Galileo Frequency & Signal Design

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Europe's program to develop an independent satellite-based positioning system — Galileo — seeks to balance several goals: taking advantage of technological innovation while optimizing the compatibility and interoperability of Galileo and GPS. Over the past two years, a task force of experts has developed a proposal for a Galileo frequency plan and signal design that can help meet these goals. This article describes the current status of their efforts.

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This article describes the Galileo frequency structure and signal design as developed by the European Commission's Galileo Signal Task Force (STF). The European Commission (EC) established the task force in March 2001. Chaired by the EC, the STF consists of experts nominated by European Union (EU) member states, official representatives of the national frequency authorities, and experts from the European Space Agency (ESA).

The Signal Task Force is playing a major role in determining the Galileo frequency and signal design. The STF reports to the EC Galileo Steering Committee through the EC for approval. One task of the STF is to look for ways to optimize the interoperability of Galileo with the Global Positioning System (GPS). The Signal Task Force also contributes to the preparation of the next World Radio Conference (WRC) to be held by the International Telecommunications Union (ITU) in 2003 (WRC2003).

This article presents the most recent proposal for the Galileo frequency and signal structure. It first discusses the relevant requirements for the system. The discussion then describes the mapping of Galileo services to signals, followed by detailed considerations (noise and multipath) of the relevant frequency bands. We discuss the results from interference analyses as well as the matter of interoperability and compatibility with GPS in terms of signal structure and geodetic and time reference frame.

Signal Requirements

The European Union intends for the Galileo system to provide four navigation services and one search and rescue (SAR) service. The primary signals of Galileo are intended to provide an "Open Service" (OS) of a high quality, consisting of six different navigation signals on three carrier frequencies. OS performance will at least equal that expected from the "follow-on" generation (Block IIF) of GPS satellites scheduled to begin launching in 2005 and the future GPS III system architecture currently being investigated.

The GPS IIF/III satellites will offer wideband signals on three civil (open) frequencies: one high-chipping rate signal (L5 centered at 1176.45 MHz) and two low-chipping rate signals (L1 at 1575.42 MHz, L2 at 1227.60 MHz). Moreover, the GPS modernization program will offer additional civil and military code structures on L2.

Compatible, Independent. Among the leading goals of the STF's efforts was ensuring compatibility and interoperability with other satellite navigation systems, particularly GPS, and other uses of the portions of the RF spectrum in which Galileo will operate. The EC policy paper that lead to the Galileo Resolution at the Transport Council Meeting on June 17, 1999, stated this objective as follows: "Galileo must be an open, global system, fully compatible with GPS, but independent from it."

At its 25–26 March 2002 meeting (during which the development phase of Galileo was finally decided), the Transport Council of the European Union again underlined its desire that compatibility and interoperability with GPS should be one of the key drivers for Galileo. The present Galileo signal plan achieves a maximum of interoperability to GPS, while still reducing vulnerability when using one system as a back-up of the other.

Independence means preventing or reducing vulnerability to simultaneous failures of GPS and Galileo. This can be achieved in part by maintaining separate space and ground infrastructures and control systems, and in part by implementing distinct signal designs and separate frequencies.

In order to discuss the term "fully compatible with GPS" in more detail, we must consider the general users of a Global Navigation Satellite System (GNSS). For their work, these users want to be able to track as many satellites as possible in order to increase positioning performance and have redundancy for signal availability, integrity, and continuity. The best way to achieve this is through use of an "all-in-view," combined (Galileo/GPS) receiver, which can be manufactured cheaply only when the design is as simple as possible.

This can be achieved well if GPS and Galileo signals use the same centre frequencies, because use of multiple frequencies by GNSS receivers would require several front-ends (antenna elements, RF integrated circuits, and low noise amplifiers) and a more complex signal processing design. Multiple frequencies also introduce frequency biases in the receiver that have to be solved either by calibration (if possible) or by incorporating extra observations into the positioning algorithm in order to determine and eliminate these biases.

Security Aspects. A global satellite navigation system, even a civilian one such as Galileo, must also consider global security aspects. Satellite navigation is nowadays — and even more in the future — used in critical infrastructure where an uninterrupted GNSS service is absolutely vital. Examples can be found in telecommunications, electrical energy distribution, banking and financial transactions, and other sectors where, in particular, GNSS time is used.

In these sectors an interrupted service would provoke a chain of other malfunctioning services. Disruption of GNSS services is a potential threat for national and world economic systems as well as safety and security-related applications. Misuse of GNSS services can threaten national security. Consequently, spectral separation and secure, controlled-access services are ways to protect GNSS users against interruption. A good example is the decoupling of military and civil services in the modernized GPS by using different waveforms. In times of a crisis, civil services must be "jammable" without affecting the military and/or security signals.

