Galileo

9. Galileo

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The European global navigation satellite system Galileo is designed as a self-standing satellite-based positioning system for worldwide service. It is independent from other systems with respect to satellite constellation, ground segment, and operation. Galileo is prepared to be compatible and interoperable with other radio navigation satellite systems, with global positioning system (GPS) as the main example. It uses the same physical principles as GPS, GLONASS, and others, that is radio signal-based ranging measurements from high-precision clocks as sources in orbit. The features of the first generation of Galileo comprise technological advances such as passive maser clock technology in orbit, plus modern system and signal concepts aligned to the planned and ongoing modernization of other systems. To the user, Galileo provides navigation signals on three frequencies E1, E6, and E5. The signals in E1 and E5 are coordinated with GPS L1 and L5, and both systems use equivalent modulation principles. This is expected to result in a benefit with respect to positioning accuracy, and in increased robustness of a positioning service derived from the combined use of multiple independent radio navigation systems. This chapter describes architecture and operations of Galileo.

The enormous potential benefits of satellite navigation for the citizens brought the European Space Agency (ESA) and the European Commission (EC) together in collaboration to develop and deploy a European radio navigation satellite system called Galileo.

Galileo development followed an iterative approach illustrated in Fig. 9.1. It was initiated in late 2003, carried out by the European Space Agency (ESA), and co-funded by ESA and the European Union.

ESA launched two GIOVE (Galileo In-Orbit Validation Element) satellites in 2005 and 2008, with a representative ground segment. These satellites secured the frequencies provisionally set aside for Galileo by the International Telecommunications Union. The satellites served also as a testbed for key technologies such as onboard atomic clocks and navigation signal generation. The GIOVE satellites are no longer active and have been moved to higher altitudes, away from the nominal Galileo orbit.

The following in-orbit validation phase aimed to perform initial validation of the system using a reduced constellation of four Galileo in-orbit validation (IOV) satellites – the minimum number for independent position and timing solutions at test locations – in combination with Galileo's terrestrial network of ground stations. This phase used the first family of Galileo satellites (GSAT010x), launched through dual launches on 21 October 2011 and 12 October 2012. These four satellites served for IOV of the Galileo system, but are also part of the operational Galileo constellation. On 12 March 2013 this ground and space infrastructure came together to perform the very first determination of a ground location through Galileo signals alone. This initial position fix of longitude, latitude and altitude took place at the Navigation Laboratory at ESA's technical heart European Space Research and Technology Centre (ESTEC), in Noordwijk, the Netherlands. From this point onward, Galileo navigation messages have

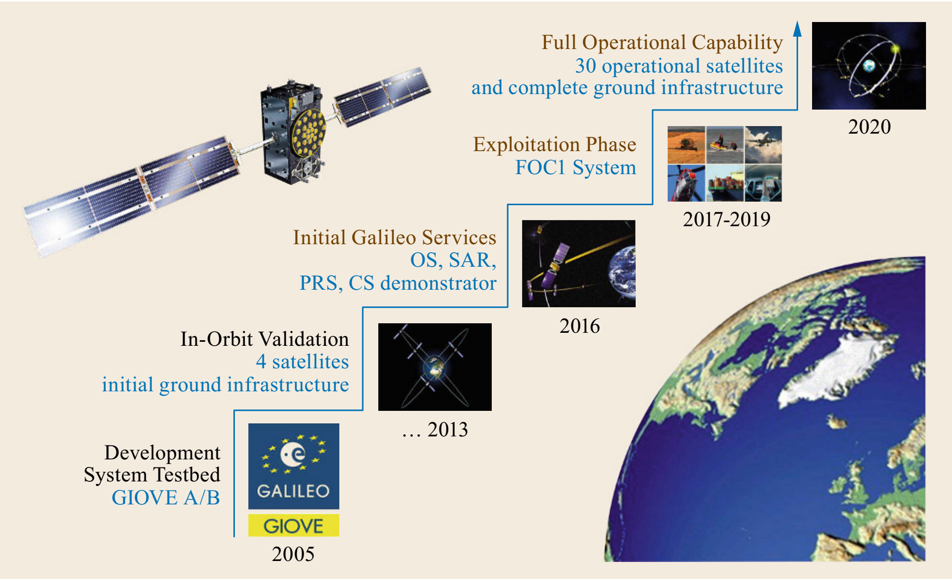

Fig. 9.1 Galileo incremental deployment (courtesy of M. Pedoussaut, S. Corvaja, Th. Burger, ESA, and pixabay.com)

been broadcast. The IOV campaign was conducted successfully throughout 2013, and the results were used as a reference to predict the expected performance of the completed Galileo constellation.

The deployment of the Galileo system until its full operational capability (FOC) is conducted under a public procurement scheme, entirely financed by the European Union. In 2007 the European Parliament and the European Commission decided to implement the system, and allocated budget for Galileo and for the European geostationary navigation overlay service (EGNOS). In 2008 the first part of the procurement of the Galileo full operational capability was launched, aiming to address full system deployment, long-term operations and replenishment. This phase will consist of the launch of all remaining satellites (up to 30) and deployment of the full operational ground segment, including all required redundancies in order to comply with the full mission requirements in terms of performance and service area. Early Galileo services are set to begin during the year 2016.

Following this, the Exploitation Phase is planned to start during the deployment of the full system, scheduled for 2017, and will consist of routine operations as well as ground segment maintenance and replenishment of the satellite constellation. This phase is planned to last over the design lifetime of the system, nominally 20 years.

9.1 Constellation

The Galileo constellation is the result of detailed studies and optimization [9.1, 2]. Table 9.1 summarizes the finally selected basic Galileo reference constellation parameters [9.3, 4].

The nominal satellite positions in space for a given time are defined by the reference Keplerian elements expressed in the Celestial Intermediate Reference System (CIRS) [9.5].

$$
\begin{aligned}
i_{\text{ref}} &= 56^\circ\,, \\
\Omega_{\text{ref}} &= \Omega_0 + 120^\circ \cdot (k_{\text{plane}} - 1) + \dot{\Omega} \cdot (T - T_0)\,, \\
u &= u_0 + 45^\circ \cdot (k_{\text{slot}} - 1) \\
&\quad + 15^\circ \cdot (k_{\text{plane}} - 1) + D_{\text{nom}} \cdot (T - T_0)\,. \qquad (9.1)
\end{aligned}
$$

$$
\begin{aligned}
\Omega_0 &= 25^\circ\,, \\
\dot{\Omega} &= -0.02764398\,^\circ/\text{d}\,, \\
T_0 &= 21 \text{ March 2010, 00:00:00 UTC} \\
u_0 &= 338.333^\circ\,, \\
D_{\text{nom}} &= 613.72253566\,^\circ/\text{d}\,. \qquad (9.2)
\end{aligned}
$$

In the equations above, the variable k_{plane} can take the values 1, 2 and 3 for, respectively, planes A, B and C [9.6]. The variable k_{slot} denotes the slots within the orbital plane and can assume values from 1 to 8. i_{ref} is the orbit inclination and Ω_{ref} the right ascension of ascending node (RAAN). The argument of latitude u is defined as along-track phase angle with respect to the equator.

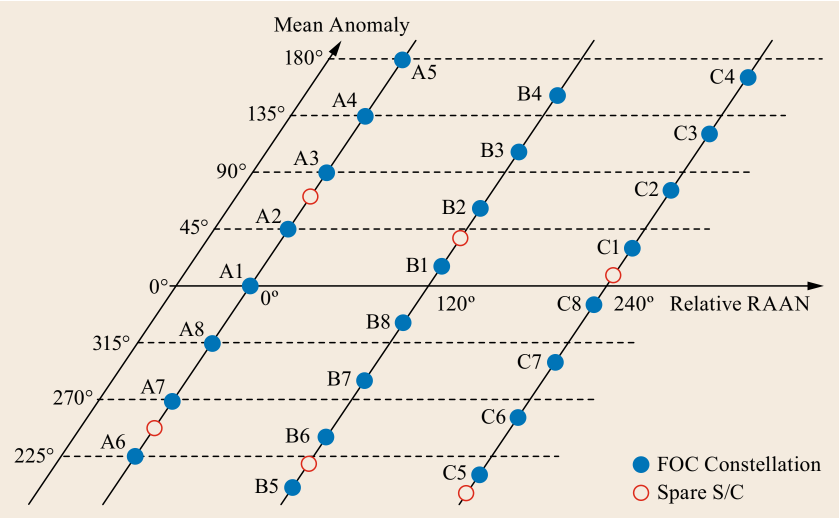

Fig. 9.2 Galileo FOC constellation slots

Table 9.1 Galileo reference constellation parameters

Parameter	Value
Reference constellation type	Walker 24/3/1 + 6 in-orbit spares
Semimajor axis	29 600.318 km
Inclination	56°
Period	14h 04m 42s
Ground track repeat cycle	10 sidereal days/17 orbits

The satellites are generally maintained within orbit slots of $\pm 2°$ in inclination and argument of latitude, and $\pm 1°$ in right ascension of ascending node (Ω) with respect to the reference. $\dot{\Omega}$ reflects both the oblateness of the Earth's gravitational field and the gravitational effect of the Moon and Sun. D_{nom} is computed taking into account the repeat ground-track pattern of 17 revolutions in ten sidereal days. Figure 9.2 shows a systematic sketch of the resulting constellation geometry and satellite locations.

The position of the spare satellites shown in Fig. 9.2 is indicative, as their actual position will be decided at the time of deployment.

The constellation geometry has been optimized to achieve consistently good geometric conditions on a global scale, leading to a good user position accuracy and availability. The inclination of the orbit planes provides for better coverage in the higher latitudes, for example when compared to GPS.

The above reference constellation of 24 satellites will yield between six to 11 Galileo satellites visible at any user location worldwide. Average visibility is more than eight Galileo satellites above 5° elevation. The reference constellation will be complemented with nominally six spare satellites. This constellation provides good local geometries with a typical vertical dilution of precision (VDOP, [9.7]) of 2.3 and horizontal dilution of precision (HDOP) around 1.3. An additional benefit of the constellation geometry is the limited number of planes, which allows for faster deployment and reduced constellation maintenance costs due to the capability to launch multiple satellites with a single launcher. For example Ariane 5 is capable of launching up to four Galileo satellites, and Soyuz is used to launch sets of two Galileo satellites.

Satellite disposal after the end of their operational life is to be considered and planned appropriately, for reasons of space debris control but also because debris avoidance maneuvers will impact the availability of operational satellites for service provision. Galileo satellites are removed from the nominal Galileo orbits after they have reached the end of their operational life. The same applies for remaining launcher stages after injection of new satellites into their orbits. The strategy followed in Galileo is to move those satellites and launcher stages to a *graveyard* orbit that is at least 300 km higher than the operational Galileo orbits.

9.2 Signals and Services

Each Galileo satellite provides coherent navigation signals on three different frequencies. Each signal contains several components, comprising always at least one pair of pilot and data components. Figure 9.3 summarizes the transmission plan.

The signals and components are assigned to three types of positioning services:

1. The Open Service (OS) comprising the data-pilot pairs E1-B/C, E5a-I/Q and E5b-I/Q, representing the publicly accessible positioning service
2. The Public Regulated Service (PRS) on E1-A and E6-A, a restricted access positioning service for government-authorized users
3. The Commercial Service (CS) through the data-pilot pair E6-B/C, a navigation signal on a third frequency, optionally encrypted, for the provision of future added value services.

As a fourth service, Galileo satellites support Cospas-Sarsat [9.8–10], an international satellite-based search and rescue system established by the US, Russia, Canada and France, capable of locating emergency radio beacons. This support is provided through a forward search-and-rescue repeater as part of the payload, and through an associated data return link embedded into the navigation message of the E1 OS data component.

E1 and E6 each provide one publicly accessible pair of pilot and data components, and E5 offers two pilot-data pairs in sidebands 15.345 MHz above (E5b) and below (E5a) the E5 carrier frequency. The sidebands E5a and E5b are foreseen for individual tracking and use, offering the equivalent of two coherent carrier frequencies within the E5 band. The overall E5 carrier including both sidebands is defined and generated coherently as an alternative BOC (AltBOC) signal [9.11]. This composite AltBOC signal can also be tracked as a single signal, offering a very large signal bandwidth of at least 51.15 MHz (50·1.023 MHz), and thus providing excellent Gabor bandwidth (Chap. 4) and multipath rejection.

Table 9.2 gives the overview of available Galileo signals and associated carrier and subcarrier frequencies.

