensitive applications. The control access policy is implemented through the encryption of the PRS signals and the management of decryption keys. The PRS will only be accessible through receivers equipped with a PRS security module loaded with a valid PRS decryption key. It will be provided in the E1 and E6 bands and will be similar to the services offered in the L1 and L2 through the P(Y) and L2M signals by GPS.
- **Commercial Service:** The Commercial Service (CS) is intended to provide ‘added value’ data with respect to the Open Service. At the time this chapter is being written, the Commercial Service is still under definition. However, it is already foreseen that these ‘added-value’ services are related to high accuracy and authentication (Fernandez et al. 2014). One of the main features the CS will bring, with respect to other GNSS, is the capability to broadcast globally external data in real time. It will be provided in the E6 band.
- **Search and Rescue Service:** The Search And Rescue (SAR) service is intended to support the Cospas-Sarsat Program in search-and-rescue operations. Due to its particularities, more details about this service are given in the following sections.

In addition to the above, the Galileo program foresaw a **Safety-Of-Life (SOL) service**, which included the provision of worldwide system integrity. The implementation of this service has been postponed until later phases of the program, and will rely on the reuse of regional solutions and a collaborative approach with other global constellation providers. Another chapter in this book explains in more detail the Galileo Integrity Concept behind the SOL service, as it was initially conceived.

The Galileo signals will be described in Chap. 3 of the book. The Galileo signals include all advanced features that are considered in modern GNSS such as transmission at several frequencies, secondary codes and pilot components, and usage of

higher power levels, larger bandwidths and error correction codes. Other features include higher chip rates, longer pseudo-noise codes and Binary Offset Carrier (BOC) modulations and variants thereof. All these aspects and their implications will be reviewed in a subsequent chapter.

Galileo Architecture Overview

The provision of the Galileo signals and services relies on the continuous and coordinated operation of a network of specialized system facilities covering different functional needs. Figure 2.2 presents the most relevant elements of the Galileo system infrastructure in an end-to-end service context.

These facilities can be grouped into three main categories: the Galileo Core Infrastructure, the Galileo Service Facilities and the Galileo Support Facilities.

The **Galileo Core Infrastructure** (CI) comprises a Medium Earth Orbit (MEO) satellite constellation continuously transmitting Galileo Signal-in-Space (SIS), i.e. the Galileo Space Segment, and a global ground system infrastructure providing all the functionality required to sustain the provision of Galileo navigation services in an independent manner.

The Galileo CI ground infrastructure comprises two main subsystems or segments, the Galileo Ground Control Segment (GCS) and the Galileo Ground Mission

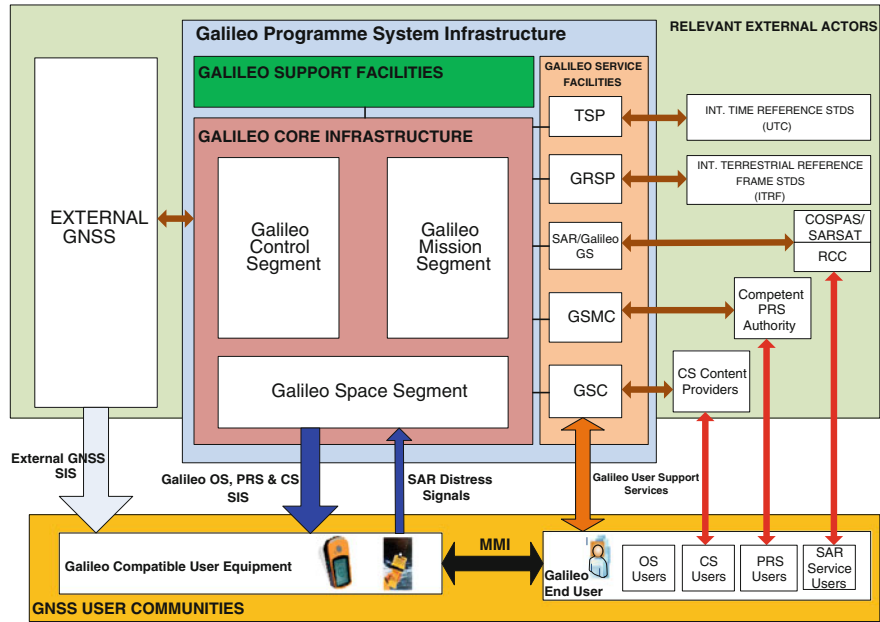


Fig. 2.2 Galileo architectural overview

Segment (GMS). While the GCS provides the Galileo constellation monitoring and control functions, the GMS supports the generation and distribution/uplink of navigation products and other mission data required for the onboard generation of the navigation messages modulated on some of the Galileo SIS components.

The operations of the Galileo CI are centrally managed from two fully redundant Ground Control Centres (GCC) located in Oberpfaffenhofen (Germany) and in Fucino (Italy) respectively.

The principal service offered by Galileo to the end users is the Galileo SIS, which can be processed by Galileo compatible receiver equipment for accurate positioning and time determination in the Galileo terrestrial reference frame (GTRF) and Galileo System Time (GST) scale respectively. Two **Galileo Service Facilities**, the so called Geodetic Reference Service Provider and Time Service Provider, monitor the alignment of GTRF and GST with the international metrological standards (ITRF and UTC) and provide the Galileo CI steering corrections to ensure a very high level of consistency between reference systems.