Interference Issues. A new GNSS service must avoid interfering with existing services that operate in the same portion of the RF spectrum, including GPS and Russia's GLONASS system. Depending on the choice of the signal power level and the chipping rate, it may be acceptable for a signal to have a spill-over of side-lobes into neighboring frequency bands as long as the interference is insignificant as defined by ITU rules and below a certain level (less than 0.25 dB). Overlays on identical carrier frequencies might even be possible using different waveforms and code structures that don't interfere significantly with each other. This latter approach represents part of the Galileo signal and frequency plan proposed by the STF.

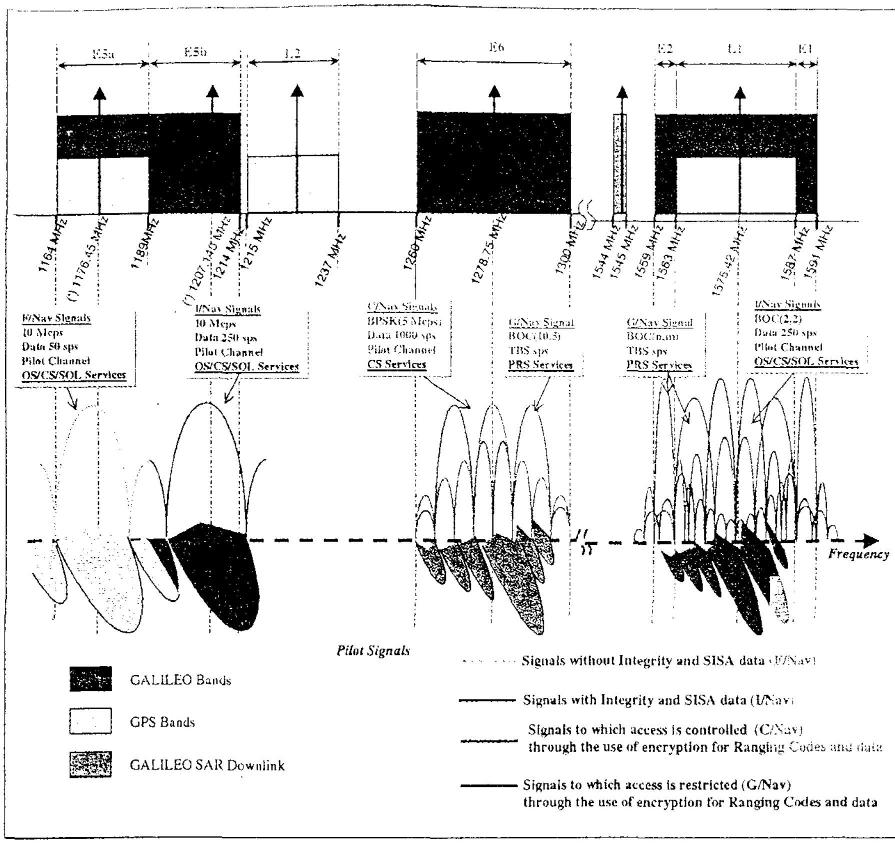

FIGURE 1 Galileo frequency spectrum

Recent Developments

During summer of 2002, several modifications took place in the baseline STF proposal previously presented, leading to a refined signal structure. (For the earlier proposal, see the article by G. Hein et al, "The Galileo Frequency Structure and Signal Design," 2001, listed in the Further Readings section at the end of this article.) The main changes and add-ons concern the following:

In the lower L-band (that is, E5a and E5b) the central frequency for E5b was moved to 1207.140 MHz in order to minimize possible interference from the Joint Tactical Information Distribution System (JTIDS) and the Multifunctional Information Distribution System (MIDS). All signals on E5a and E5b are using chip rates of 10 Mcps. The modulation for that band is still being optimized with the possibility of processing very wideband signals by jointly using the E5a and E5b bands. This joint use of the bands has the potential to offer enormous accuracy for precise positioning with a low multipath. Data rates have also been fixed.

In the middle (that is, E6) and upper (E2-L1-E1) L-band data and chip rates were also defined as well as Search and Rescue (SAR) up- and downlink frequencies.

Extensive interference considerations took place in E5a/E5b concerning Distance Measuring Equipment (DME), the Tactical Air Navigation System (TACAN) and the Galileo overlay on GPS L5; in

E6 concerning the mutual interference to/from radars and in E2-L1-E1 frequencies with regard to the Galileo overlay on GPS L1.

The EC Signal Task Force and ESA have refined criteria for the code selection and have as well formulated the requirements on each frequency. Reference codes have been selected allowing initial assessments. Parallel investigations are on-going addressing alternate solutions for the Galileo codes and targeting improved performances. (See the article, A New Class of Spreading Codes Exhibiting Low Cross-Correlation Properties, by T. Pratt in the Further Readings section.)

Frequency, Signal Baseline

Galileo will provide 10 navigation signals in right-hand circular polarization (RHCP) in the frequency ranges 1164–1215 MHz (E5a and E5b), 1260–1300 MHz (E6) and 1559–1592 MHz (E2-L1-E1), which are part of the Radio Navigation Satellite Service (RNSS) allocation. (The frequency band E2-L1-E1 is sometimes denoted as L1 for convenience.)