Galileo and GPS, as the system with the longest heritage and current most wide use, are considered compatible (sharing of resources without degrading the performance of the other radio navigation satellite system) and interoperable (allowing the user to successfully combine pseudorange measurements from more than one global navigation satellite system (GNSS) into position/velocity/time solutions):

1. Two carrier frequencies are shared (E5a/L5 and E1/L1), with equivalent modulations

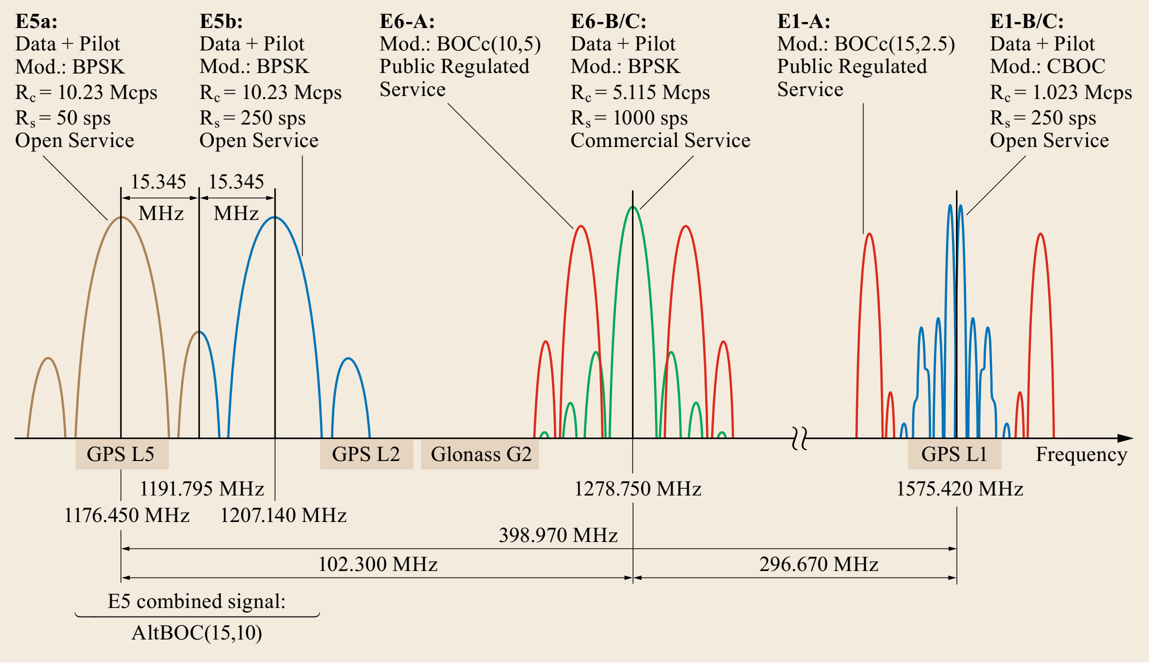

Fig. 9.3 Galileo frequency bands, signals and components

Table 9.2 Overview of Galileo signals

Galileo signal	Carrier frequency (MHz)	Subband	Subband frequency (MHz)	Carrier aligned with
E1	1575.420	n/a	n/a	GPS L1 C/A, L1C
E6	1278.750	n/a	n/a	
E5	1191.795	E5b	1207.140	
		E5a	1176.450	GPS L5

2. Fundamental message concepts are comparable, such as ephemeris, almanac, clock correction, GST-UTC (Galileo System Time - Universal Time Coordinated), and bias group delay
3. Terrestrial reference frames and reference time systems are aligned, as indicated in the following sections of this chapter.

These concepts and measures are intended to simplify and optimize user receiver hardware implementation (radio frequency front-end design and digital preprocessing), but also receiver software and algorithms.

9.2.1 Signal Components and Modulations

All Galileo signals and their signal components are derived from the same onboard master clock, and are thus coherent. Table 9.3 provides a summary of the modulation schemes and component parameters. Four pairs of pilot and data components are provided for public use: E1-B/C, E6-B/C, E5a-I/Q and E5b-I/Q. All pilot/data pairs use a 50% power sharing.

The modulation-specific recommendations for receiver bandwidths are driven by the components to be tracked. Recommended receiver bandwidths are as listed in Table 9.4.

When choosing a receiver bandwidth, manufacturers are recommended to carefully consider the interference situation in each band. Some selected examples follow (the list is not complete). In E6 the presence of terrestrial pulsed interference, for example from radar systems, is to be expected, and the band is shared with amateur radio users that use it for audio and video transmitters and relays (HAM TV). Often also other unidentified low-power sources have been observed, especially in urban areas. Receivers will need to be resistant against high-power radio frequency (RF) pulses

Table 9.3 Overview of Galileo public signal components and modulations. Legend: R_c = primary code chip rate (in multiples of 1.023 MHz), R_{sc} = subcarrier frequency (in multiples of 1.023 MHz), R_d = symbol rate (symbols/s), R_{sec} = secondary code chip rate (chips/s)

Signal	Component	Modulation	R_c	R_{sc}	R_d, R_{sec}	Message	Service	Multiplex	Min received Power
E1	E1-B Data	Composite binary offset carrier (CBOC) 1/11	1	1&6	250	I/NAV	OS	in	−160 dBW
1575.420 MHz	E1-C Pilot	CBOC 1/11	1	1&6	250	–	OS	phase	−160 dBW
E6	E6-B Data	Binary phase-shift keying (BPSK)	5	–	1000	C/NAV	CS	in	−158 dBW
1278.750 MHz	E6-C Pilot	BPSK	5	–	1000	–	CS	phase	−158 dBW
E5b	E5b-I Data	BPSK	10	–	250, 1000	[I/NAV]	OS	0°	−158 dBW
1207.140 MHz	E5b-Q Pilot	BPSK	10	–	1000	–	OS	90°	−158 dBW
E5a	E5a-I Data	BPSK	10	–	50, 1000	F/NAV	OS	0°	−158 dBW
1176.450 MHz	E5a-Q Pilot	BPSK	10	–	1000	–	OS	90°	−158 dBW

Table 9.4 Recommended receiver bandwidths for Galileo navigation signals

Component	Rx Bandwidth (double sided)			
	Min	Recommended	Max	Note
E1-B/C tracked as BOC(1,1)	2.0 MHz	2.0...24.6 MHz	≈31 MHz	In steps of 2.023 MHz
E1-B/C tracked as CBOC	14.3 MHz	14.3...30.7 MHz	≈31 MHz	Good multipath robustness already at 14.3 MHz
E6-B/C BPSK(5)	10.2 MHz	10.2...20.5 MHz	≈41 MHz	In steps of 10.23 MHz
E5a-I/Q BPSK(10)	20.5 MHz	20.5 MHz	≈41 MHz	In steps of 20.46 MHz
E5b-I/Q BPSK(10)	20.5 MHz	20.5 MHz	≈41 MHz	In steps of 20.46 MHz
E5 as AltBOC	51.2 MHz	51.2 MHz	≈72 MHz	Center frequency 1191.795 MHz

in-band, and against continuous transmitters close to band. The E5 band is mainly shared with air traffic control and positioning systems like DME (Distance Measuring Equipment, primary user), where the DME ground stations transmit within the E5 navigation band. DME transmissions are pulse pairs, each pair a few tens of μs long, transmitted at average rates up to several kHz and pulse powers in the range of 1 kW.

Selected Galileo Modulation Details

Galileo uses CBOC (Composite Binary Offset Carrier) modulation in E1 and AltBOC (alternative binary offset carrier) modulation in E5. These modulations are specific for Galileo and are shortly explained below. The Galileo E6 public signal uses conventional BPSK (binary phase shift keying) modulation as described in Chap. 4, and is thus not elaborated here. A full description of the public Galileo modulations is published in the Galileo public Open Service Signal in Space Interface Control Document (OS SIS ICD) [9.11].

CBOC as used for the Galileo E1 public signal is a composition of a 1.023 Mcps spreading sequence combined with a two-component spreading symbol. The spreading symbol comprises the sum of a BOC(1,1) subcarrier at 10/11 power and a BOC(6,1) subcarrier at 1/11 power. The spreading symbol of the data channel combines the two subcarriers in-phase and the spreading symbol of the pilot channel combines them in antiphase, as illustrated in Figs. 9.4 and 9.5. As a result of the additive combination of the two binary offset carrier (BOC) subcarriers with nonequal amplitude, the time domain CBOC spreading symbols are four-level pulses. The spreading pulses of the CBOC data and pilot components differ with respect to the phase of their BOC(6,1) subcarriers.

When tracking using a conventional dual-level BOC(1,1) despreading is possible with minor losses (≈ 0.4 dB) that are also a function of the receiver bandwidth. Direct CBOC tracking requires a four-level correlator with amplitude stages of $\{\pm 1.25, \pm 0.65\}$. An approximation of the replica levels using two bit representations of the replica is possible, but not optimum. Alternative techniques, for example combing separate binary correlators for the BOC(6,1) and BOC(1,1) parts are increasingly becoming subject to publications and patents [9.12–14], demonstrating the feasibility of efficient tracking of CBOC modulated signals.

The phase of the BOC(6,1) components in the data and pilot spreading symbols is inverted. Thus the com-

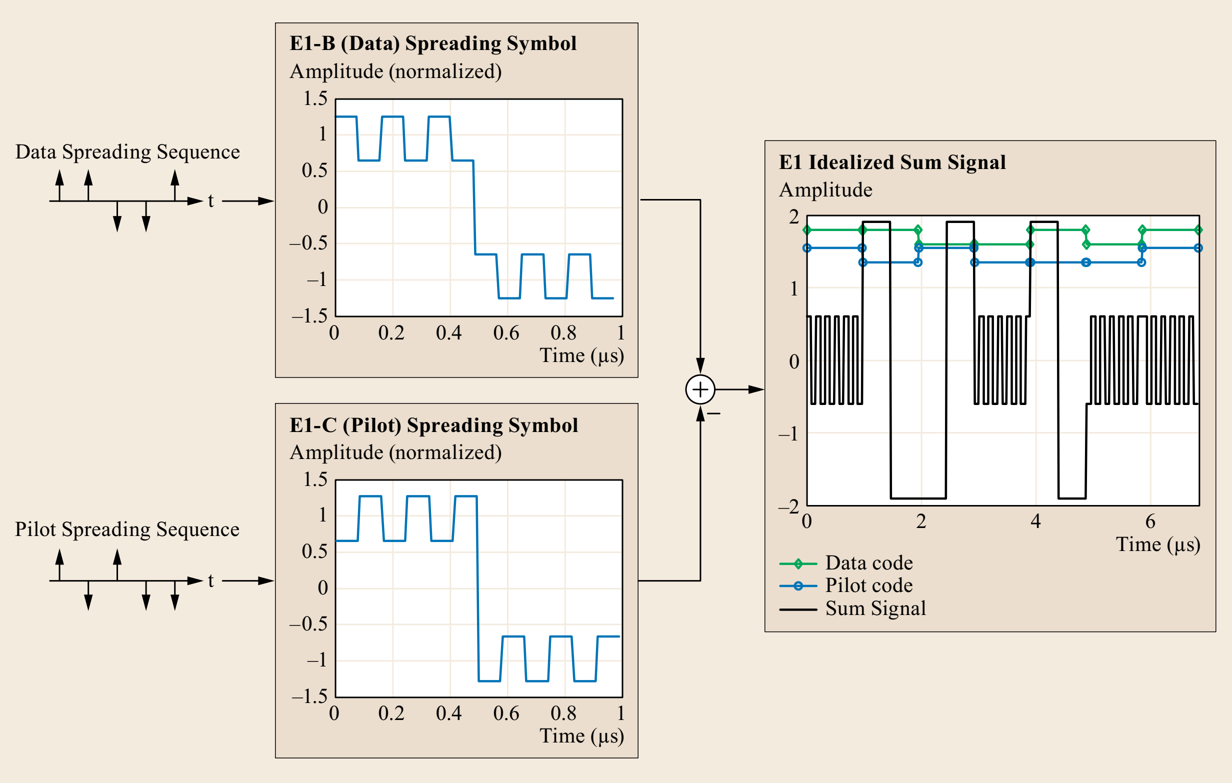

Fig. 9.4 Galileo CBOC principle

bined signal of pilot and data channel, as the in-phase addition of the pilot and data baseband signals, has only four levels in total. The combined signal has the interesting property that always only either BOC(1,1) or BOC(6,1) is transmitted, in time multiplex. The subcarrier phase is set according to the combination of the spreading chips from pilot and data channels. This opens a range of possible highly efficient correlation mechanisms for tracking the combination signal, using time multiplex techniques.