Further to the GTRF and the TSP, there are other Galileo Service Facilities to provide Galileo-related services to the wide public and to specific user communities. They are the GNSS Service Centre (GSC), the Galileo Security Monitoring Centre (GSMC) and the SAR Galileo Ground Segment.

The **Galileo Support Facilities** is a further category of facilities not directly involved in the routine provision of services but playing an essential role in the deployment, commissioning and maintenance of Galileo. These include among others two external satellite control centres supporting the Launch and Early Operations Phase (LEOP) of each Galileo spacecraft and a ground In Orbit Test (IOT) station for satellite commissioning operations.

The Galileo end users are represented at the bottom of the Fig. 2.2. Although not explicitly indicated, most Galileo users will have multi GNSS interoperable receivers able to track signals from other navigation systems such as GPS. Figure 2.2 indicates as well the main links between the Galileo system facilities, the Galileo service end users and other actors outside the Galileo system perimeter.

The following sections provide a more detailed description of the Galileo Space Segment, Ground Mission Segment and Ground Control Segment.

Galileo Space Segment

Galileo Satellite Constellation

At the time of writing, the Galileo reference constellation or constellation standard foresees 24 nominal orbital positions or operational slots in Medium Earth Orbit (MEO) homogeneously distributed in three orbital planes (i.e. 8 slots equally spaced per plane). At the end of the FOC phase all the orbital positions defined in the constellation standard will be populated with operational Galileo satellites. Besides the core reference constellation, additional satellites will be deployed on

each orbital plane in order to ensure the maintenance of the Galileo services upon satellite outages. At present, there are not reference orbital positions defined for these in-orbit spare satellites.

It shall be noted that the Galileo constellation standard has experienced some changes since the Galileo early definition phase. During the constellation design trade-offs analysis, the number of satellites in the core constellation was essentially driven by the Safety of Life (SoL) service of Galileo, initially defined as global integrity service with demanding requirement in terms of time-to-alert, availability and continuity. In order to meet the stringent SoL service requirements, the initial Galileo reference constellation was based on 27 orbital positions (Walker 27/3/1).

Following the program decisions in 2012 to re-profile the SoL service, the impact on the constellation design has been reassessed and several analyses have shown that a reduced constellation with 24 operational satellites deployed in Walker 24/3/1 configuration can meet the Galileo services requirements in terms of accuracy and availability.

The nominal trajectory followed by the operational Galileo satellites is a circular orbit with a radius of approximately 29,600 km (equivalent to 23,229 km altitude over the Earth surface) and an orbital period of approximately 14 h. This choice ensures a satellite ground-track repeat cycle every 17 orbits (or 10 days) (Fig. 2.3).

The main orbital parameters of the reference Galileo constellation are summarized below:

- Semimajor axis: 29,600 km
- Eccentricity: 0.0001 (i.e. circular orbit)
- Inclination 56°
- Argument of perigee: $\pm 180^\circ$ (i.e. not defined for circular orbits)
- RAAN: 0° , 120° and 240°

Fig. 2.3 Galileo reference constellation representation—24 operational satellites (courtesy of EC)

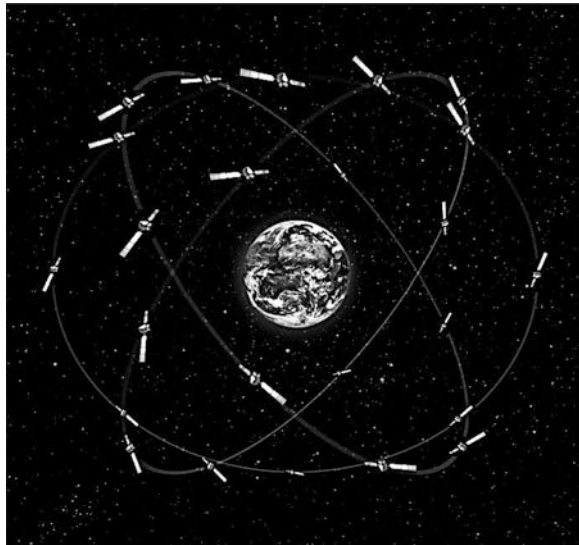


Table 2.1 Galileo satellite position on May 1st, 2013, 00:00:00 UTC

S/C	Position		Semi-major axis km	Eccentricity	Inclination deg	RAAN deg	Arg. perigee deg	True anomaly deg
	Plane	Slot						
GSAT0101	B	5	29599.8	0.0001	56.0	113.6	0.0	295.9
GSAT0102	B	6	29599.8	0.0001	56.0	113.6	0.0	335.9
GSAT0103	C	4	29599.8	0.0001	56.0	233.6	0.0	269.2
GSAT0104	C	5	29599.8	0.0001	56.0	233.6	0.0	309.2

Source European GNSS Service Centre website—www.gsc-europa.eu

More specifically, the satellites are positioned in a Walker 24/3/1 configuration, which means that satellites in each plane are equally spaced by 45° and satellites in adjacent planes are phased by 15° between each other. The satellite plane inclination for Galileo is 56° .

The Right Ascension of the Ascending Node (RAAN) defines the relative angular phasing between the constellation orbital planes and the vernal equinox. The True Anomaly indicates the angular position of each satellite within a given orbital plane.