Figure 1 presents an overview of these signals, indicating the type of modulation, the chip rate, and the data rate for each signal. The figure also highlights the carrier frequencies, as well as the frequency bands that are common to GPS. All the Galileo satellites will share the same nominal frequency, making use of code division multiple access (CDMA) techniques compatible with the GPS approach.

Six signals, including three data-less channels or pilot tones (ranging codes not modulated by data), are accessible to all Galileo users on the E5a, E5b, and E2-L1-E1 carrier frequencies for OS and Safety-of-life Services (SoL). Two signals on E6 with encrypted ranging codes, including one data-less channel, are accessible only to some dedicated users who gain access through a given Commercial Service (CS) provider. Finally, two signals (one in E6 band and one in E2-L1-E1) with encrypted ranging codes and data are accessible to authorized users of the Public Regulated Service (PRS).

A 1/2-rate Viterbi convolutional coding scheme is used for all the transmitted data messages.

Four different types of data are carried by the different Galileo signals:

- OS data, which are transmitted on the E5a, E5b and E2-L1-E1 carrier frequencies. OS data are accessible to all users and include mainly navigation data and SAR data.
- CS data transmitted on the E5b, E6 and E2-L1-E1 carriers. All CS data are encrypted and are provided by service providers that interface with the Galileo Control Centre. Access to those commercial data is provided directly to the users by the service providers.
- SoL data that include mainly integrity and Signal in Space Accuracy (SISA) data. Access to the integrity data may be controlled, however this is not foreseen in the short term.
- PRS data, transmitted on E6 and L1 carrier frequencies.

A synthesis of the data mapping on Galileo signals appears in **Table 1**.

Modulation Schemes

Given the frequency plan defined earlier and the target services based on the Galileo signals, the type of modulation of the various Galileo carriers results from a compromise among the following criteria:

- Minimization of the implementation losses in the Galileo satellites, making use of the current state of the art of the related satellite components.
- Maximization of the power efficiency in the Galileo satellites.
- Minimization of the level of interference induced by the Galileo signals in GPS receivers.
- Optimization of the performance and associated complexity of future Galileo user receivers.

The following subsections describe the modulation chosen for each Galileo carrier frequency. For the E5 band in particular, the trade-off analysis is continuing. Consequently, we will describe the two alternate solutions under consideration.

The main modulation parameters for Galileo signals are summarized in Table 1. Equations 1–3 use the following notation:

- $C_X^Y(t)$ is the ranging code on the Y channel ("Y" stands for I or Q for two-channel signals, or for A, B, or C for three-channel signals) of the X carrier frequency ("X" stands for E5a, E5b, E6 or L1).
- $D_X^Y(t)$ is the data signal on the Y channel in the X frequency band.
- F_X is the carrier frequency in the X frequency band.
- $U_X^Y(t)$ is the rectangular subcarrier on the Y channel in the X frequency band.
- m is a modulation index, associated with the modified Hexaphase modulation.

Modulation of the E5 Carrier. The modulation of E5 will be done according to one of the following schemes:

Case A: Two quadrature phase shift keying or QPSK(10) signals will be generated coherently and transmitted through two separate wideband channels on E5a and E5b respectively. The two separate E5a and E5b signals will be amplified separately and combined in RF through an output multiplexer (OMUX) before transmission at the 1176.45 MHz and 1207.14 MHz respective carrier frequencies. In Case A the E5 signal can be written as **Equation 1**.

Equation 1

$$S_{E5}(t) = (C_{E5a}^{I}(t)D_{E5a}^{I}(t)\cos(2\pi F_{E5a}t) - C_{E5a}^{Q}(t)\sin(2\pi F_{E5a}t)) + (C_{E5b}^{I}(t)D_{E5b}^{I}(t)\cos(2\pi F_{E5b}t) - C_{E5b}^{Q}(t)\sin(2\pi F_{E5b}t))$$

Case B: One single wideband signal generated following a modified binary offset carrier (BOC) modulation called AltBOC(15,10) modulation. The arguments (f_s, f_c), denote the subcarrier frequency f_s and the code rate f_c. This signal is then amplified through a very wideband amplifier before transmission at the 1191.795 MHz carrier frequency.

The modulation in Case B is a new modulation concept. The most interesting aspect of this concept is that it combines the two signals (E5a and E5b) into a composite constant envelope signal, which can then be injected through a very wideband channel. This wideband signal then can then be exploited in the receivers.

The alternate BOC modulation scheme is based on the standard BOC modulation. The standard BOC modulation is a square subcarrier modulation in which the signal is multiplied by the rectangular subcarrier of the frequency f_s, which splits the spectrum of the signal into two parts located at the left and right side of the carrier frequency. The alternate BOC (AltBOC) modulation scheme aims at generating a single subcarrier signal adopting a source coding similar to the one involved in the standard BOC. The process allows to keep the BOC implementation simplicity and a constant envelope while permitting to differentiate the lobe. A detailed description of the AltBOC modulation can be found in the articles by L. Ries et al. (2002b and 2003) listed in the "Further Readings" section.