AltBOC modulation was proposed in 2002/2003 [9.15, 16] as wideband complex sideband modulation. AltBOC can be understood in baseband representation as the sum signal of coherently generated and individually quadrature modulated complex upper (E5b) and lower (E5a) subcarriers, then adding an intermodulation function (IM) to achieve a constant envelope on the transmit side [9.17]. The OS SIS ICD [9.11] baseband representation

$$s_{E5}(t) = \sqrt{1/8}\cdot\left[\begin{array}{ll}\left.\begin{array}{l}\left[e_{E5a\text{-}I}(t)+je_{E5a\text{-}Q}(t)\right]\cdot\\ \left[sc_S(t)-jsc_S\left(t-\frac{T_s}{4}\right)\right]\\ +\left[e_{E5b\text{-}I}(t)+je_{E5b\text{-}Q}(t)\right]\cdot\\ \left[sc_S(t)+jsc_S\left(t-\frac{T_s}{4}\right)\right]\end{array}\right\} & \text{Signal Part}\\ \left.\begin{array}{l}\left[\bar{e}_{E5a\text{-}I}(t)+j\bar{e}_{E5a\text{-}Q}(t)\right]\cdot\\ \left[sc_P(t)-jsc_P\left(t-\frac{T_s}{4}\right)\right]\\ +\left[\bar{e}_{E5b\text{-}I}(t)+j\bar{e}_{E5b\text{-}Q}(t)\right]\cdot\\ \left[sc_P(t)+jsc_P\left(t-\frac{T_s}{4}\right)\right]\end{array}\right\} & \text{Intermodulation Part}\end{array}\right] \quad (9.3)$$

contains in its first two lines the four independent bipolar $\{-1,+1\}$ spreading sequences $e_{E5\{a,b\}\text{-}\{I,Q\}}(t)$ (spreading code, secondary code and data modulation) in sideband modulation with their subcarrier $sc_S(t)$, and in the last two lines the IM consisting of the bipolar sequences $\bar{e}_{E5\{a,b\}\text{-}\{I,Q\}}(t)$ with their IM subcarrier $sc_P(t)$. All IM sequences are triple-product terms of the nominal spreading sequences $e_{E5\{a,b\}\text{-}\{I,Q\}}(t)$, for example

$$\bar{e}_{E5a\text{-}I}(t) = e_{E5a\text{-}Q}(t)e_{E5b\text{-}I}(t)e_{E5b\text{-}Q}(t)\ .$$

The subcarriers before band limitation are discrete multilevel signals with period $T_S = (15.345\,\text{MHz})^{-1}$ and are defined as shown in Fig. 9.6.

The description provided in [9.11] is ideal wideband and yields a final signal constellation diagram (signal part combined with intermodulation function) that represents an eight PSK-type modulation (Fig. 9.7a). The main energy content of the IM is located around and beyond ±46 MHz offset from the E5 carrier (Fig. 9.7b), and lies outside the recommended AltBOC receive bandwidth (51.2 MHz). Receivers will see only a small fraction of the theoretical IM power and may thus safely decide to neglect the IM for the purpose of AltBOC tracking.

Various alternative AltBOC tracking concepts have already been published, and all require an AltBOC replica generation. One fundamental concept to generate the replica using a lookup table approach appears suitable for receiver implementation and is provided in [9.11], together with the direct mathematical description. This concept represents a baseline; it is to be expected that actual receiver implementations will use optimized forms, for example of combined replica generation and correlation computation.

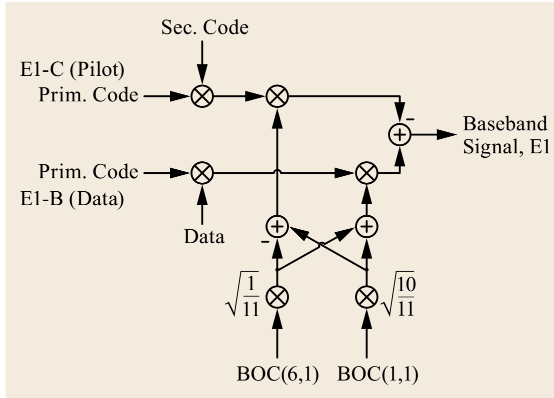

Fig. 9.5 CBOC generation block diagram

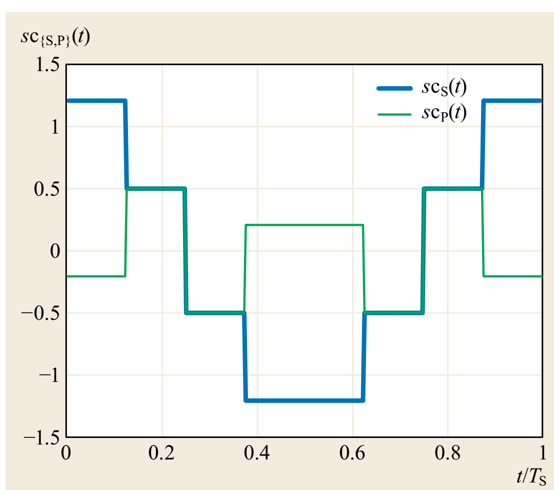

Fig. 9.6 AltBOC subcarrier functions

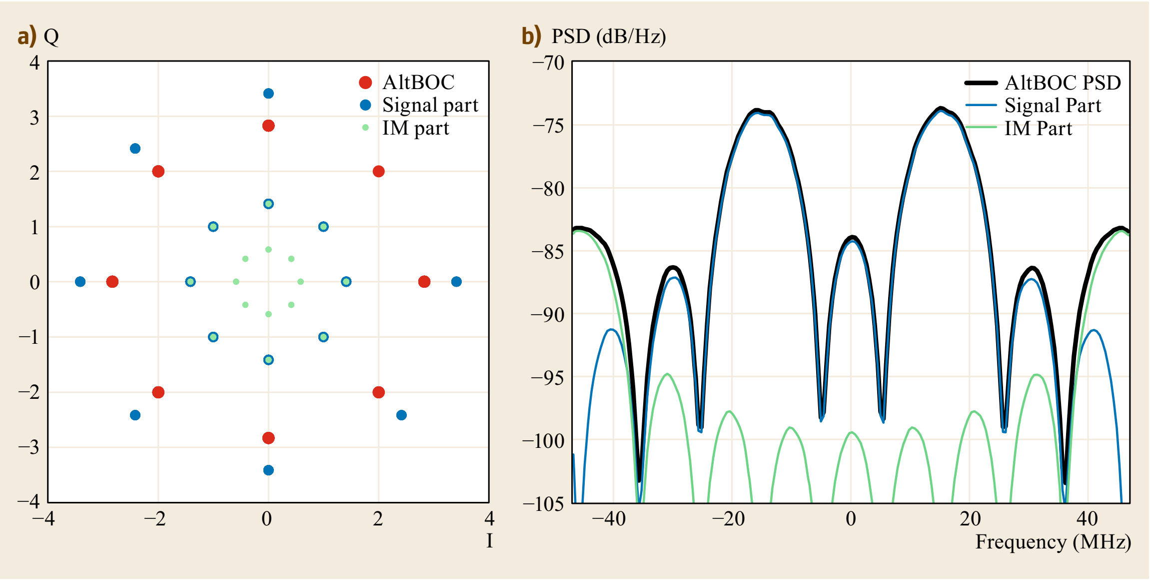

Fig. 9.7a,b AltBOC wideband signal vector diagram **(a)** and example power spectral density **(b)**

It is to be recalled that the Galileo navigation messages do not formally provide a direct message for use with AltBOC. The ephemeris information is unproblematic; any of the ephemeris sets provided in the Galileo navigation messages may be used. The clock correction is more critical, since the clock corrections as provided in the two public Galileo navigation messages are individual for specific frequency pairs (Sect. 9.2.2). If needed, either of these clock corrections and broadcast group delays (BGDs), or an average of them, may be used as good approximations.

In the case where only sidebands are to be tracked, then each of the four signal components $e_{\text{E5\{a,b\}-\{I,Q\}}}(t)$ can be acquired and tracked individually, as BPSK(10)-type navigation signal components. The two components on each sideband are configured as pairs of pilot and data. The two sidebands E5a and E5b of an AltBOC signal are fully coherent, thus any crosstalk between those sidebands is stationary. Tracking accuracy can suffer nonnegligible side effects from this crosstalk. Individual components $e_{\text{E5\{a,b\}-\{I,Q\}}}(t)$ should thus be tracked using a receive bandwidth centered on the desired sideband E5a or E5b, and narrow enough to suppress the other sideband. For this reason Table 9.4 recommends component tracking bandwidths of 20.46 MHz.

Galileo Spreading Codes and Sequences

Each unencrypted signal component from each satellite is using individual, unique periodic spreading sequences (Table 9.5). The length (period) of the spreading sequences of data components is chosen such as to span full symbols of the data channel. If this requires more than 10230 chips, a two-tiered construction of a primary spreading code overlaid with a slower secondary code is used. The spreading sequences of pilot components generally use the two-tiered construction, with the length of the primary code equaling the primary code of the corresponding data channel, and the length of the secondary code chosen such as to pro-

Table 9.5 Overview of Galileo spreading codes (LFSR = linear feedback shift register)

Signal component		Primary code				Secondary code		
		Type	Chips	Period (ms)	#	Chips	Period (ms)	#
E1-B	Data, CBOC(1,6,1/11), 250 sps	Memory	4092	4	50	–	–	–
E1-C	Pilot, CBOC(1,6,1/11)	Memory	4092	4	50	25	100	1
E6-B	Data, BPSK(5), 1000 sps	Memory	5115	1	50	–	–	–
E6-C	Pilot BPSK(5)	Memory	5115	1	50	100	100	50
E5b-I	Data, BPSK(10), 250 sps	LFSR	10230	1	50	4	4	1
-Q	Pilot, BPSK(10)	LFSR	10230	1	50	100	100	50
E5a-I	Data, BPSK(10), 50 sps	LFSR	10230	1	50	20	20	1
-Q	Pilot, BPSK(10)	LFSR	10230	1	50	100	100	50

vide a total of 100 ms nonrepetitive length of the pilot spreading sequence.

The two-tiered spreading sequence generation works comparably to a pseudodata modulation, where the secondary code represents the (a priori) symbol modulation. Accordingly, the secondary code clocks with one chip per period of the primary code, and is modulo-2 combined with the primary code. Figure 9.8 illustrates this principle.

The design objective was to limit the length of the primary code to less than or equal to 10230 chips, to avoid excessive code search space during acquisition, but also to provide a nonrepetitive sequence length of either one symbol for data components or 100 ms for pilot components. Primary spreading sequences have been carefully selected and optimized for good orthogonality across each family, and are responsible for ensuring sufficient isolation between signal sources. Secondary codes have been mainly tuned for low autocorrelation sidelobes, and as a consequence, a flat power spectrum in the frequency domain.

The two-tiered construction cannot reach the correlation quality of an optimized single-stage spreading sequence with the same length as the combination of primary and secondary code. Instead, for coherent integration covering multiple primary code lengths, or over the full period of the tiered code, the correlation result will repeat the primary code autocorrelation modulated with the shape of the secondary code (partial) autocorrelation. This means there will be repeating correlation peaks every period of the primary code, not with the full amplitude of the main correlation peak, but still with significant levels. Receivers using coherent integration times longer than the primary code period will need to consider this behavior through appropriate hypothesis tests during acquisition to find the correct main peak and secondary code phase. But once the phase of the secondary code is identified, this resolves the code phase unambiguously up to the length of the tiered code. The two-tiered code concept with its pseudodata modulation in the form of the secondary code is also intended to reduce the sensitivity to narrowband interference, compared to repetitive primary codes without secondary code, while maintaining a reasonably length-limited primary code.

The secondary code on pilot components allows the resolution of the code phase relative to Galileo System Time (GST) with an ambiguity interval of 100 ms. This approximately equals the maximum propagation delay between any visible Galileo satellite of the nominal constellation and terrestrial users, and is more than four times the difference between the propagation delay to the closest and the farthest user on Earth. It is therefore considered possible to derive time-free position solutions for users on the surface of Earth, using only code phase measurements including the secondary code of any pilot signal, and provided the receiver already has ephemeris and clock correction information available.