The first Galileo operational satellites, resulting from the Galileo IOV phase, were launched respectively on 21st October 2011 (IOV PFM and FM2) and on the 12th October 2012 (FM3 and FM4). Their nominal position can be represented by the following orbital elements (Table 2.1) for the reference time 1 May 2013 at 00:00:00 UTC (note that the difference in the argument of perigee between 180° and 0° is irrelevant as the orbits are almost circular). It must be noted that the orbital positions assigned to these first 4 IOV Galileo satellites correspond to the former Walker 27/3/1 reference constellation geometry.

The coordinate reference frame used is the Celestial Intermediate Reference System CIRS (McCarthy and Petit 2003) (true equator). In order to represent the RAAN precession, the RAAN has to be modified at a rate of $-0.027644^\circ/\text{day}$ while the True Anomaly evolves at a rate of around $613.7^\circ/\text{day}$, equivalent to 1.7 revolutions per day, or 17 in 10 days, as mentioned above.

Galileo Satellites

At the time of writing, the four Galileo IOV operational satellites launched from Kourou (French Guyana) and Soyuz launchers and manufactured by ASTRI-UM GmbH (now renamed Airbus Defense and Space) have been deployed in their nominal orbits, as mentioned above. The other 22 additional Galileo operational satellites are being manufactured by OHB-System AG as part of the Galileo FOC phase and will be launched with Soyuz and Ariane 5 launchers from Kourou as well.

Table 2.2 Evolution of galileo satellites from GIOVE-A to Galileo FOC

Parameter	GIOVE-A	GIOVE-B	IOV (PFM-FM4)	FOC (FM5-FM26)
Launch mass	600 kg	530 kg	730 kg	732.8 kg
Total power	700 W	1100 W	1980 W	1900 W
Size	$1.3 \times 1.8 \times 1.65$ m	$0.95 \times 0.95 \times 2.4$ m	$2.7 \times 1.2 \times 1.1$ m	$2.5 \times 1.2 \times 1.1$ m
Design lifetime	27 months	27 months	12 years	12 years
Launch dates	28 Dec 2005 (decommissioned)	26 Apr 2008 (decommissioned)	PFM/FM2: 21 October 2011	FM5/FM6: Q3 2014 (scheduled)
	5 Jun 2012)	23 Jul 2012)	FM3/FM4: 12 October 2012	1 launch every 3/4 months (plan)

The remaining constellation satellites as well as replenishment satellites will be ordered in 2015 and are expected to be available in the 2018–2019 timeframe.

The Galileo IOV satellites perform essentially the same functions as the FOC satellites and their respective designs share a number of common elements dealing with mission critical technologies (e.g. atomic frequency standards, navigation signal generators, or mission data receivers). However, the transition from IOV to FOC has also been used to improve the signal performances in terms of effective radiated power and bandwidth, leading to a change of technology in some units, in particular the high power amplifiers. The satellite description presented in the following sections is based on the Galileo FOC satellites, which will constitute the main part of the Galileo constellation when fully deployed (Table 2.2).

The Galileo satellite in flight configuration and its high-level decomposition block diagram is shown on Fig. 2.4. The Galileo satellites are made of two main components: the platform and the payload, which are further decomposed into modules as shown in the figure. The first four Galileo satellites (called IOV satellites) exhibit some small differences with regards to the Galileo FOC satellites but are very similar in terms of functionalities, overall budget envelope and performances.

The Galileo satellites are designed to be launched in dual launch configuration on Soyuz and in a quadruple launch configuration on Ariane 5. The satellites are directly injected by the launcher into their final orbit and as a result the propulsion capabilities of the satellites can be limited to small out-of-plane orbital corrections, in-plane slot adjustment for constellation spare relocation strategy and graveyarding operations at spacecraft's end of life.

In addition to the main navigation and SAR payloads, the Galileo satellite design includes also the following secondary payloads:

- The Laser Retro-Reflector Array (LRA), a passive instrument that allows Galileo satellites to be tracked by Satellite Laser Ranging (SLR) stations on the ground.
- The Environmental Monitoring Unit (EMU) whose main purpose is to measure the number of heavy ion and the electric charges in the MEO orbit over the whole 11-year solar cycle.

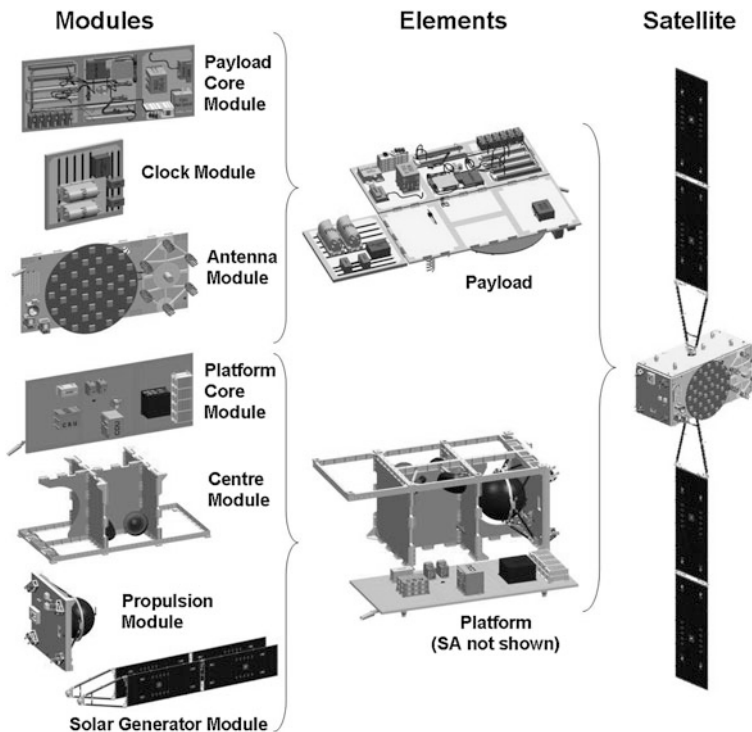


Fig. 2.4 Galileo satellite flight configuration (courtesy of OHB)