Implementation trade-offs and performance comparison between the processing of the very wideband BOC(15,10)-like signal and the joint processing of two separate QPSK signals of 10 Mcps on E5a and E5b is ongoing.

Modulation of the E6 Carrier. The E6 signal contains three channels that are transmitted at the same E6 carrier frequency. The multiplexing scheme among the three channels is a major point under consideration

TABLE 1 Main Galileo navigation signal parameters. QPSK = quadrature phase shift keying; BPSK = binary phase shift keying

Frequency Bands	E5a		E5b		E6			E2-L1-E1		
Channel	I	Q	I	Q	A	B	C	A	B	C
Modulation type	being optimized [AltBOC(15,10) or two QPSK(10)]				BOC(10,5)	BPSK (5)	BPSK(5)	flexible	BOC(2,2) BOC(n,m)	BOC(2,2)
Chip rates	10 Mcps	10 Mcps	10 Mcps	10 Mcps	5.115 Mcps	5.115 Mcps	5.115 Mcps	m × 1.023 Mcps	2.046 Mcps	2.046 Mcps
Symbol rates	50 sps	N/A	250 sps	N/A	TBD sps	1000 sps	N/A	TBD sps	250 sps	N/A
User minimum received power at 10° elevation	−158 dBW	−158 dBW	−158 dBW	−158 dBW	−155 dBW	−158 dBW	−158 dBW	−155 dBW	−158 dBW*	−158 dBW*

* a value of −160 dBW is currently under consideration for B and C channels, E2-L1-E1

today, which shall be carefully optimized. This optimization process shall take into account the complexity of the modulation concepts' implementation in the satellite payload and receivers as well as associated performance (including compatibility aspects).

The investigated solutions are time multiplexing and a modified hexaphase modulation (or interplex modulation). The modified hexaphase is taken as the baseline, but the final selection process is on going between those two potential solutions.

For the modified hexaphase modulation, a QPSK signal resulting from the combination of two channels is phase modulated with the third channel, with a modulation index being used to set the relative power among the three channels.

With this current assumption, the E6 signal can be written as **Equation 2**.

Equation 2

$$S_{E5}(t)=(C_{E6}^{A}(t)D_{E6}^{A}(t)U_{E6}^{A}(t)\cos m - C_{E6}^{C}(t)\sin m)\cos(2\pi F_{E6}t) - (C_{E6}^{B}(t)D_{E6}^{B}(t)\cos m + C_{E6}^{A}(t)D_{E6}^{A}(t)U_{E6}^{A}(t)C_{E6}^{B}(t)D_{E6}^{B}(t)C_{E6}^{C}(t)\sin m)\sin(2\pi F_{E6}t)$$

To be consistent with the relative power required among the three channels, a value of m = 0.6155 has been chosen for the modulation index.

Modulation of the E2-L1-E1 Carrier. In the same way as the E6 signal, the L1 signal contains three channels that are transmitted at the same L1 carrier frequency using a modified hexaphase modulation. Time multiplexing is also being analyzed.

With the baseline modified Hexaphase based solution, the E2-L1-E1 signal can be written as **Equation 3**.

The same modulation index of m=0.6155 is used.

Equation 3

$$S_{L1}(t) = (C_{L1}^{A}(t)D_{L1}^{A}(t)U_{L1}^{A}(t)\cos m - C_{L1}^{C}(t)U_{L1}^{B,C}(t)\sin m)\cos(2\pi F_{L1}t) - (C_{L1}^{B}(t)D_{L1}^{B}(t)U_{L1}^{B,C}(t)\cos m + C_{L1}^{A}(t)D_{L1}^{A}(t)U_{L1}^{A}(t)C_{L1}^{B}(t)D_{L1}^{B}(t)C_{L1}^{C}(t)\sin m)\sin(2\pi F_{L1}t)$$

Spreading Codes

In addition to the carrier frequencies and the modulation schemes, the pseudorandom noise (PRN) code sequences used for the Galileo navigation signals determine important properties of the system. Therefore, the signal plan needs a careful selection of Galileo code design parameters. These parameters include the code length and its relation to the data rate as well as the auto- and cross-correlation properties of the code sequences. Cold-start acquisition times also help characterize the performance of the Galileo codes.

The STF proposal retains a first set of reference codes that offer a compromise between acquisition time and protection against interference. These codes are based on shift-registered codes, which will be generated onboard.

The reference ranging codes are constructed tiered codes, consisting of a short duration primary code modulated by a long duration secondary code. The resulting code then has an equivalent duration equal to the one of the long duration secondary codes. The primary codes are based on classical gold codes with register length up to 25. The secondary codes are given by predefined sequences of length up to 100.

Further alternative codes are presently investigated (Pratt, 2002) and flexibility in the onboard implementation is being considered to foresee the generation of other types of codes.