The Galileo primary and secondary spreading codes for public use are provided in the OS SIS ICD [9.11]. Note that the memory codes are provided only in the downloadable electronic (PDF) version of that document. The occasionally available paper printed version

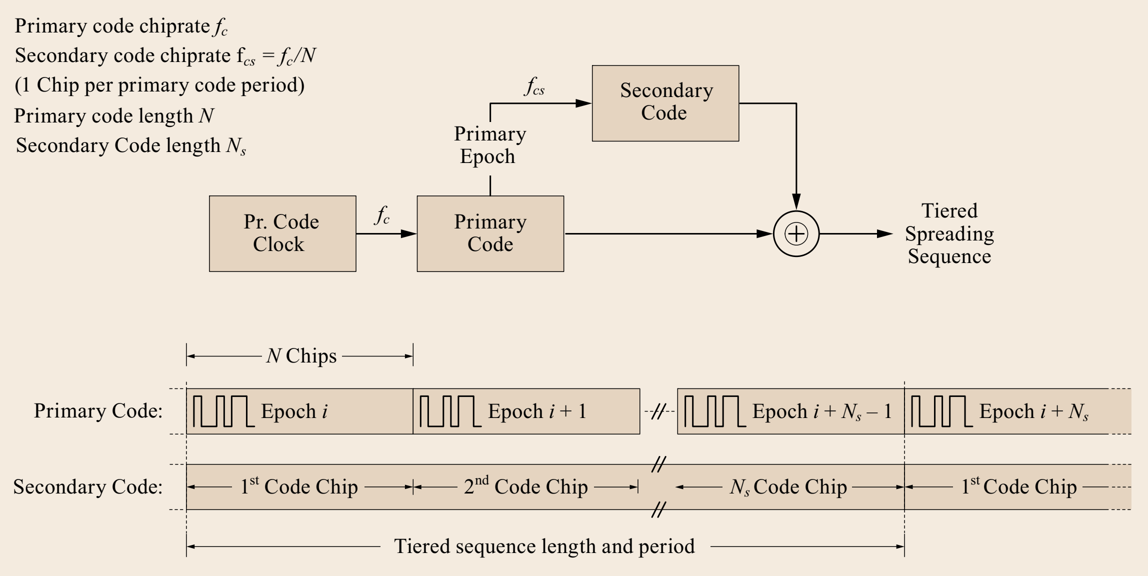

Fig. 9.8 Principle of the tiered code construction

may not contain hexadecimal representations of the memory codes.

9.2.2 Navigation Message and Services

Three different types of public navigation messages are provided through the Galileo navigation signals: the high data rate and short page length I/NAV (historically derived from Integrity NAVigation message), the low data rate F/NAV (Free NAVigation message) and the fast C/NAV Commercial channel NAVigation message. The message types are assigned to signal components as described in Table 9.6. The OS SIS ICD [9.11] and its annexes and associated support documents serve as reference documentation for these message types. OS SIS ICD [9.11] will be gradually extended and amended with new content, following service deployment and the progress of system validation. This section will thus reference to [9.11] and otherwise focus on receiver relevant differences and specifics.

The content of the navigation messages can be roughly differentiated into position/velocity/time (PVT) relevant content, which is mostly repetitive, and nonrepetitive low latency message elements.

Both I/NAV and F/NAV provide direct support to PVT determination, through provision of GST in the form of week number (WN) and time of week (TOW), and of ephemeris and clock correction for the transmitting satellite, but also through ionosphere model parameters, bias group delay information needed for single-frequency users, data validity and signal health flags, almanac and other supplementary information. The fundamentals of ephemeris, clock correction, GST-UTC, almanacs and usage algorithms are consistent with GPS legacy definitions, with format adjustments to Galileo. The ionosphere correction message uses a Galileo-adapted version of the more recent NeQuick model. The detailed user algorithm reference model will be published as annex [9.18] to [9.11].

For low-latency content, I/NAV on E1 includes the return link channel supporting the Cospas-Sarsat search-and-rescue (SAR) system [9.8–10]. This return link is a near-real-time channel for short messages to SAR beacons equipped with a Galileo navigation receiver. Further low latency channels are embedded into the I/NAV message but are not yet formally published, being considered a functional reserve of the Galileo navigation message for future development. In case such low-latency channels are influencing and altering the flow of the message data stream, these changes need to be known to receivers and to be considered already now. One example is I/NAV on E1 and on E5b, which includes capabilities to replace nominal transmissions on a per second basis with one-time low-latency short message pages [9.11]. Despite these messages not being brought into use yet, receivers will need to be robust against such insertions as they may appear in future.

The C/NAV data stream on E6 is also implemented as a near-real-time message stream with short latency. At the time of writing C/NAV applications are under development [9.19] and no content is published yet.

All low-latency data channels are served only from satellites with active uplink from the Galileo ground segment. Their data content can differ between different satellites.

The content of I/NAV and F/NAV messages is compatible with almanac, ephemeris information, GST-UTC and GST-GPS time conversions. Clock correction parameters of I/NAV and F/NAV messages are specific per message type, and are expected to be very similar but are not guaranteed to be identical. This difference is the result of Galileo being a native multifrequency system, where both I/NAV and F/NAV messages are being optimized for specific pairs of frequencies. The I/NAV message, especially its clock correction, is calculated for dual-frequency reception of E1 and E5b, and F/NAV is optimized for the dual-frequency reception of E1 and E5a. As a result the ephemeris and clock corrections provided in F/NAV and I/NAV messages are directly applicable for dual-frequency receivers of the above frequency pairs. Any single-frequency receiver needs to use the bias group delay correction provided within the assigned message type to adjust the clock correction for the single frequency to be measured. Figure 9.9 illustrates this rule.

None of the messages published so far supports PVT using E6 measurements or triple-carrier measurements. Such content could be envisaged to be provided in the C/NAV message as future services or through external sources and communication channels.

Table 9.6 Message content coverage

Message type	Component	Content		
		Positioning	Search and Rescue	Supplementary
F/NAV	E5a-I	✓		
I/NAV	E1-B	✓	✓	Individual low latency content
	E5b-I	✓		Individual low latency content
C/NAV	E6-B			C/NAV low latency content

Message Timeline and Structure

All Galileo message streams are structured in *pages* as the smallest interpretable data blocks. For F/NAV and C/NAV each page consists of a predefined set of synchronization symbols followed by the rate-1/2 convolutional encoded and cyclic redundancy check (CRC)-protected block of information. One F/NAV page lasts for 10 sec and provides 238 bits of effective information, exclusive of sync and tail symbols. I/NAV transmits data pages in two consecutive blocks, namely the *odd* and *even* words. Each word starts with the I/NAV synchronization symbols followed by a block-encoded data field, and lasts one second. A full I/NAV page (*odd* and *even* words combined) takes two seconds for transmission and provides a usable capacity of 245 bits, exclusive of sync and tail symbols.

The sequence of pages as transmitted from each satellite is organized such that the information required for PVT is provided within a well-defined maximum interval of time. Parts of information with less or no direct relevance for PVT and with longer validity, for example almanacs, are distributed over longer intervals. Figure 9.10 illustrates the concept for F/NAV.

It needs to be noted that [9.11] provides these structures for information with several reservations on possible changes and evolutions, intended to preserve some space for possible future improvement and extensions of the navigation message. Modulation up to symbol level will not change, and existing pages will not disappear. Backward compatibility for legacy receivers will be maintained. But new features may be gradually introduced, using the available degrees of freedom and spare room of parameters like page type identifiers. User receiver designers are asked to consider these reservations appropriately. Some examples are:

1. The nominal sequence of pages as described in [9.11] is not to be relied upon, but may change in the future. This implies that the page sequence may not be the same for all active satellites within a Galileo constellation. The receivers need instead to identify received pages by their page type identifier.
2. The relative timing between I/NAV pages in E1 and in E5b may change, for example through the above changes of page sequences.
3. New page types may be introduced. This will not degrade the PVT quality achievable with legacy data content. However, receivers are expected to react to page types not known to them in a well-controlled manner. Similarly, other spare space in identifier value ranges may be explored and combined with new definitions of data content, for example almanacs for space vehicle identifiers (SVIDs) outside the currently defined range.

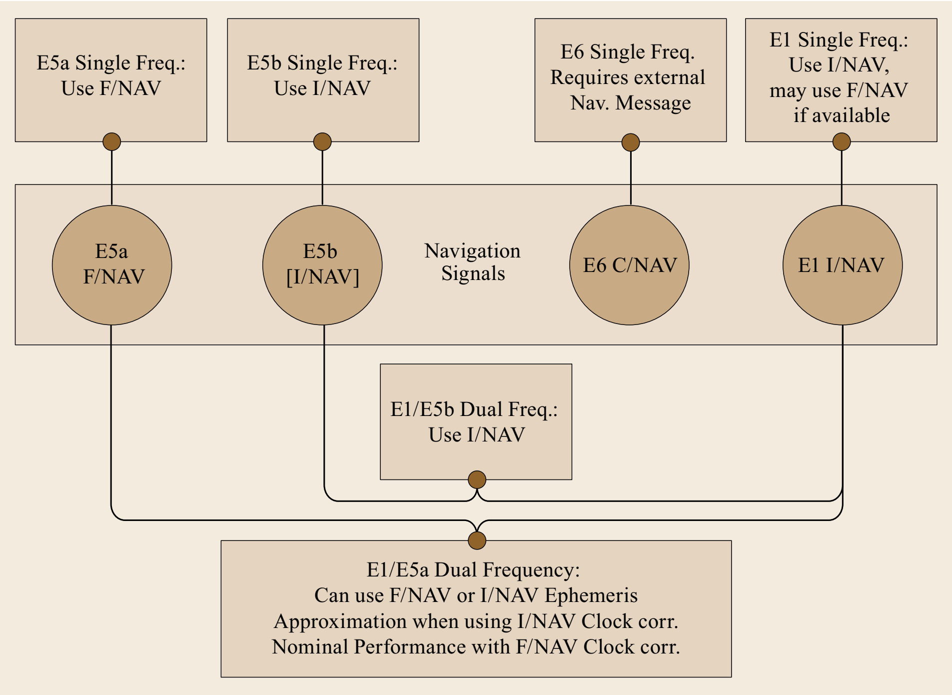

Fig. 9.9 Rules of use of Galileo navigation messages for PVT

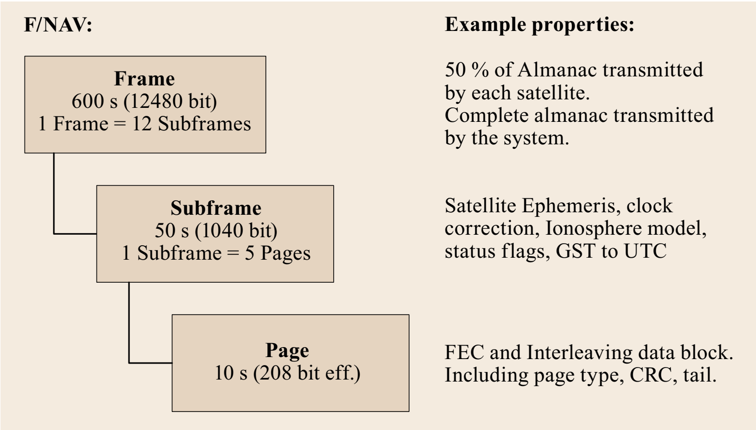

Fig. 9.10 F/NAV page transmission planning

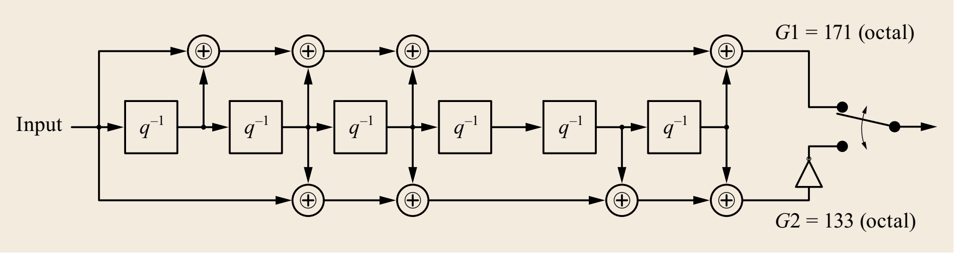

Fig. 9.11 Galileo FEC encoder

4. There will always be studies and discussions on more caveats to be considered, to reserve further headroom for message evolution. As an example, receivers can be expected to be robust against segments of unknown symbol sequences and failing standard forward error correction (FEC) decoding, as would follow from special page formats, for example with modified effective symbol rates and FEC. It can be assumed that such evolutions will be limited to symbol-level encoding up to message level. Unquestioned baselines of all such discussions is always that modulations are not changed, and existing message content will continue to be provided, such that legacy receivers are not disabled.

Forward Error Correction Coding (FEC) and Block Interleaving

Galileo data components employ a well-established low computational effort rate-1/2 Viterbi forward error correcting coding with constraint length 7 to improve message transmission robustness. The encoder polynomials are identical to the GPS L5 civil navigation message (CNAV) encoder, but Galileo applies an additional inversion to the output of the G2 polynomial, to ensure that continuous zero inputs do not create a constant symbol output (Fig. 9.11). Encoding comprises always pages or half pages of the navigation message as independent data blocks without overlaps with earlier or later blocks.

The combination of convolutional encoding with a blockwise concept requires the consideration of *constraint length − 1* predefined tail bits to provide FEC protection for the complete information content of each navigation page; tail-free convolutional encoding, for example tail biting, was not implemented due to potential patent or infliction of intellectual property rights.

Each block is subject to block interleaving using blocks with eight rows and a number of columns according to the page size in symbols (Fig. 9.12), supporting the textual representation in [9.11].