Galileo Ground Mission Segment

The main roles of the Galileo Ground Mission Segment (GMS) are the generation of the Galileo C-Band uplink signals including the data required in the Galileo navigation downlink signals and the online monitoring of the downlink navigation signals in closed-loop.

The main GMS functional chains are the *mission data generation chain*, responsible for the generation of the OS and PRS navigation products, and the *mission data distribution chain* responsible for the timely distribution of the navigation products to the Galileo satellites. Moreover, the GMS interfaces with the Galileo Service Facilities briefly introduced previously in this Chapter and it also exchanges mission data required to deliver the Galileo services.

More specifically, the GMS is responsible for the following main functions:

- Generation and distribution of Galileo System Time (GST) to all elements within the Galileo Core Infrastructure perimeter, including the satellites, and support the overall system time steering.
- Generation and distribution to Galileo spacecrafts of mission products for generation of Galileo OS and PRS navigation messages.

- Distribution to Galileo spacecrafts of mission data forwarded by Galileo Service Facilities supporting provision of Galileo CS and SAR services.
- Provision of the physical interface for the exchange of data products with Galileo Service Facilities to support smooth provision of Galileo services.
- Provision of the physical interface for the exchange of data products with the US Naval Observatory (USNO) for coordinating the generation of GPS Galileo interoperability mission products defined in the OS navigation message (i.e. GPS To Galileo Time Offset)
- Galileo mission monitoring and control and archiving

Besides the main service related functions listed above, the GMS supports other internal support functions related to the management and operations of the ground infrastructure. The coordination of the system operations both in ground and in orbit is paramount to ensure the continuity of the Galileo services. In order to support this coordination as efficiently as possible, the GMS design includes physical interfaces with the Galileo Ground Control Segment (GCS) at each Galileo Control Centre.

GMS Architecture

The GMS comprises a worldwide network of facilities that include the following three types of ground elements:

1. Ground Sensor Stations (GSS)
2. Mission Ground Control Centres (GCC)
3. Mission Up-link Local Station (ULS),

A dedicated low latency global telecommunication network ensures the permanent connectivity of the remote sites (i.e. GSSs and ULSs) with the mission ground control center for the routing of mission data and system monitoring and control signals.

Figure 2.5 shows the geographical location of the GMS facilities already deployed or under procurement. It shows also the GCS facilities that are described later in the chapter.

The Ground Sensor Stations

The GSS is an unmanned GMS facility whose main role is the collection of L-Band sensor data from all Galileo satellites in view in all frequencies and forward those data to the GCC for navigation processing and mission monitoring. It is essentially a high-quality Galileo receiver with some additional elements. The collected sensor data includes carrier phase and code phase measurements based on the processing of the pilot components, navigation message symbols demodulated from the data components and some signal quality indicators. The GSS can support SIS measurement rates up to 1 Hz (one measurement every second) in order to ensure continuous SIS monitoring and, in case of anomaly, reduce the notification time to Galileo users.



Fig. 2.5 Galileo GMS and GCS sites

The GSS are equipped with rubidium atomic frequency standards and high performance Galileo receivers, which are the core equipment of the Galileo Receiver Chain (GRC). The GSS design allows hosting two GRC types, the first one supporting the GMS PRS mission data generation chain and the second one supporting the OS and CS mission data generation chains. In addition, each GSS is equipped with Dual-Frequency COTS GPS receivers to support site synchronization with Galileo System Time and realization of the Galileo Terrestrial Reference Frame during the early system operations phase until the number of Galileo satellites deployed ensures the system standalone synchronization worldwide.

The Mission Ground Control Centres

The GMS operations are managed from two fully redundant Galileo Ground Control Centres located in Oberpfaffenhofen (Germany) and Fucino (Italy).

The GCCs centralise several GMS key functions critical for the provision of the Galileo services such as GST generation, navigation data generation and distribution, management of the Galileo system interfaces with external entities, and mission monitoring and control. Outside the perimeter of the GMS, the GCCs play also a central role in the monitoring and control operations of the Galileo satellite constellation, as explained later in the section devoted to the Ground Control Segment (GCS).

The Mission Up-Link Local Stations

The continuous routing of Galileo ground mission data from the GCC to each operational spacecraft is required for the onboard generation of Galileo Signal In Space with meaningful service information (i.e. navigation messages). The ULSs are unmanned facilities which realize the physical ground to space interface supporting the mission data distribution functional chain.

Each operational ULS receives mission data from the GCC for uploading to the Galileo constellation according to a satellite contact plan received also from the GCC. In order to perform this function, each ULS can host up to four dish steerable antennas of 3.5-m diameter to upload mission data in the C-Band part of the RF spectrum (around 5 GHz). Each ULS antenna can track a single Galileo spacecraft at a time.