TABLE 2 Spreading codes main characteristics

Channels	Types of data	Code sequence duration	Primary code length	Secondary code length
$E5a_I$	OS	20 ms	10230	20
$E5a_Q$	no data	100 ms	10230	100
$E5b_I$	OS/CS/SoL	4 ms	10230	4
$E5b_Q$	no data	100 ms	10230	100
$E6_A$	PRS	TBD	—	—
$E6_B$	CS	1 ms	5115	—
$E6_C$	no data	100 ms	10230	50
$L1_A$	PRS	TBD	—	—
$L1_B$	OS/CS/SoL	4 ms	8184	—
$L1_C$	no data	100 ms	8124	25

Code Length. The code length for Galileo channels carrying a navigation data message shall fit within one symbol of the Viterbi encoded data message stream in order to eliminate code ambiguity. The resulting code lengths are shown in **Table 2**.

For the data-less channels, the basic approach is to consider long codes of 100 ms length. Alternate solutions, however, are being investigated. The first alternate one is to follow a GPS L5 approach consisting of a short code of 1 ms length equally long to the code in quadrature. The second one is to have a much longer code, which could have duration of 0.75 second as in the case of the L2 civil signal. Especially in the case of E5a and E5b it would be useful to determine the data-less code length by analyzing the susceptibility against local interference.

Auto- and Cross-Correlation. The cross-correlation properties (interference) are partly determined by the actual code sequences, which we will discuss later in this article. Especially for E5a, careful code selection is necessary because at this frequency band

Galileo and GPS use the same modulation scheme and code rate.

Acquisition Time. Acquisition time, including time to first fix, primarily depends on the applied receiver acquisition technique, but is generally anticipated to be 30–50 seconds for cold-start acquisition for simple receivers using the E5 or the E2-L1-E1 signal and 30 seconds using E6 in a single-frequency product. Again, we stress the point that acquisition time performance is largely a function of receiver design (for example, single-frequency versus multifrequency) and the associated cost implications.

Encryption

Simple, inexpensive code encryption, which can be removed on request from the ground, is foreseen for the encrypted CS. Code encryption should be realized as a technique controlling the access of code and data without imposing too many constraints and efforts on the user segment. The removal of the encryption should not create a legacy mantle in the user segment, and the complexity of the encryption should result from a trade-off analysis of prospective CS markets and adequate protection needed for securing those markets.

Service Mapping on Signals. The data carriers will be assigned to provide the following service categories which are summarized in **Table 3**. OS signals would use unencrypted ranging codes and unencrypted navigation data messages on the E5 and E2-L1-E1 carriers. A single frequency (SF) receiver uses signals E2-L1-$E1_B$ and E2-L1-$E1_C$ and might receive the GPS C/A code signal on L1. A dual frequency (DF) receiver uses additionally signal $E5a_I$ and $E5a_Q$ and potentially the GPS L5 signal. Improved accuracy (IA) receivers could also use the $E5b_I$ and $E5b_Q$ signals.

The Safety of Life (SoL) service would use the OS ranging codes and navigation data messages on all E5 and E2-L1-E1 carriers. The Value Added (VA) CS signals would use the OS ranging codes and navigation data messages on the signal E2-L1-$E1_B$ and E2-L1-$E1_C$ as well as additional CS encrypted data messages and ranging codes on the signal $E6_B$ and $E6_C$. In addition to these signals, the Multi-Carrier (MC) Differential Application CS could use the OS ranging codes and navigation data messages carried on the E5a and E5b signals.

The PRS signals would use the encrypted PRS ranging codes and navigation data messages on the E6 and E2-L1-E1 carriers, represented by signals $E6_A$ and E2-L1-$E1_A$.

Galileo's SAR Capability. SAR distress messages (from beacons emitting calls to SAR operators) will be detected by the Galileo satellites in the 406–406.1 MHz band and then rebroadcast to the dedicated receiving ground stations in the 1544–1545 MHz band, called L6 (below the E2 navigation band and reserved for the emergency services). Returning SAR data (from SAR operators to the distress emitting beacons) used for alert acknowledgement and coordination of rescue teams, will be embedded in the OS data of the signal transmitted in the E2-L1-E1 carrier frequency.

TABLE 3 Galileo services mapped to signals

	OS SF	OS DF	OS IA	OS SoL	CS VA	CS MC	PRS
$E5a_{I,Q}$							
$E5_{bI,Q}$							
$E6_A$							
$E6_{B,C}$							
$L1_A$							
$L1_{B,C}$							

CS = Commercial Service
DF = Dual Frequency Receiver
IA = Improved Accuracy Receiver
MC = Multiple Carrier Receiver
OS = Open Service
PRS = Public Regulated Service
SoL = Safety of Life Service
SF = Single Frequency Receiver
VA = Value Added

Performance Parameters

Overall performance evaluation of Galileo signals is currently under investigation. Major differences between Galileo signals and the currently transmitted GPS signals include the BOC (resp. AltBOC) modulation scheme and the large bandwidth employed for most of the signals.