This ensures that burst errors of the channel are deinterleaved to at least eight symbols distance between single symbol errors at the decoder input, supporting the FEC decoder to correct such errors.

9.2.3 Ranging Performance

The Galileo ranging performance and consequently also positioning performance is driven by three groups of error contributions originating from the Galileo system, the environment and the user receiver.

The Galileo user equivalent range error (UERE) budget considers all key contributors as a function of satellite elevation:

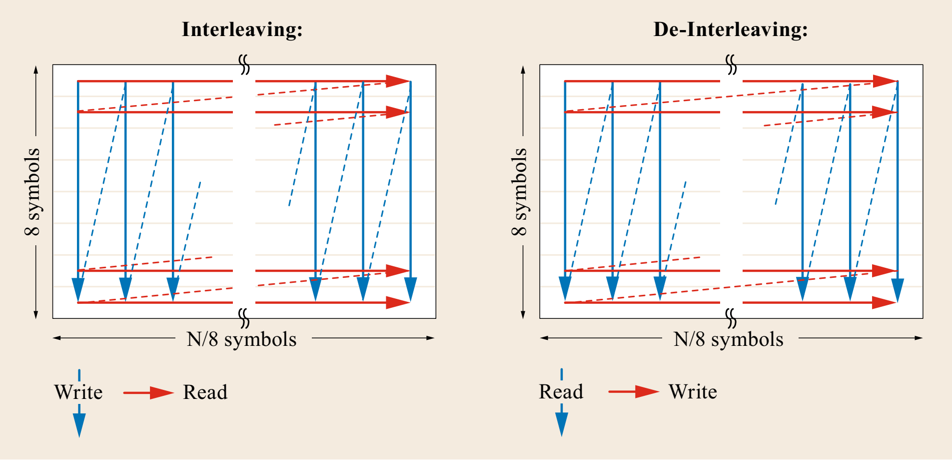

Fig. 9.12 Galileo message interleaving and de-interleaving

1. Ionospheric error: residual error due to the imperfection of the ionosphere model as provided in the navigation message, used to correct for ionospheric delays (only for single-frequency users)
2. Tropospheric error: residual error due to the imperfection of the model used to estimate the tropospheric delays. Models like Saastamoinen [9.20] combined with International Telecommunication Union (ITU)-R P.835-3, -4 will easily fulfill the assumptions reflected in Table 9.7
3. Interference, multipath, receiver thermal noise error: errors in the user receiver equipment due to *local* effects on code error, such as thermal noise, radio frequency interference and multipath
4. Orbit determination and time synchronization error: error caused by imperfections in the system-provided reference data (ephemeris and clock correction) for the computation of the satellite orbits and clocks at user level
5. Broadcast group delay (BGD) error: residual error due to the imperfection of the correction for transmitter delay differences between carriers (only relevant for single-frequency users).

Table 9.7 provides indicative root mean square (RMS) magnitudes of the error contributions expected to be achieved for the Galileo Open Service (OS) once the system has reached full operational capability. The values are valid for satellites at medium elevations around 45 degrees, at the maximum operational age of data.

The total UERE for a specific user and its environment combined with the local reception geometry, expressed for example through the dilution of precision (DOP), can be used to estimate the user position accuracy.

Table 9.7 Indicative root mean square (RMS) magnitudes of the Galileo user equivalent range error (UERE) contributions

UERE Contributor	Single	Dual
	Frequency user	
Residual ionosphere error	< 500 cm	≈ 5 cm
Residual troposphere error	< 50 cm	< 50 cm
Thermal noise, interference, random multipath and multipath bias error	< 70 cm	< 100 cm
Orbit determination and time synchronization error	≈ 65 cm	≈ 65 cm
Satellite broadcast group delay	≈ 35 cm	0
Total (RMS)	**< 513 cm**	**< 130 cm**

Galileo comprises a worldwide network of initially 16 sensor stations to collect the ranging measurements required to generate the navigation message. The number of stations and their distribution accounts for eventual temporary sensor station and network outages. This ensures the required level of ground network robustness and performance as needed for the provision of nominal ranging, position and timing accuracy.

The Galileo system has been designed with position accuracy targets for E1/E5 dual-frequency Open Service users set to 4 m (95%) horizontal and 8 m (95%) vertical. The ranging accuracy considered necessary to reach these accuracy targets is 130 cm (95%). These targets are used to benchmark the performance predictions and to determine the expected availability of the service accuracy. Figure 9.13 provides global-scale simulated *expected performance* for an Open Service dual-frequency Galileo-only users in the vertical and horizontal position domain with 99.5% availability according to the above benchmark thresholds.

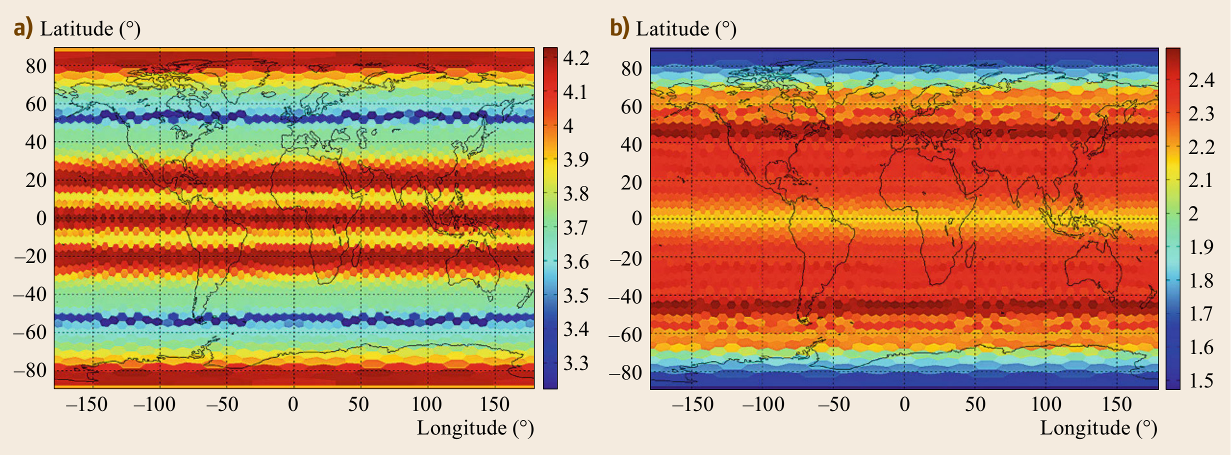

Fig. 9.13a,b Simulation of expected performance (color-coded positioning error in meters) for an Open Service dual-frequency Galileo-only user in the vertical **(a)** and horizontal **(b)** position domain with 99.5% availability

Orbit and Clock Errors

As for most radio navigation satellite systems, the basic information generated by the Galileo system for provision to users are orbit and clock correction for each satellite. The mission ground segment *estimates*, *predicts* and *parametrizes* this information into the navigation message. The message is then *uplinked* to the satellites and *disseminated* to the user through the navigation signals.

Clock and orbits are *estimated* by the orbit determination and time synchronization (ODTS) process, which operates as a least-squares estimator on data batches, operationally running every 10 min. Observation data used for this estimation process are always dual-frequency pairs of measurements:

- E1-E5a observables for F/NAV products
- E1-E5b observables for I/NAV products
- E1-E6 observables for PRS products.

Once estimated, clocks and orbits are *predicted* for the time interval for which the navigation message is to be generated. The reference time of these predictions is located at the beginning of each prediction interval. The result is subsequently *parameterized* and formatted into navigation messages, and finally disseminated to the user. Users will observe a difference (*age of data*) between reference time and time of use of the message. The signal-in-space error (SISE) at the user age of data, that is the imperfection of clock and orbit parameters when applied by the user, determines the ranging performance.

Stability and predictability of the satellite payload implementation, and especially the onboard clock system, is a major contribution to SISE. For this reason the quality of clock and orbit estimations is validated systematically. A specifically interesting time for such measurements are the in-orbit tests (IOTs) following each satellite launch. During these periods all clocks on board can be operated, even if only for a limited time, and can be observed.

A selection of typical results for RMS clock prediction errors (clock predictability) is shown in Fig. 9.14, as a function of the prediction interval. The prediction model used is a second-order polynomial, equivalent to the clock correction within the navigation message, but in high numerical resolution and therefore without parameter quantization effects. Figure 9.14 is intended to show clock quality as much as possible isolated from other contributions. Therefore the clock estima-

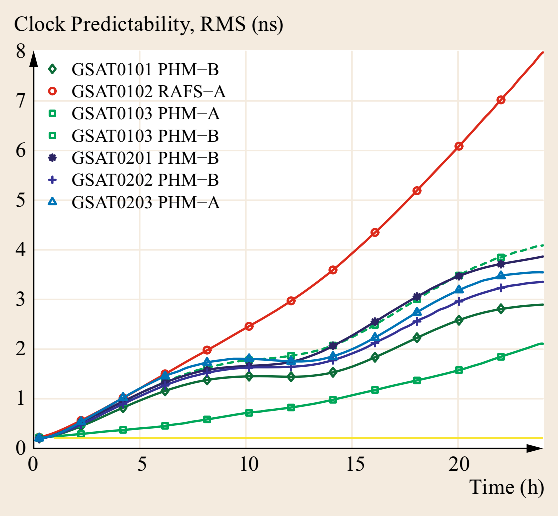

Fig. 9.14 RMS clock predictability for typical Galileo passive hydrogen maser (PHM) and RAFS

tion used originates from an independent verification system based not only on Galileo sensor stations but also including other project internal sensor stations, otherwise used for verification purposes, and sensor stations of the Multi-GNSS Experiment (MGEX), which is maintained by the International GNSS Service (IGS). A highly stable active maser independent of the Galileo system is used as ground time reference. The vertical bias for very short prediction intervals indicates the measurement noise of the input data as used for the analysis and the resulting model fitting error. Only one rubidium atomic frequency standard (RAFS) is shown, but its behavior is quite representative for the typical predictability of the GSAT010x and GSAT02xx RAFS. The difference between RAFS and passive hydrogen maser (PHM) predictability is clearly visible, especially for longer prediction intervals. The PHM quality and predictability is such that orbit determination imperfections can still be recognized, despite the offline processing using a larger database than available to the system itself.

Each satellite operates two clocks in parallel, nominally one PHM as a master clock and one RAFS as a hot redundant backup. In normal operation the ground segment commands switches between clocks, for example due to maintenance or, eventually, due to failures. Expectation is that at the time of switching to a backup clock, this clock has been in operation already for a prolonged time as a hot redundant clock. Thus its performance will have stabilized and settled, and the switch can be performed with minimum impact on service provision. Planned switches have meanwhile been exercised seamlessly, that is without interrupting service provision from the affected satellite.

Following established practice the ephemeris and clock correction message is generated with respect to a common reference point (apparent center of phase) geometrically close to the frequency-dependent individual centers of phase of the navigation transmit antenna. The user computes the position of this common reference point as a function of GST [9.11]. The vector from satellite center of mass to antenna reference point will be considered for possible publication, following validation.

Galileo establishes its own Galileo Terrestrial Reference Frame (GTRF), to which the above orbit and clock errors are referring. The GTRF is aligned to the International terrestrial reference frame (ITRF) with respect to origin, scale, orientation and rate, such as to remain within 3 cm (2-sigma) of the ITRF.

Ionospheric Error and Broadcast Group Delay

The ionospheric model parameters include the broadcast coefficients a_{i0}, a_{i1}, and a_{i2} used to compute the effective ionisation level Az, and the *ionospheric disturbance flags* (also referred as *storm flags*), provided for five different regions.

The ionospheric algorithm for single-frequency users is based on an adaptation of the three-dimensional (3-D) empirical climatological electron density model NeQuick [9.21–23].

The performance of the Galileo NeQuickG model is regularly evaluated. An early but still valid result was measured during the IOV campaign (March to August 2013) [9.21, 24]. The achieved residual error as measured was already reaching expectations for the full operational constellation of Galileo, and was better than the GPS Klobuchar model especially at equatorial latitudes. The global absolute ionospheric error $(1-\sigma)$ for the reported period was 1.34 m RMS achieved with the NeQuickG model and 1.9 m RMS with Klobuchar model. The absolute difference at equatorial latitudes expands to well beyond 1 m.

An example level of correction and comparison of NeQuickG and Klobuchar model results is provided in Fig. 9.15 for 21 May 2015, close to the vernal equinox and the seasonal ionosphere maximum. The performance was measured with receivers in the marked locations (more than 100 stations). From white to green the achieved ionospheric error correction capability was at least 70% RMS or better. Red color markings indicate a correction performance lower than 70%. This result is computed following the description in [9.25], and is in line with these earlier observations.