The accuracy of the Galileo Positioning Velocity Timing (PVT) services depends directly on the accuracy of the mission data uploaded to the Galileo satellites. It shall be noted that a part of the mission data are predictions based on dynamic or empirical models and therefore their accuracy degrades rapidly with time (“ageing” effect). This applies in particular to the satellite GST clock offset prediction broadcast model. In order to meet the minimum Galileo PVT accuracy performance requirements continuously worldwide, it is essential that the design of the ULS network allows for refreshing the satellite onboard mission information of the whole constellation at the required latency on a continuous basis. When the Galileo ULS network is fully deployed, the maximum time between navigation data uploads to any Galileo spacecraft should not exceed 100 min under nominal operational conditions.

Galileo Ground Control Segment

The Galileo GCS is responsible for the management of the Galileo constellation during the normal operation of the system. For achieving this goal, the GCS can exchange monitoring and control signals with individual Galileo spacecraft at scheduled contacts. Further to the monitoring and control data, the GCS can also upload Galileo mission data through the telecommand uplink channel to ensure the continuity of Galileo navigation services under degraded GMS operation modes.

GCS Architecture

The GCS elements are located worldwide and comprise two main facility types:

1. Constellation Galileo Control Centres (GCC)
2. Telemetry, Tracking and Commanding (TT&C) Stations

The Constellation Ground Control Centres

The GCCs host all centralised functions of the GCS, including spacecraft Constellation Monitoring & Control, spacecraft Constellation Planning, Flight Dynamics and Operations Preparation. The GCC implements as well the GCS network interface with external Galileo entities involved in the system operations such as the External Satellite Control Centers (ESCCs) and the In Orbit Test (IOT) station located at Redu, Belgium.

The Telemetry, Tracking and Commanding Facility

The GCS architecture comprises a worldwide network of Telemetry, Tracking and Control ground stations or facilities connected to the Galileo Control Centres. At the time of writing the Telemetry, Tracking and Commanding Facility (TTCF) network includes stations in 5 locations. Additional stations might be added to the TTCF network in the future.

Each TTCF supports telemetry (TM) downlink, telecommand (TC) uplink and can also support collection of satellite tracking data for the management of the constellation. The transmitted TC signal data, and received TM data, together with the TT&C monitoring and control data is exchanged between the TT&C stations and the GCC via a dedicated communication network. Under nominal operations conditions, the TTCFs are autonomous and manned intervention is only required for the purpose of either anomaly investigation or maintenance purposes.

In routine operations, the TT&C stations are utilised to upload TCs to and to receive TM from the Galileo spacecraft through an RF data channel. Besides supporting routine satellite housekeeping tasks, the TTCFs have also the capability to collect satellite tracking data (i.e. two-way ranging measurements) intended for off-line satellite orbit determination under special spacecraft operation scenarios.

The link between the TTCF ground station and the Galileo satellites is established through a 11 m dish antenna. The TT&C facility operates over specifically allocated S-Band RF ranges, between 2 and 2.2 GHz approximately (Fig. 2.6).

Cospas-Sarsat and Galileo

The LEOSAR system developed by the International Cospas-Sarsat Program currently provides accurate and reliable distress alert and location data to help search and rescue (SAR) authorities to assist persons in distress. In 2000, consultations started between the Cospas-Sarsat Program and the European Commission on the feasibility to install 406 MHz SAR instruments on the Medium Orbit navigation satellites systems in order to develop a 406 MHz MEOSAR component to the Cospas-Sarsat system. The main benefits of the MEOSAR system will be the near instantaneous global coverage with accurate independent location capability

Fig. 2.6 TTCF S-band 11 m dish antenna (courtesy of ESA)



(in opposition with the current LEO system which has a higher latency to provide location information). The USA MEOSAR program based on GPSIII is called the Distress Alerting Satellite System, (DASS), the European System based on Galileo is called SAR/Galileo, and the Russian program based on GLONASS is referred to as SAR/GLONASS. This has a direct impact on the probability of survival of the person in distress at sea or on land.

The Galileo Program involvement into Cospas-Sarsat goes beyond the space component of the MEOSAR system. Indeed, the European Union has deployed a significant Ground Segment infrastructure, which provides localization services for distress alerts transmitted by SAR beacons over a wide area comprising continental Europe, and vast oceanic areas around the continent (see Fig. 2.7 below). The SAR/Galileo Ground Segment can receive and process SAR distress signals relayed by any operational Galileo spacecraft or other satellite of the COSPAS/SARSAT MEOSAR constellation and determine thereby the location of the beacon within the coverage area.

The ground segment of the Search and Rescue Service of Galileo consists of 3 receiving ground stations, called Medium Earth Orbit Local User Terminal (MEOLUTs), which receive the distress signals relayed by the Galileo Search and Rescue repeater in the 1544 MHz band. Each MEOLUT includes a minimum of 4 antennas tracking different Galileo satellites.

Receiving the signal relayed from four different satellites makes it possible to determine the distressed beacon position by triangulation using Time of Arrival (TOA) and Frequency of Arrival (FOA) techniques. The MEOLUT then decodes the distress signal message, determines the beacon localization and provides this information to the Cospas-Sarsat Mission Control Center (MCCs).