In this context an important parameter derives from the pseudorange code measurement error caused by thermal noise. **Table 4** shows the Cramer-Rao lower bound (See Further Readings, J. Spilker, 1996) for this value of all Galileo signals and the GPS C/A and L5 signals. Assuming a receiver delay-lock loop (DLL) bandwidth of 1 Hz, we used a value of –205 dBWs to convert the minimum received power to a typical carrier-to-noise density value. The power of the processed signals in one frequency and service (that is, data and pilot channels) are combined.

Table 4 reveals that BOC signals exhibit low pseudorange code measurement errors because the power spectral density is located at the lower and upper boundary of the frequency spectrum and not at the center as it is for BPSK or QPSK signals. The results also imply that the autocorrelation function of BOC signals shows multiple peaks, which necessitates implementation of dedicated algorithms in a receiver to track the correct (central) peak. Tracking of BOC signals is discussed in (Betz, 1999 and Pany et al, 2002).

Large signal bandwidths allow the use of a very narrow correlator spacing. Low thermal noise and low code multipath are the resulting benefits. Code multipath envelopes differ significantly for BOC and

TABLE 4 Code accuracy due to thermal noise

Processed signals	Modulation	Power [dBW]	Bandwidth [MHz]	Code noise [cm]
E5a or E5b	BPSK(10)	–155	24	4.6
E5a + E5b, non-coh.	BPSK(10)	–152	24	3.2
E5a + E5b, coh.	BOC(15,10)	–152	51	0.8
$E6_A$	BOC(10,5)	–155	40	1.7
$E6_B + E6_C$	BPSK(5)	–155	24	6.2
$L1_A$	BOC(14,2)	–155	32	1.2
$L1_B + L1_C$	BOC(2,2)	–155	24	5.5
GPS C/A	BPSK(1)	–160	24	23.9
GPS L5	BPSK(10)	–154	24	4.1

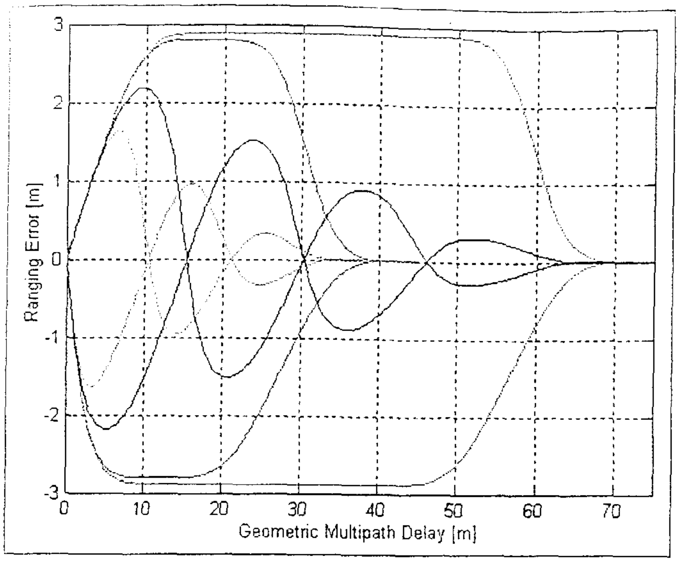

FIGURE 2 Multipath error envelope green: BOC(15,10), black: BOC(10,5), blue: BPSK(10), red: BPSK(5)

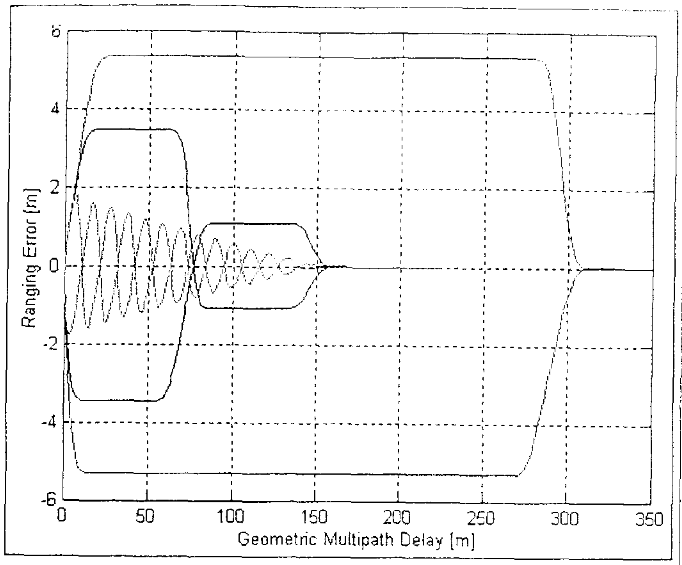

FIGURE 3 Multipath error envelope black: BOC(2,2), red: BOC(14,2), blue: BPSK(1)

BPSK signals, as shown in **Figure 2** and **Figure 3**, respectively. These two figures use a coherent early-minus-late code discriminator with a common discriminator spacing of d = 1/14 to allow for visual comparisons of all signals and to track the central peak of the BOC(14,2) signal. The multipath signal power is −3 dB weaker than the direct signal. (Note that typical multipath amplitudes range between −7 and −10 dB.)