Similar to other GNSSs, the Galileo clock corrections are generated for dual-frequency users, and single-frequency users will need to use the broadcast group delay $\mathrm{BGD}(f_1,f_2)$ provided through the Galileo navigation message as an additional correction. $\mathrm{BGD}(f_1,f_2)$ is defined as follows

$$\mathrm{BGD}(f_1,f_2)=\frac{\mathrm{TR}_1-\mathrm{TR}_2}{1-\left(\frac{f_1}{f_2}\right)^2}\,, \tag{9.4}$$

where f_1 and f_2 are the carrier frequencies of the involved Galileo signals 1 and 2, while $\mathrm{TR}_1-\mathrm{TR}_2$ is the delay difference of the signals as contributed by the satellite payload. This formulation allows for easy translation of the dual-frequency clock correction information from the navigation message when using only a single-frequency receiver [9.11]. BGD accuracy was characterized, for example during the IOV campaign, and was found to be as expected around 30 cm. It is noted that BGD does not distinguish between pilot and data components. The ground segment measures BGD on the pilot components of the associated dual-frequency combination. The data components are

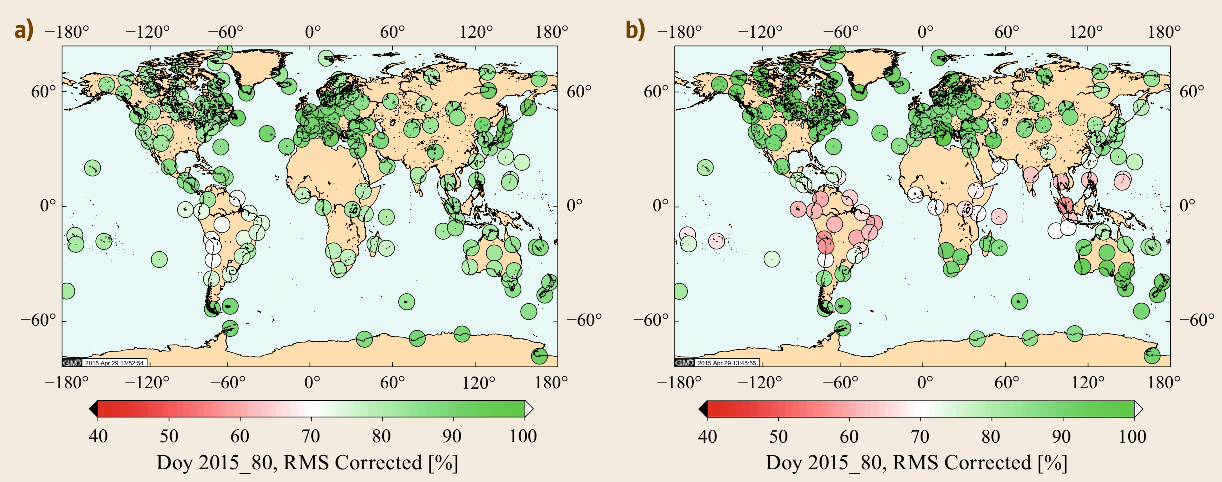

Fig. 9.15a,b Level of ionospheric correction and comparison of Galileo NeQuick G model **(a)** versus GPS Klobuchar model **(b)** for 21 May 2015

nearly identical to their pilot counterparts, in spectrum and modulation, and the method of signal generation on board ensures that tracking offsets between a data component and its pilot counterpart remain within a few cm, an order of magnitude smaller than BGD accuracy.

Message Uplink and Dissemination

The navigation message information is routinely generated by the orbitography and synchronization processing facility (OSPF) at intervals of 10 min. To decrease parameterization and quantization errors, the navigation message is generated in sets of eight batches, each batch marked through individual and unique issue of data (IOD) values. Subsets consisting of the first four batches are uploaded through mission uplink contacts and stored on board, using always the latest available sets. During the duration of mission uplink connections to each satellite, the message information broadcast from this satellite will thus also update approximately every 10 min, and the user is provided with the most recent and up-to-date navigation information. Between mission uplinks the satellites operate on the sets stored on board, broadcasting each message batch until it reaches a configured age of, for example, 180 min. Then the satellite selects the next message batch for dissemination, and will so step through the message batches in storage. In this example the broadcast of batches 2, 3, and 4 would start 3, 6, and 9 hours after the last mission uplink.

Navigation message batches can also be uplinked via telemetry, tracking and commanding (TT&C) stations. These uplinks can provide all batches 1–8 of a set, which allows longer operation on stored batches. In the above example, batches 5–8 would become valid 12, 15, 18, 21 hours after the last uplink contact. If there are no uplinks for intervals longer than the example 21 hours, the last message will be continuously transmitted regardless of its age.

In nominal operation the mission uplinks to the Galileo satellites will be scheduled tightly, for example such that the age of the onboard navigation message does not exceed 100 min, in support of using RAFS as master clocks. While using PHM master clocks the time between uplinks can then be extended.

These constraints need to be taken into account for sizing and location of the uplink station network. Accordingly, plans are for at least five uplink stations, where each station can operate up to four uplink antennas. This allows the supply of the complete Galileo constellation with timely navigation message data.

The broadcast of valid Galileo navigation messages started 12 March 2013, using the first four Galileo satellites, and then allowed for the first Galileo autonomous position fix [9.26].

Open Service Position and Ranging Error Accuracy

Position accuracy is monitored regularly. Receiver determined position solutions at user level, obtained in 2013 during periods with at least four Galileo satellites in visibility, are reported in [9.24], and since then the continuous deployment of the constellation and ground segment has led to the expected improvements. Position solutions collected in February 2016 are shown in Fig. 9.16, covering one 10 day ground track repeat cycle of the Galileo constellation. The position fixes were achieved through a dual-frequency E1b-E5a receiver

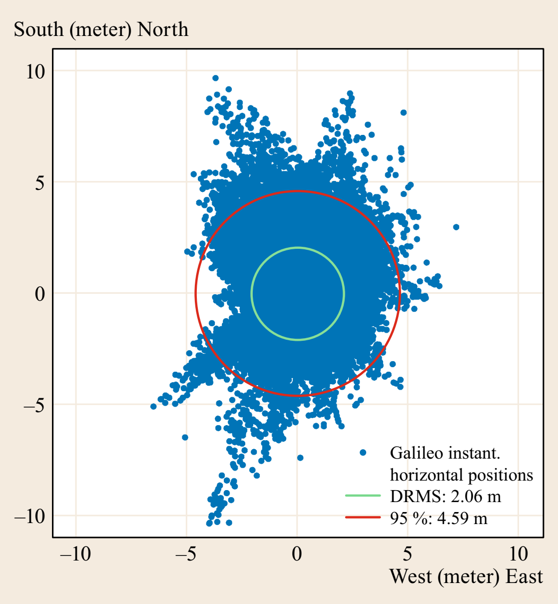

Fig. 9.16 Horizontal position accuracy at end-user level, Noordwijk, February 2016

where the geometry has been constrained for a geometric dilution of precision (PDOP) better or equal to 5. The measured horizontal accuracy shown in this example is well within expectations, exhibiting here less than 5 m 95% (green circle in Fig. 9.16).

These position results include the effect of dilution of precision, which is still not at nominal level due to the limited number of satellites available at the time of measurement.

The ranging accuracy is a figure of merit describing system performance per signal, before dilution of precision comes into effect. For example, SISE is derived by combining clock and orbit errors projected into the user direction. Its history during the project phases reflects the progress of system deployment and tuning. During IOV in 2013 only four satellites were available, and the ground segment was using only a subset of sensor stations. This initial validation achieved SISE results around 1.3 m 67%. In 2014 the SISE performance was approximately 1.0 m 67%, while in 2015, following the update of the ground segment, a SISE of 0.69 m 67% has been reached.

9.2.4 Timing Accuracy

The Galileo internal reference time is the Galileo System Time (GST), and is linked to Universal Time Coordinated (UTC). The navigation message provides GST-UTC information to allow estimation of UTC as an international time reference. To support interoperability with GPS, Galileo also provides the measured GPS-to-Galileo time offset (GGTO).

System Time Generation

GST is a continuous coordinate time scale in a geocentric reference frame, steered towards UTC modulo 1 second. GST is not subjected to leap seconds.

GST is used as reference time throughout all Galileo system facilities, ground station and satellite clocks.

The broadcast navigation message is time-tagged with GST and provides GST as a 32-bit binary field composed of Galileo week number (WN) and time of week (ToW) [9.11].

The initial epoch of GST is defined to be 00:00 UTC on Sunday 22nd August 1999. This corresponds to the last rollover of the GPS week number. The offset between GST and UTC at the initial epoch is defined as 13 seconds. The GST-UTC offset is changing with the introduction of new leap seconds. This definition is a contribution to GPS-Galileo interoperability insofar as GST has zero integer seconds offset to GPS Time.

The Galileo Time Service Provider (GTSP) links GST to UTC, through selected European timing laboratories, and provides the required frequency steering correction such that GST can be steered to UTC within 50 ns 95% modulo 1 s. The GTSP also provides the GST-UTC offset and the leap second announcements.

GST is generated by the Galileo Ground Mission Segment based on the atomic clocks of the Galileo Precise Time Facility (PTF). Galileo uses two redundant PTFs, one in each of the two control centers in Fucino, Italy and in Oberpfaffenhofen, Germany. Each PTF is equipped with two active hydrogen masers in hot-redundant configuration, and with four high-performance Cesium clocks. The physical realization of GST is defined as the maser output, steered to UTC modulo 1 second according to the GTSP steering corrections.

The quality of GST steering towards UTC is demonstrated for example through a collaboration with several European timing laboratories, comprising Istituto Nazionale di Ricerca Metrologica (Italy), National Physical Laboratory (UK), Observatoire de Paris (France), Physikalisch-Technische Bundesanstalt (Germany), Real Instituto y Observatorio de la Armada (Spain), and Swedish National Testing and Research Institute (Sweden). Already the early verification in 2013 demonstrated very good alignment and stability [9.27]. The subsequent monitoring confirms this steering quality, during all deployment stages of the related subsystems. Figure 9.17 shows an example measurement covering the period from 1 January 2014 to 31 May 2014. In this period the offset UTC – GST be-

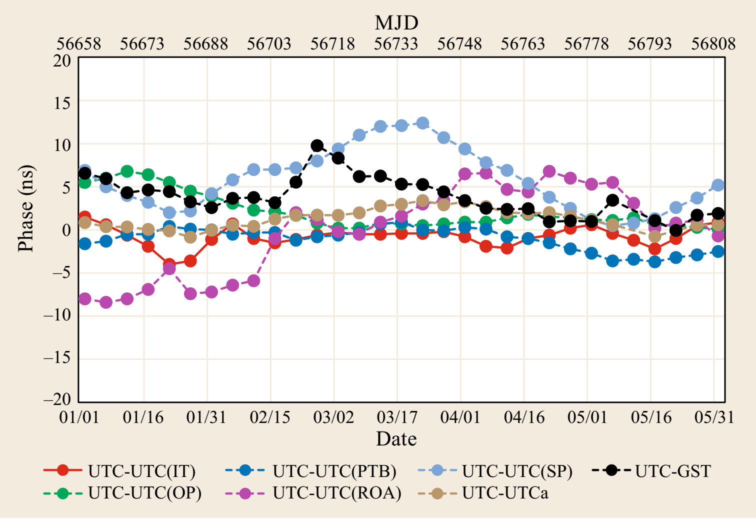

Fig. 9.17 GST versus UTC offset, relative to European timing laboratories; results from January to May 2014

tween the GST physical realization and UTC remains well within 10 ns, and the behavior of GST relative to UTC is quite similar to the evolution of the UTC offsets of the involved timing laboratories.

UTC Dissemination

In accordance with ITU Recommendation TF.460-6 [9.28], Galileo disseminates Universal Time Coordinated. For this purpose the Galileo navigation message contains GST-UTC conversion parameters including the total number of leap seconds (i. e., GST-UTC integer offset), announcement of introduction of new leap seconds with the associated date, fractional GST-UTC offset, and slope. Galileo users estimate GST from the broadcast navigation signals, then use the GST-UTC conversion parameters from the navigation message to estimate UTC for their applications. The GST-UTC conversion parameters are generated by the GTSP and updated daily.

The achievable Galileo UTC dissemination performance is being monitored by the Timing Validation Facility, a test and validation facility developed by ESA. Figure 9.18 shows the GST offset to UTC as disseminated by Galileo (UTC(SIS)) versus the rapid UTC solution, an official product of the Bureau International des Poids et Mesures (BIPM) closely approximating UTC. During the reported period May to September 2015 the UTC dissemination error was already well within expectations, but shows minor side effects and improvements in stability and offset due to ongoing calibration and equipment deployment.