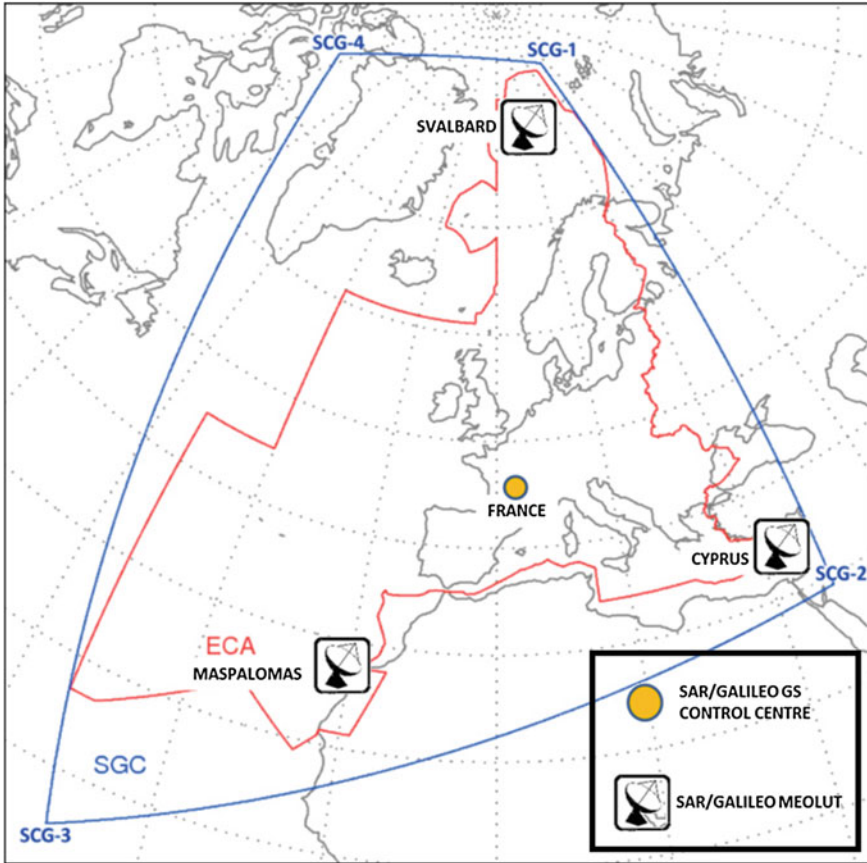


Fig. 2.7 SAR/Galileo European coverage area and ground facilities

The 3 European MEOLUTs are located in Svalbard (Norway), Makarios (Cyprus) and Maspalomas (Spain) and provide the SAR/Galileo service over the European Coverage Area (ECA) as shown in Fig. 2.7. Each MEOLUT is connected to a central facility, the MEOLUT Tracking Coordination Facility (MTCF) located at the SAR/Galileo control centre in Toulouse, (France) and which optimizes the MEOLUT tracking plan of the 3 European MEOLUT in order to achieve the best location accuracy and availability over the European Coverage Area.

As a component of the Cospas-Sarsat MEOSAR system (Cospas-Sarsat 2012), the SAR/Galileo ground segment is also capable of receiving the distress signal relayed by the MEOSAR payloads embarked on the Glonass and GPS satellites (SAR/Glonass and GPS/DASS payloads).

The performances achieved by the SAR/Galileo Service when the full Galileo constellation is operational are indicated in Table 2.3

The SAR/Galileo ground segment also includes the Return Link Service Provider (RLSP), which is responsible for providing Return Link Acknowledgment

Table 2.3 SAR/Galileo service performance recorded at ground segment

Performance parameter	Value
Detection probability	99.5 %
Localization probability	98.0 %
Localization accuracy	<5 km (2σ) within 10 min
Worst case service availability	95.0%

Messages to the COSPAS-SARSAT distress beacons equipped with a Galileo receiver. The Return Link Messages are embedded within the navigation message of the E1 signal.

Galileo User Segment

Definition

The Galileo user segment (GUS) is the third and largest segment that forms the Galileo system. Contrary to the other two segments, namely, the Galileo space segment and the Galileo ground segment, the GUS is certainly the one with the closest connection to the end user. In particular, the GUS is targeted at providing the means for allowing end users to fully exploit all the capabilities of signals being transmitted by the Galileo satellites. It is therefore, the segment encompassing user applications and services, as well as user receiver technologies.

Galileo Receivers, the Key to Galileo Success

The Galileo user receiver is the key technological equipment for translating the Galileo signals received from space into practical applications and services. The goal of Galileo receivers, as it happens with many other GNSS receivers, is to provide the end user with an accurate estimate of its current position and time. This is typically achieved in three steps:

1. The signals from space impinging on the user's receiver antenna are amplified and filtered by the receiver RF front-end in order to compensate for the huge propagation losses undergone in their way from the satellites to the Earth. This signal conditioning is typically followed by an analog-to-digital conversion, which allows processing the received signal in a reliable manner by means of digital signal processing (DSP) techniques.
2. The user receiver generates a local replica of the Galileo signal of interest, which is gradually aligned to the actual signal received from space. As a result of this alignment process, the receiver is able to coarsely determine the actual time-delay and carrier parameters of the received signal (i.e. this is the so-called

“acquisition” stage). Later on, these parameters are further refined and monitored as a function of time (i.e. the so-called “tracking” stage).