The figures show that multipath performances of BOC signals is generally better than for BPSK signals, but detailed investigations taking into account multipath mitigation algorithms and dedicated multipath scenarios will provide more insight (Winkel, 2002).

Coherent tracking of E5a and E5b results in an extremely low code tracking error due to thermal noise (see line 3 of Table 4) and good multipath mitigation performance. If the E5a and E5b are tracked separately (non-coherently) as QPSK(10) signals and combined after correlation (that is, averaging the E5a and E5b pseudoranges), the performance gain is much less (see line 2 of Table 4).

Recent Interference Studies

Aeronautical radionavigation services' use of the frequency range 960–1215 MHz, containing the lower L-band E5a and E5b, is reserved on a worldwide basis to airborne electronic aids to air navigation and any directly associated ground-based facilities and, on a primary basis, to radionavigation satellite services. This multiple allocation causes interference, which has to be assessed carefully to allow the usage of GPS/Galileo navigation signals for safety-critical applications.

Researches have studied the effects of interference from DME/TACAN, JTIDS/MIDS, and radar out-of-band radiation on L5, E5a and E5b for several years. Interference due to these ground-based sources increases with altitude, because more interfering signals are received.

The most sensitive parameter in this context is the limited acquisition threshold margin that GNSS signals have to cope with interference, for example, 5.8 dB for GPS L5, 4.8 dB for Galileo E5a, and 3.3 dB for E5b. Tracking threshold and data demodulation threshold values are a few decibels higher. In establishing the margins, researchers assumed use of a standard time domain pulse blanking receiver and advanced signal processing (Hegarty et al, 2000). We should note that, in contrast to the United States, Europe does not currently plan to reallocate certain DMEs to circumvent this problem.

Compatibility, Interoperability

As mentioned at the outset, EU policy mandates that Galileo shall be designed and developed using time, geodesy, and signal-structure standards interoperable and compatible with civil GPS and its augmentations. In this context, compatibility implies that Galileo or GPS will *not* degrade the stand-alone service of the other system. Interoperability refers to the ability for the combined use of both GNSSs to improve upon accuracy, integrity, availability, and reliability through the use of a single, common receiver design.

Signal in Space

Galileo/GPS interoperability is realized by a partial frequency overlap with different signal structures and/or different code sequences. At E5a (corresponding to L5) and E2-L1-E1 (or L1), Galileo and GPS signals are transmitted using identical carrier frequencies. At L1 spectral separation of GPS and Galileo signals is accomplished by use of different modulation schemes. This allows jamming of civil signals without affecting GPS M-code or the Galileo PRS service.

Using the same center frequencies drastically simplifies receiver front-end design at the cost of mutual interference of both systems. This so-called *inter-system* interference comes in addition to the interference of navigation signals belonging to the same system, or *intra-system* interference. Only the sum of both types of interference is relevant for determining the receiver performance.

Interference has been extensively described in (Hein et al, 2001, de Mateo et al., 2002 and Ries et al, 2002a); so, we will provide only a brief overview and update here. For details we refer to the article by J. Godet et al listed in the Further Readings section, which describes satellite orbital parameters, antenna diagrams, user locations, and signal characteristics. The studies have shown that the C/N0 degradation of GPS C/A code signals due to Galileo BOC(2,2) signals never exceeds 0.2 dB over the world at any time. For the International Space Station, it is 0.22 dB. **Figure 4** presents a global map showing the maximum inter-system C/N0 degradation as a function of geographical coordinates.

The maximum intra-system or self-interference that the GPS C/A codes are currently suffering is below 2.7 dB and much higher than the potential inter-system interference from Galileo signals.

The maximum inter-system interference (0.2 dB) does not occur at the same time nor in the same space as the maximum intra-system interference. Conversely, the maximum intra-system interference is reached when the inter-system interference is minimal. The maximum total (intra- plus inter-system interference) is shown to be slightly above 2.7 dB, which in the worst case yields a degradation due to Galileo signals of the current GPS C/A-code link budget of only 0.05 dB. (By modifying the GPS constellation — number of satellites and power — this value could go as high as 0.08 dB. See article by J. Godet et al.)

C/A degradation due to other Galileo signals is much less than for the BOC(2,2) signal (Hein et al., 2001). Therefore, we find a high confidence that no GPS user will be affected by interference from the Galileo signal overlay on L1.

On E5a and L5 inter-system interference is generally higher, because identical modulation schemes might be used. For example, **Figure 5** shows GPS L5 signal C/N0 degradation due to Galileo E5a as a function of geographical coordinates.