GGTO Dissemination

GPS and Galileo system times are derived independently from each other. Both are kept aligned to UTC

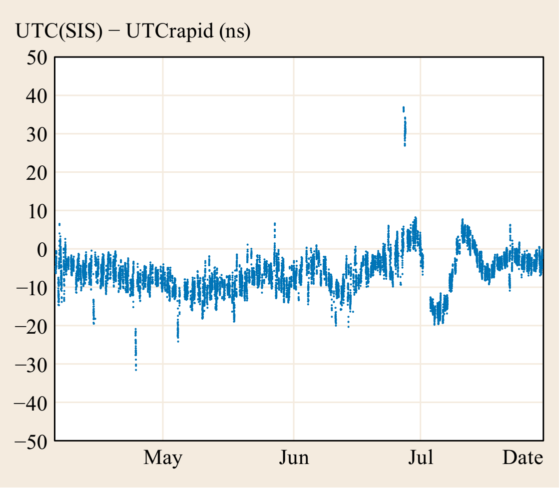

Fig. 9.18 Offset of UTC as disseminated by Galileo (UTC(SIS)) versus rapid UTC solution in 2015

within their respective GNSS. The Galileo PTF measures the offset between both system times and determines the GPS-to-Galileo time offset (GGTO), defined as the difference between the Galileo and GPS timescales, $\mathrm{GGTO} = t_{\mathrm{Galileo}} - t_{\mathrm{GPS}}$ [9.29–31]. GGTO is then distributed through Galileo's navigation message [9.11] to support combined use of Galileo and GPS systems. The provision of GGTO is expected to benefit user receivers in situations with obstructed field of view and limited numbers of visible satellites from a mixed constellation, can support integrity monitoring, and can support receiver internal calibration.

GPS has been chosen as the reference due to being the best established GNSS at the time. Currently Galileo does not provide offsets to other GNSS than

GPS. If all GNSS would provide their time offset relative to the same common reference, then a receiver could determine all required offsets for using any combination of measurements from mixed constellations for PVT computation. There would be no functional need to provide multiple offsets to different GNSSs within each navigation message. However, if this common reference would fail, all related and derived offsets may degrade or become unavailable. If the approach of a common reference were chosen, at least two independent references are recommended for use and the respective deltas to be provided through the navigation message(s). UTC may be one, and a selected GNSS the other.

Figure 9.19 shows an example measurement of the difference between broadcast GGTO and a posteriori measured GGTO, in August/September 2015.

During the IOV phase, the broadcast GGTO parameters were computed based on time transfer between the Galileo Precise Time Facility and the US Naval Observatory. In the completed Galileo ground segment the GGTO is being measured using calibrated Galileo-GPS receivers, which will improve the accuracy of this parameter.

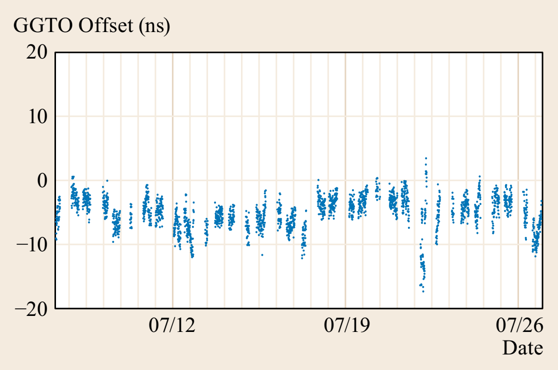

Fig. 9.19 Deviation of broadcast GGTO from measured GGTO in the period 25 November – 6 December 2013

9.3 Spacecraft

Galileo satellites are 700 kg/1500 W class spacecraft (Fig. 9.20, [9.32]). The first Galileo satellites GSAT0101...0104 were manufactured by EADS Astrium GmbH as satellite prime, and launched in pairs: a first dual launch to orbital plane A on 21 October 2011, followed by a dual launch to plane B on 12 October 2012.

The next family of Galileo satellites GSAT02xx is being manufactured by OHB System AG in Bremen, Germany, as prime [9.33]. A total of 22 satellites will be produced under this order. The first dual launch of this family in August 2014 was impaired by a malfunction in the Fregat stage of the Soyuz launcher, and the satellites GSAT0201 and -0202 were placed into a nonnominal elliptic orbit. In 2015 their orbits were corrected as far as possible using the onboard resources. The navigation payloads were then activated and tested, to validate technology and performance, and the satellites since then broadcast navigation signals and are used for clock technology validation. Since nominal orbits were not reached these satellites cannot be accommodated in parts of the navigation message. GSAT0201 and -0202 are however healthy, and ESA is working to incorporate these satellites into the ground processing. The follow-

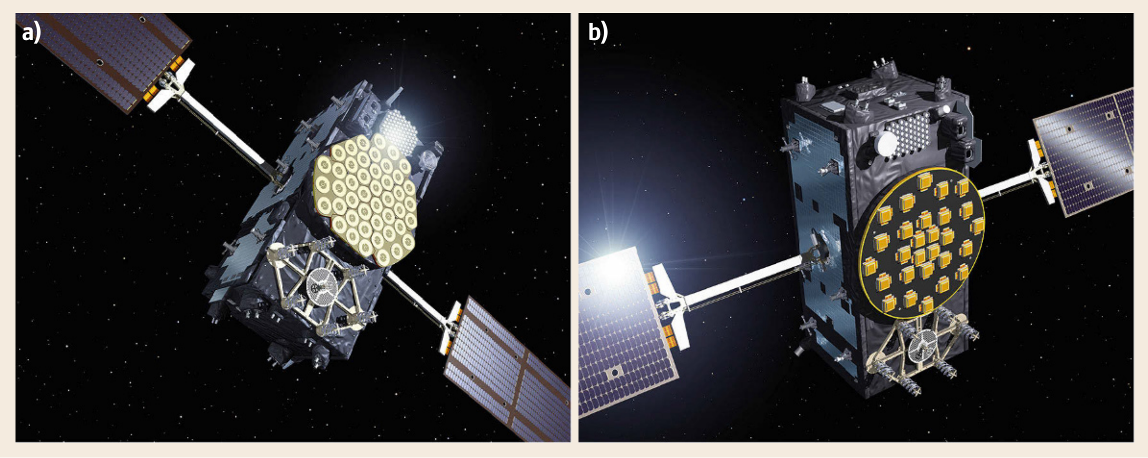

Fig. 9.20a,b Galileo satellites (artistic pictures, **(a)** GSAT010x, **(b)** GSAT02xx), (courtesy of ESA/P. Carril)

ing dual launches in March 2015, September 2015 and December 2015 reached the foreseen orbits, and the satellites became part of the nominal constellation.

9.3.1 Satellite Platform

A Galileo satellite can be partitioned into the classical components of a satellite design, that is platform (Table 9.8) and payload. The platform then comprises further subsystems for onboard data handling and control, attitude and orbit control including propulsion, power generation and distribution, thermal control, telemetry, and a laser retro reflector.

The attitude and orbit control system (AOCS) of the Galileo satellites is using three-axis attitude control during all phases and maneuvers [9.34] Several operational modes are derived to support the mission sequence of events:

1. During the launch and early orbit phase (LEOP) as well as in contingency situations and safe modes, dedicated acquisition modes are used for Earth or Sun acquisition.
2. Orbit acquisition, station-keeping maneuvers, and end-of-life (EOL) decommissioning can use a dedicated orbit change mode. According to the Galileo orbit design very limited need of station-keeping maneuvers is anticipated [9.1, 6].
3. Normal mode is the nominal operational mode with full nadir pointing performance. This mode uses yaw steering to orient the solar panels towards the Sun, and to support the thermal control of the satellite.

In normal mode, the AOCS sensor/actuator configuration is based on Earth and Sun sensors for keeping the satellite pointed at Earth: the infrared Earth sensors detect the temperature contrast between the cold of deep space and the warmth of Earth's atmosphere, while the Sun sensors are visible-light detectors measuring the angle to the Sun. Angular momentum provided through reaction wheels is used to control attitude and rotational rate. The satellite rotates twice per orbit, to facilitate Sun-pointing of the solar wings. The angular momentum gradually accumulated by the reaction wheels is unloaded through magnetorquers, magnetic coils controlled to deliver the needed torque through interaction with the Earth magnetic field. Gyros are available for additional rate sensing. In operational modes except the nominal mode, thrusters can be used for impulse and attitude control.

The propulsion subsystem is based on monopropellant thrusters. The propulsion subsystem is typically equipped with a set of eight thrusters. Each thruster provides, under beginning of life (BOL) conditions, a nominal thrust of 1 N using monopropellant-grade hydrazine. GSAT010x and -02xx are designed for direct injection into the final orbit, thus their propulsion subsystems need to provide only the delta-velocity capability needed for orbit correction maneuvers.

The power subsystem is responsible for the generation, storage conditioning and distribution of relevant power to the satellite. For the GSAT010x and -02xx families a classical regulated 50V bus architecture has been selected, which consists of

1. A power conditioning and distribution unit providing electrical power to all units on board the spacecraft
2. Two solar array wings supplying electrical power to the spacecraft during sun exposition and in parallel charging the battery after the eclipse phases
3. And a Li-Ion battery, storing the power provided by the solar arrays during the Sun phases and providing it during the eclipse phases.

The TT&C subsystem of GSAT010x and -02xx satellites is the link to the ground control segment by providing redundant command reception and telemetry transmission at S-Band. The TT&C subsystem operates in both ESA standard TT&C mode and spread spectrum mode. Accurate range-rate (Doppler) measurements are possible when the S-Band transponder is operated in coherent mode. S-Band TT&C operations are provided via hemispherical-coverage helix antennas situated on opposite sides of the satellite. Designed for orthogonal circular polarization, together they provide omnidirectional coverage for reception and transmission. Ranging operation is performed simultaneously with telemetry transmission.

The laser retro reflector (LRR) allows the measurement of the satellite's distance to within a few centimeters by reflecting a laser beam emitted from a ground station. The cat's eye reflector array of the LRR can be recognized on the Nadir panels of both Galileo satellite families shown in Fig. 9.20, just aside the navigation transmit antenna of the satellite. Laser ranging campaigns using the LRR are planned to be performed on average about once a year. In between the LRR campaigns, altitude measurements via S-band telemetry and telecommand link are used, which are sufficiently accurate to serve as intermediate measures.

9.3.2 Satellite Payload Description

The payload of Galileo satellites comprises a fully redundant triple-band navigation payload, and a SAR repeater [9.35].

The navigation payload can be functionally grouped into the mission uplink data handling system, a tim-

Table 9.8 Overview of main satellite platform characteristics

	GSAT010x	GSAT02xx
Satellites	4	22
Mass at launch	Approx. 700 kg	Approx. 715 kg
Size with solar array deployed	2.7 m × 1.6 m × 14.5 m	2.5 m × 1.1 m × 14.7 m
Design lifetime	12 years	12 years
Available power	1.4 kW	1.9 kW

ing subsystem, and the signal generation and transmitter subsystem.

The mission uplink data handling system receives the navigation message data and all related support data, through a dedicated code division multiple access (CDMA)-type C-band uplink served by the uplink stations of the Galileo ground segment.

The timing subsystem generates the onboard frequency reference, derived from an atomic clock as reference. Two different types of onboard clock technology are deployed, that is a rubidium atomic frequency standard and a passive hydrogen maser as shown in Fig. 9.21. The navigation payload contains two units of each technology, four clocks in total. Nominally one clock is operated as master clock, and one clock is hot redundant spare. The interface between the four clocks and the navigation signal generator unit is provided by a dedicated clock monitoring and control unit, which is also used for synchronization of master clock and active spare clock [9.36, 37]. This allows the spare to take over seamlessly should the master clock fail.

The navigation payload provides navigation signals on three carriers E1, E6 and E5 in the lower L-band. The generation of all navigation signals and their components is strictly coherent to the common frequency reference from the timing subsystem. E5 offers a wideband AltBOC signal of more than 50 MHz bandwidth containing two BPSK(10) subcarriers 30.69 MHz apart, each providing a pilot/data pair. The open signals on E6 and E1 are BPSK- and BOC-type modulations offering 31–41 MHz usable bandwidth (Table 9.4). The navigation signals are radiated through a dual-band transmit antenna, using a common antenna subsystem for E5 and E6 [9.38, 39].

Stability of the onboard reference frequency is one of the core performance parameters for the quality of the navigation payload. Example Allan deviation (ADEV) measurements from mid-2015 are shown in Fig. 9.22, covering exemplary RAFS and PHM results of GSAT010x and GSAT02xx satellites. The typical performance of the two clock technologies is clearly discernible.