3. Once the receiver is precisely synchronized to the actual received signal, and more than four satellites are in view, the refined and accurate signal parameters are used to solve the navigation equations, which lead to the user position, velocity and time information (i.e. the so-called “navigation” or “PVT” solution).

The above three steps are rather standard in most GNSS receivers, but for the particular case of a Galileo receiver, the key point is being able to fully exploit the specific features that Galileo signals bring to end users:

From a physical-layer perspective, this involves receivers taking advantage of the Binary-Offset Carrier (BOC) modulation format adopted in Galileo signals. Due to this format, which can be understood as a one-bit quantization of a sinusoidal signal, and for a given total bandwidth, it is possible to achieve a larger mean square bandwidth (also known as Gabor bandwidth) than with a traditional binary phase shift keying (BPSK) modulated signal. This involves that Galileo receivers may provide an improved accuracy in the determination of the user position, particularly when compared to traditional mass-market receivers that make use of the traditional BPSK-modulated GPS C/A signal.

From a frequency planning perspective, this involves paving the way for the development of multi-frequency receivers, which take advantage of processing different frequency bands with the goal of providing additional diversity and compensating ionospheric effects. These bands correspond to the E1 band compatible with current GPS mass-market receivers and centered at 1.575,42 MHz; the E6 band, centered at 1.278,75 MHz; and the E5 band, which is further split into two adjacent bands, namely the E5a and E5b bands, with center frequencies at 1.176.45 and 1.207,14 MHz, respectively. The availability of these frequency bands is certainly a key feature to be exploited by advanced Galileo receivers. Moreover, the coexistence with GPS within the E1 band opens the door for the use of the so-called multi-constellation GNSS receivers, capable of processing both GPS and Galileo signals with the same front-end, and thus solving the problems of limited visibility of satellites that are suffered in certain working scenarios (e.g. in urban canyons).

From a data perspective, Galileo signals allow the emergence of a myriad of new applications and services due to the definition of different types of data channels, such as the case of open and publicly available data channels, authenticated data channel and even possibly encrypted data channels.

Paving the Way Forward for Galileo User Receivers

The development and widespread deployment of Galileo receivers is certainly the necessary piece to guarantee the success of Galileo. In that sense, the validation of the above-mentioned Galileo features, and their proof-of-concept, has been undertaken in the framework of several R + D initiatives carried out in the recent years.

Most of these efforts have been supported by public funding, either through the 6th and 7th Framework Programs funded by the European Commission, through research projects funded by the European Space Agency (ESA), or through different initiatives funded by national authorities. The goal of all these efforts has been to foster the development of Galileo user receiver technologies and to achieve the deepest and broadest development of Galileo applications. This is particularly important when taking into account the wide range of fields and applications where the potential benefits of Galileo have already been recognized. They span across several domains such as location-based services (LBS) powered by smartphones or portable devices, road and maritime transportation, aviation, precision agriculture, safety or environment protection, just to mention a few. In general terms, GNSS positioning and timing information is expected to have a critical impact in economic terms of more than 6 % of the whole GDP of the European Union (European Commission 2010).

From this perspective, it becomes clear that the expected economical impact of Galileo in a commercially competitive environment is certainly one of the main differences with respect to previous GNSS systems. GPS and GLONASS were mainly developed for military applications with military funding, without a pre-determined mass-market orientation, although in the end GPS in particular has had a huge commercial impact. This is inline with the fact that barely 10 % of the US total public spending in R + D has a market or application-driven orientation, whereas for the EU, this amount exceeds 40 % (Fernández-Hernández 2011). This example shows the actual importance of the GUS, and the determined efforts that are being taken in order to make it successful. With Galileo receivers at the forefront of the GUS, most of these efforts have concentrated on the development of Galileo user receivers and technologies. This is the case of the three calls (in 2002, 2003 and 2005) launched by the former Galileo Joint Undertaking (GJU) under the Galileo work program, where nearly 90MEur were dedicated to promote the development of Galileo receiver technologies, applications as well as the standardization of different aspects of Galileo and its mission implementation.

One of the key initiatives being funded under the first GJU call was the “Galileo receiver development activities” (GARDA) project, whose goal was to develop a Galileo receiver analysis and design application (GRANADA) in order to serve as a test-bench for integration and evaluation of technologies, on one side, and as a software receiver tool for Galileo application developers, on the other side (Marradi et al. 2006). The validation of this software tool was carried out by the development of a Galileo simulator according to the Galileo signal-in-space (SIS) interface control document (ICD) available at that time. For the subsequent calls, GJU funding on the GUS targeted the introduction of mass-market Galileo receivers, such as in the GAMMA project (Abwerzger et al. 2006) (which was followed by the GAMMA-A project), where low-cost and low-power receiver solutions were developed for specific market applications. Two main applications were identified: location-based services (LBS) and the automotive area, with the latter involving route guidance, fleet management or road tolling. Complementarily, the GRAIL project focused on the development of Galileo receivers for rail applications, where

the emphasis was placed on safety-critical applications related to the European Train Control System (ETCS) (Albanese et al. 2006). Finally, the HIMALAYA activity focused on the design and development of a “ready-to-market” single chip GNSS mass-market receiver for GPS, EGNOS and GALILEO signals. Many other projects have been funded in the last years, and being exhaustive exceeds the goals of this introductory chapter.