We also investigated Galileo signal degradation due to GPS signals and have summarized the results in **Table 5.** This research shows that reciprocal interference levels are very low on L1, but more significant in E5a/L5. We noted in the previous section that DME interference of E5a and L5 leaves only a small margin to civil aviation users at high altitudes, especially over Europe where no DME reallocation is planned. Therefore, GPS degradation on Galileo in E5a must be carefully assessed in future work.

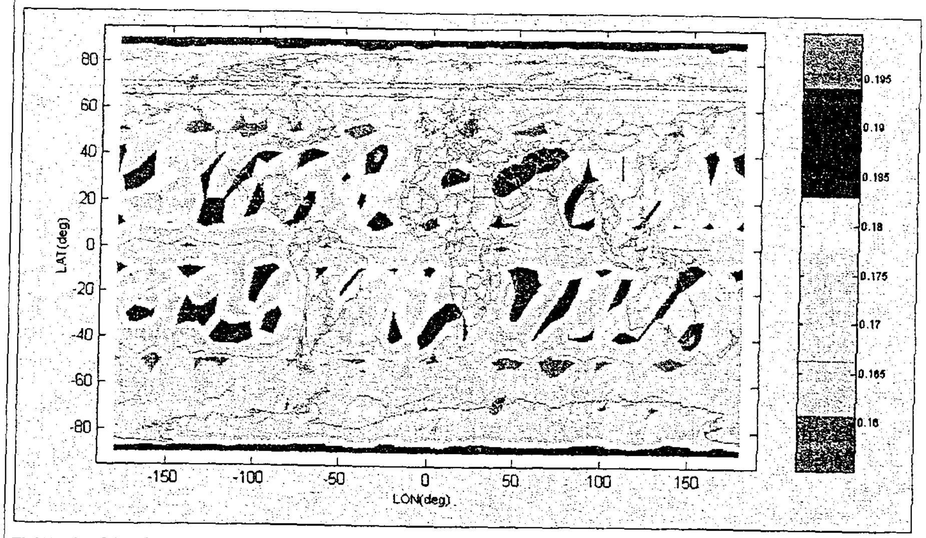

FIGURE 4 Maximum GPS C/A code C/N0 degradation in [dB] due to inter-system interference from a Galileo BOC(2,2) signal on E2-L1-E1

FIGURE 5 Maximum GPS L5 C/N0 degradation in [dB] due to inter-system interference from Galileo E5a

TABLE 5 Reciprocal level of interference (worst case link budget degradation / inter-system C/N0 degradation)

Frequency band	GPS-induced interference on Galileo	Galileo-induced interference on GPS
L1	0.03 dB/0.09 dB	0.05 dB/0.2 dB
E5a/L5	0.5 dB/0.8 dB	0.2 dB/0.4 dB

Coordinate Reference Frame

The Galileo coordinate reference system will adopt international civilian standards. However, the realization of the Galileo coordinate and time reference frames should be based on geodetic reference stations and clocks different from those used by GPS. This will ensure independence and vulnerability of both systems, allowing one system to act as a backup solution for the other.

The Galileo Terrestrial Reference Frame (GTRF) shall be in practical terms an independent realization of the International Terrestrial Reference System (ITRS) established by the Central Bureau of the International Earth Rotation Service (IERS). The resulting reference frame is based on the coordinates of the Galileo ground stations. GPS uses WGS84 as a coordinate reference frame, which is practically also a realization of the ITRS that uses the coordinates of the GPS control stations. The differences between WGS84 and the GTRF are expected to be only a few centimeters.

Consequently, in terms of the interoperability of both GNSS systems, this implies that WGS84 and GTRF will be practically identical within the accuracy available from both realizations of ITRS (that is, the coordinate reference frames are compatible). This accuracy is sufficient for navigation and most other user requirements; the remaining discrepancies at the two-centimeter level are only of interest for research in geosciences. If needed at all, transformation parameters could be provided by an external Galileo geodetic reference service provider. The current STF proposal does not foresee a need to put such information into the navigation data message broadcast by Galileo satellites.

A coordinate reference frame has to be accomplished by an Earth's gravity model. For example, the WGS84 uses a spherical harmonic expansion of the gravity potential up to the order and degree 360. For Galileo a similar model must be considered, and is expected to draw upon results from the European satellite gravity missions GOCE and CHAMP as well as the American mission, GRACE.

Time Reference Frame

The Galileo System Time (GST) shall be a continuous coordinate time scale steered towards the International Atomic Time (TAI) with an offset of less then 33 nanoseconds. The GST limits, expressed as a time offset relative to TAI, should be 50 nanoseconds for 95 percent of the time over any yearly time interval. The difference between GST and TAI and between GST and UTC(Pred) shall be broadcast to the users via the signal-in-space of each Galileo service.

The Galileo ground segment will monitor the offset of the GST with respect to the GPS system time and eventually broadcast the offset to users. The offset could also be estimated in the user receiver by "spending" just one satellite observation. The accuracy of the receiver solution would probably be higher than the one (eventually) transmitted. Thus, broadcasting might not be necessary for the general navigation user.

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