The search-and-rescue repeater provides enhanced distress localization functionality for the provision of a SAR service. It is part of the Cospas-Sarsat MEOSAR System, and is interoperable with other MEOSAR repeaters on Globalnaja Nawigazionnaja Sputnikowaja Sistema (Russian Global Navigation Satellite System) (GLONASS) and future GPS satellites [9.8–10]. The SAR transponder on Galileo satellites receives distress alerts in the 406.0–406.1 MHz band from any Cospas-

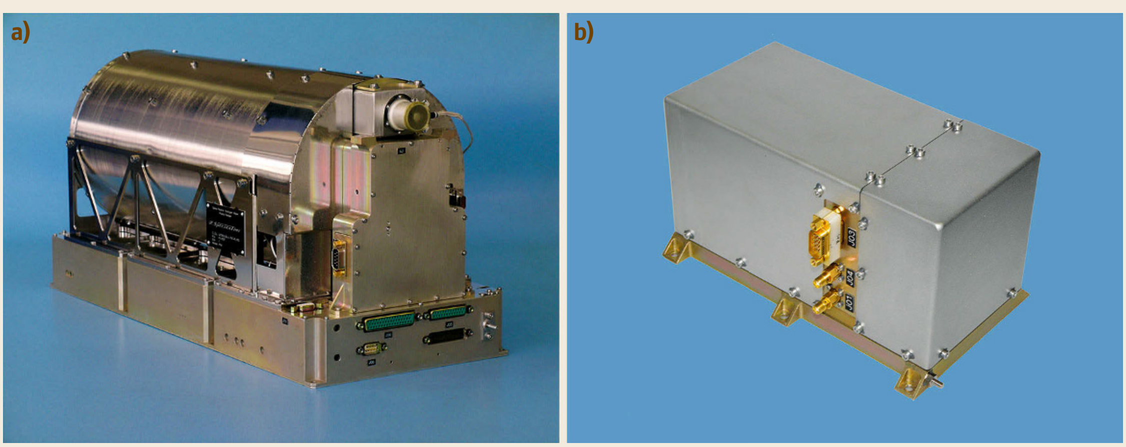

Fig. 9.21a,b Galileo passive hydrogen maser clock **(a)** and rubidium atomic frequency standard **(b)** (courtesy of Spectratime)

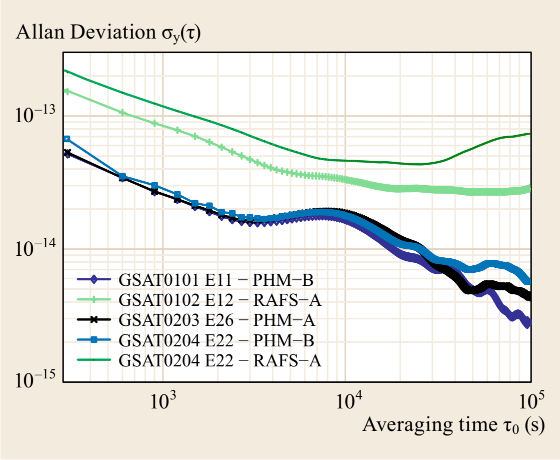

Fig. 9.22 Galileo PHM and RAFS frequency stability in mid-2015

Sarsat beacon, translates them to the SAR downlink band at 1544 MHz and rebroadcasts this signal to dedicated ground stations, medium altitude Earth orbit (MEO) Local User Terminals, which perform beacon localization in near real time based on difference of arrival (DOS) measurements of time and frequency [9.40].

Galileo also provides a SAR return link service, initially foreseen to inform the alerting beacon and thus the distressed people that the distress message has been received by the Cospas-Sarsat system. This acknowledgment is embedded in the navigation message [9.41].

9.3.3 Launch Vehicles

Galileo satellites are launched from the Guiana Space Centre, Europe's Spaceport in French Guiana, using Soyuz and Ariane launchers. The first twelve satellites were using Soyuz launchers, in a series of dual launches on October 2011, October 2012 (Fig. 9.23), August 2014, and March, September and December 2015.

The Soyuz launcher is the workhorse of the Russian space program, in continuous production since the 1960s, and a descendant in design terms of the R-7 rocket that launched Sputnik 1 in 1957, inaugurating the Space Age.

Soyuz has performed more than 1700 manned and unmanned missions. It is designed to extremely high reliability levels for its use in manned missions – today supporting operations of the International Space Station. The launch of GSAT0201 and -0202 in August 2014 ending in a nonnominal orbit will therefore hopefully remain an exception.

For French Guiana launches, this three-stage rocket plus the Fregat upper stage is assembled horizontally in the traditional Russian approach, then moved to the vertical so that its payload can be mated from above in the standard European way. A new mobile launch gantry aids this process, while also protecting the satellites and the launcher from the humid tropical environment.

For Galileo, a specially designed dispenser holds the two IOV satellites in place side by side during launch and then releases them sideways into their final orbits.

Fig. 9.23 Soyuz Launch Base at the European Space Port (CSG) French Guiana, ©ESA/S. Corvaja

A special version of the Soyuz launcher is also being used: the more powerful Soyuz ST-B variant, including a Fregat-MT upper stage, delivers the Galileo satellites into their final circular 23 222 km orbit.

The re-ignitable Fregat was previously used in its baseline version to deliver ESA's GIOVE-A and -B experimental satellites. Fregat-MT carries an additional 900 kg of propellant.

Alternatively a requalified Ariane 5 ES *Galileo* is available, able to deploy four Galileo satellites into MEO orbit. The first such fourfold launch is foreseen for the last quarter of 2016.

The Ariane 5 ES version is an evolution of the initial Ariane 5 generic launcher that has been upgraded to allow re-ignition and long coast phases. These capabilities are necessary to inject a cluster of four Galileo satellites into their operational orbit. Re-ignition is also required to vacate the injection orbit after releasing the payload, for graveyarding of the last launcher stage outside the nominal Galileo orbit.

9.4 Ground Segment

The Galileo ground segment (Fig. 9.24) comprises a Ground Control Segment (GCS) for satellite and constellation control, and a Ground Mission Segment (GMS) for service-related tasks.

The ground control segment performs all functions related to command and control of the satellite constellation. It includes a worldwide network of S-band TT&C stations hosted on Galileo remote sites, to provide global coverage.

The ground mission segment measures and monitors the Galileo navigation signals, computes the navigation message data and distributes it to the satellites. For this purpose the GMS includes two worldwide networks of stations:

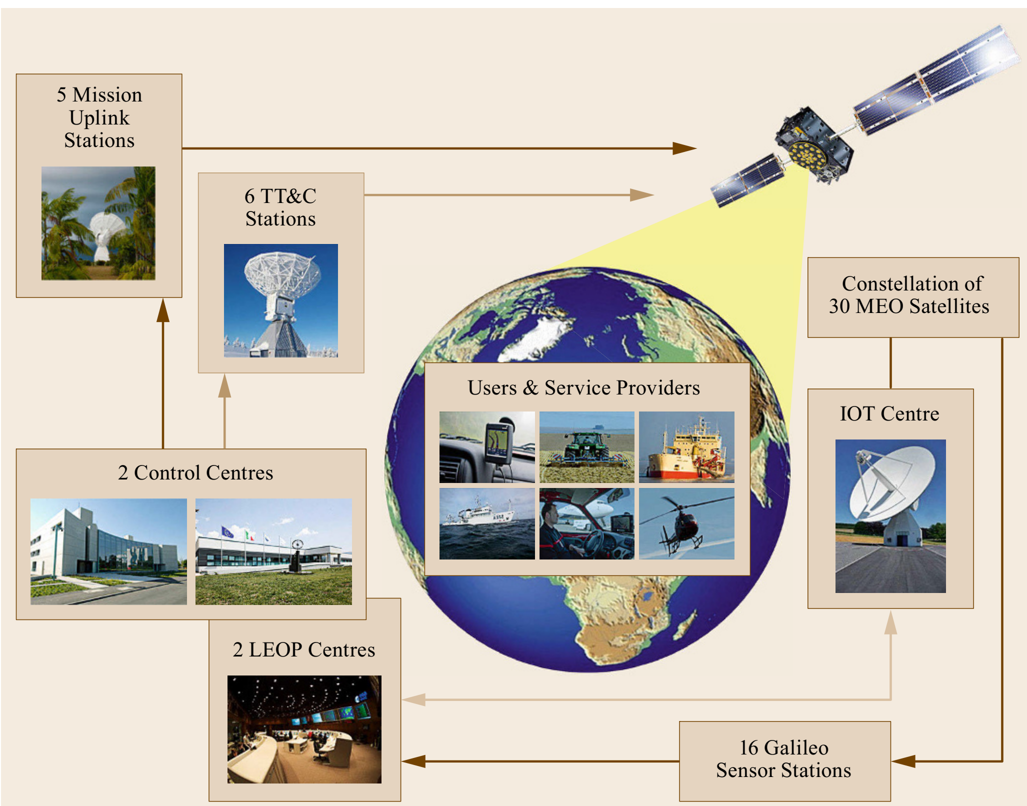

Fig. 9.24 Galileo system overview (courtesy of ESA/M. Pedoussaut, ESA/S. Corvaja, ESA/J. Mai, ESA/J. Huart, DLR, Telespazio)

1. L-band Galileo sensor stations (GSS) to collect ranging measurements of the Galileo navigation signals, for orbit determination, time synchronization and monitoring of the signal in space
2. C-band uplink stations (ULS) to uplink mission data (e.g., ephemerides and clock prediction, SAR return link and commercial service data).

GCS and the GMS core facilities are deployed in two Galileo control centers (GCC) located in Oberpfaffenhofen (Germany) and Fucino (Italy). A global data dissemination network connects all ground facilities. In their final configuration both control centers and the data dissemination network will be redundant such as to ensure service and operations continuity.

Two additional launch and early operation (LEOP) control centers (LOCC) located in Toulouse (French Space Agency, CNES) and Darmstadt (ESA Operations Centre, ESOC) provide the necessary services to take control of the satellites after their separation from the launch vehicle and until they have reached their position within the assigned orbital slots.

Each LEOP is followed by in-orbit testing (IOT) to verify satellite payload health and survival of the launch. These tests are supported by the designated IOT station in Redu (Belgium), which comprises a calibrated high-gain antenna and measurement system for the L-band navigation signals, and testing equipment and transmitters for the C-band and SAR UHF RF links. A second use of the IOT station Redu is for regular signal characterization during routine operations.

The ground segment manages interfaces to the satellite manufacturers, needed for onboard software maintenance, operations support and telemetry analysis, and in support of eventual troubleshooting of satellite platform and payload units.

Further external interfaces of the Galileo ground segment are installed, to connect to entities contributing to the provision of Galileo services:

1. The GNSS service center (GSC), foreseen as an interface between the Galileo system and external data providers for the Galileo open service (OS) and the Galileo commercial service (CS). The GSC facility is located near Madrid, Spain.
2. The Galileo security monitoring centers (GSMC) providing system security monitoring, management of the public regulated service user segment, and the point of contact platforms (POCP) to interface with national competent PRS authorities (CPA). GSMC facilities are located in France and in the United Kingdom.
3. The time and geodetic reference service providers (TSP, GRSP) to monitor and steer Galileo System Time and Galileo Terrestrial Reference Frame vis-a-vis international meteorological standards.
4. The SAR Galileo data service provider (SAR GDSP) to carry out the position determination of the distress alert emitting beacons once they have been detected by the dedicated ground segment, and to provide SAR return link messages for dissemination through the Galileo navigation signals. The SAR GDSP premises are located in Toulouse, France.
5. The Galileo reference center (GRC) to provide independent performance monitoring of the Galileo services. The GRC facility will be located in Noordwijk, the Netherlands.

These service providers are procured, coordinated and operated by the European GNSS Agency (GSA), an institution of the European Union tasked with the operation of the Galileo system, and in charge of service provision and quality of the operational system.

9.5 Summary

Galileo is a joint initiative of ESA and the European Commission (EC), to deploy a highly accurate and independent GNSS under civilian control. Compatibility and interoperability with existing GNSSs and especially with GPS were important requirements during the concept and design studies. The procurement of the Galileo system was launched in 2008, and has since then proceeded with space and ground segment development, manufacturing and deployment. The number of signals from Galileo satellites available for testing and development is increasing with deployment, and this enabled the first Galileo-only position fix to begin 2013 and successful in-orbit validation in the second half of 2013. The simultaneous successful build up of the ground mission and control segments with their worldwide infrastructure is bringing the system into an operational state. Interfaces to external service providers as well as the services themselves are being installed. All these deployments are accompanied by a continuous process of system verification and tuning, visible in the steady improvement of the already good initial results. The sum of these efforts will allow the start of initial services in 2016, with nine nominal satellites plus two satellites in nonnominal orbits, and with the prospect of six more satellites to be launched in 2016. Successful validation of this system configuration will be the starting point of the exploration phase, planned for 2017, where Galileo will become officially available. The full constellation of 24 satellites plus in-orbit spares and the completion of the ground segment will be reached in 2020.

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