Security, environment protection and SoL applications are also key research lines where efforts are being devoted for the development of advanced Galileo receivers. Integrity (not necessarily provided by the system, but by the receiver) is currently emerging as a critical requirement for high-end Galileo receivers, due to the increasing concerns on potential threats to GNSS users caused by the presence of interference, spoofing and other disturbing effects (e.g. multipath, non-line-of-sight). The study of this problem is indeed the goal of the iGNSSrx project funded by the European Commission and initiated in 2012, whose objective is to improve positioning services to terrestrial users by developing user receiver technologies for integrity monitoring, at signal and observable level.

Finally, the integration of Galileo receivers with external technologies is also one of the main topics that are expected to pave the way for the success of Galileo receivers. Such integration can be used to further improve the overall performance of Galileo, particularly in the presence of harsh working scenarios with signal blockages and limited sky visibility. For instance, the work carried out within the IADIRA project has focused on the tight integration of Galileo with external information coming from inertial sensors (INS) (Silva et al. 2006). A step forward was addressed in the DINGPOS project funded by ESA, where apart from the use of INS, wireless communication technologies such as WiFi were also considered for developing a fully integrated platform capable to provide seamless location in indoor environments (López-Salcedo et al. 2008). Indeed, the advent of new applications and services are gradually pushing the use of GNSS in working conditions different from the ones for which the system was designed to operate (Seco-Granados et al. 2012). This is the case of LBS in handheld devices (e.g. location-aware marketing), social networking applications, indoor navigation, etc. In that sense, the integration of the GUS with communication technologies (e.g. WLAN or cellular networks such as Long Term Evolution—LTE Del Peral-Rosado et al. 2012) is certainly one of the most promising future research lines for which significant efforts will be devoted in the coming years.

Galileo Interoperability and Compatibility

While the independence of systems may be a way to promote competition among systems and could virtually provide greater reliability and integrity, the advantages of interoperability and compatibility are widely recognized by all actors. An early (February 1999) Communication of the European Commission (EC) stated: “Galileo must be an open, global system, fully compatible to GPS, but independent

of it...” Later on, the EU-US Agreement on the Promotion, Provision and Use of Galileo and GPS Satellite-Based Navigation Systems and Related Applications signed June 26, 2004, in Dublin, Ireland, set up the models and methodology for the radio frequency compatibility of satellite navigation systems, in particular between GPS and Galileo. Further, Global and regional system providers at the third meeting of the Providers’ Forum of the International Committee on Global Navigation Satellite Systems (ICG) in 2008 agreed that at a minimum, all global navigation satellite systems (GNSS) signals and services must be compatible. To the maximum extent possible, open signals and services should also be interoperable, in order to maximize benefit to all GNSS users. For many applications, common carrier frequencies are essential to interoperability and commonality of other signal characteristics is desirable. In some cases, carrier frequency diversity may be preferable to improve performance. The definitions of *compatibility* and *interoperability* according to the ICG are as follows (International Committee on Global Navigation Satellite Systems 2008).

Interoperability refers to the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system:

- i. Interoperability allows navigation with signals from different systems with minimal additional receiver cost or complexity;
- ii. Multiple constellations broadcasting interoperable open signals will result in improved observed geometry, increasing end-user accuracy everywhere and improving service availability in environments where satellite visibility is often obscured;
- iii. Geodetic reference frames realization and system time steering standards should adhere to existing international standards to the maximum extent practical;
- iv. Any additional solutions to improve interoperability should be encouraged.

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

- i. The International Telecommunication Union provides a framework for discussions on radiofrequency compatibility. Radiofrequency compatibility should involve thorough consideration of detailed technical factors, including effects on receiver noise floor and cross-correlation between interfering and desired signals;
- ii. Compatibility should also respect spectral separation between each system’s authorized service signals and other systems’ signals. Recognizing that some signal overlap may be unavoidable, discussions among providers concerned will establish the framework for determining a mutually acceptable solution;
- iii. Any additional solutions to improve compatibility should be encouraged.

In the particular case of Galileo, the application of the interoperability principle with GPS was guided by the following considerations (Hein 2006).

- **Signals-in-Space.** The driver was the selection of common center frequencies (at least for some signals such as L1/E1 and L5/E5a) since this aspect has a clear impact of the cost of multi-frequency receivers and it is necessary to make combined processing of phase observation possible. The choice of CDMA instead of FDMA was also a definite step in favor of the interoperability between Galileo and GPS. GLONASS, which uses FDMA, can be considered to be “system interoperable” but not “signal interoperable” with Galileo. Although the use of the same modulations, data messages, etc. is not considered as an essential feature to facilitate interoperability because digital receivers can easily encompass a variety of formats, the military GPS-M code and the Galileo Public Regulated Service (PRS) have signal interoperability on L1 band.
- **Coordinate Reference Frame.** Although the Galileo Terrestrial Reference Frame (GTRF) is different to the GPS coordinate reference frame (WGS84), both of them differ less than very few centimeters with respect to the International Terrestrial Reference Frame (ITRF), hence guaranteeing interoperability for most applications.
- **Time Reference.** Galileo System Time (GST) as well as GPS Time are different real-time realizations of UTC (Universal Time Coordinated)/TAI (Atomic Time), which is the international civilian time standard. Both times are expected to be within the nanoseconds order of magnitude. The service providers have agreed to broadcast the GPS/Galileo time offset, and alternatively the offset can be determined in a combined receiver with very high accuracy at the very small cost of using one satellite observation.

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