Status of Galileo Frequency and Signal Design

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BIOGRAPHIES

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Jérémie Godet, Navigation Engineer at the European Space Agency, is responsible of Galileo signals and frequencies at the Galileo Interim Support Structure. He is also technical coordinator of the Galileo Signal Task Force. He formerly worked in the Radio Navigation Department at CNES and is involved in GNSS-related activities since 1997. He graduated from the "Ecole Nationale Supérieure des Télécommunications de Bretagne (Télécom Bretagne, France)" and received a M.S. degree from the International Space University. He wrote several articles on multipath calibration techniques and Galileo related interference studies.

Jean-Luc Issler is the head of CNES Radio Navigation Department. He his involved in several European space borne navigation receiver projects (GPS, DORIS, pseudolites). He gives expertise about Galileo signal performances and hardware through CNES developments of Galileo demonstrators (navigation payload, simulator, receiver).

Jean-Christophe Martin is the chairman of the Galileo Signal Task Force and has security and frequency responsibility in the Galileo Unit of the European Commission.

Philippe Erhard is a Navigation System Engineer in the ESA Galileo Project Office. He is coordinating Galileo Signals Design, Performance and Validation activities and is supporting Galileo Receiver Developments. He received his engineer degree from the E.N.A.C (French Civil Aviation University) and joined Alcatel Space Industries Toulouse France where he was involved in previous GALA and GalileoSat studies. He joined ESA late in 2001, as Galileo Project Signal Expert.

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Dr. Tony Pratt graduated with a B.Sc. and Ph.D. in Electrical and Electronic Engineering from Birmingham University, UK. He joined the teaching staff at Loughborough University, UK in 1967 and remained until 1980. He held visiting professorships at Yale University, IIT New Delhi and at the University of Copenhagen. In 1980, he joined Navstar Ltd, as Technical Director. In 1991, he joined Peek acting in several roles including running Tollstar, a road tolling opportunity. He left Peek in 1997 and joined Navstar Systems Ltd as Technical Consultant. He is now Technical Director (GPS) with Parthus. He is also a Special Professor at the IESSG, University of Nottingham, UK. He acts as Consultant to the UK Government in the development of Galileo Satellite System.

ABSTRACT

The paper presents the status of the Galileo frequency and signal structure, status Sept. 2002. The Galileo carrier frequency, modulation scheme and data rate of all 10 navigation signals are described as well as parameters of the search and rescue service. The navigation signals will support services addressed to three different types of users. The signal performance in terms of the pseudorange code error due to thermal noise and multipath is discussed as well as interference from other radionavigation services. The interoperability and compatibility of Galileo and GPS is realized by having two common center frequencies in E5a/L5 and L1 as well as adequate geodetic coordinate and time reference frames. New results on reciprocal GPS/Galileo signal degradation due to signal overlay are presented showing a minimum impact and confirming the high level of interoperability of the two systems.

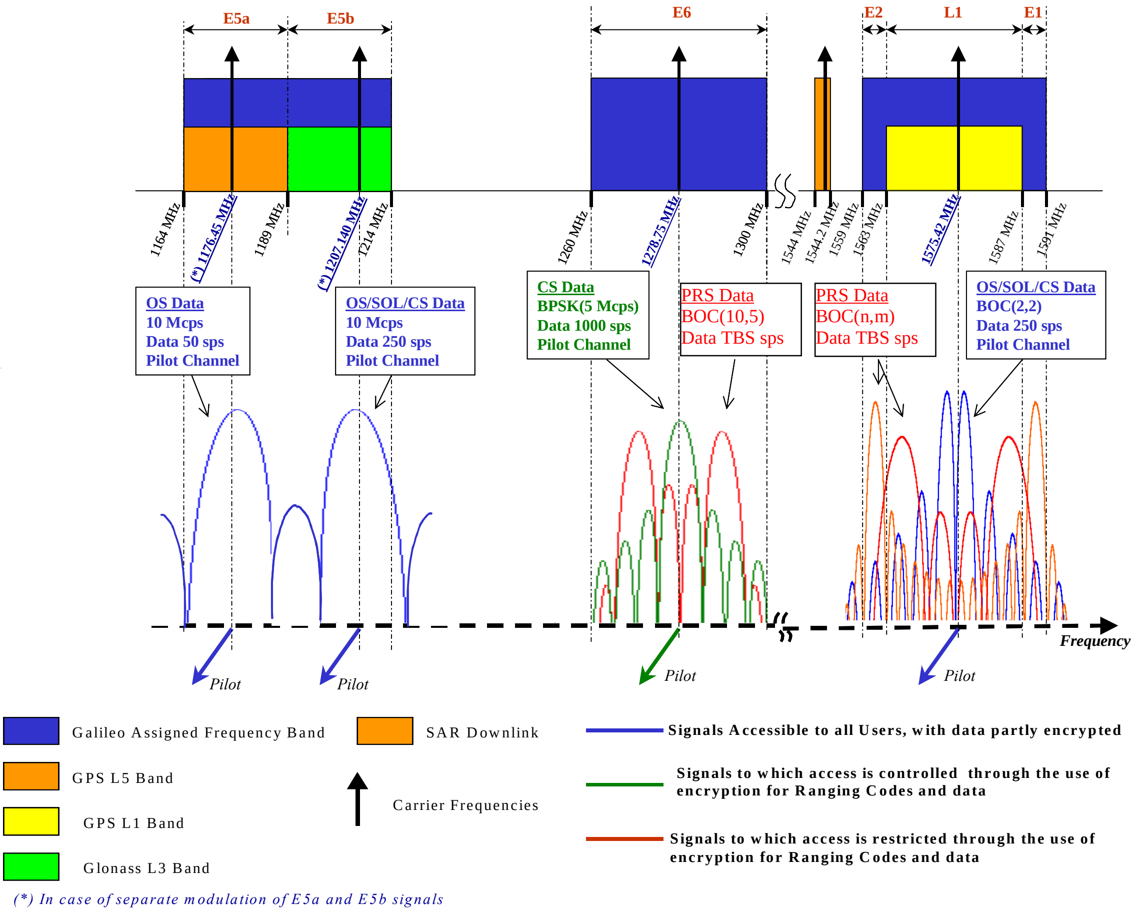

Figure 1. Galileo frequency spectrum

INTRODUCTION

After having presented a tentative Galileo frequency and signal plan at the ION GPS-2001 *(Hein et al, 2001)* it became meanwhile the baseline for the development of Europe´s satellite navigation system. Over the last months several modifications took place leading to a refined signal structure. The main changes and add-ons concern the following:

In the lower L-band (i.e. 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 to process 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 (i.e. E6) and upper (i.e. 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 e.g. *(Pratt, 2002)*.

The Transport Council of the European Union has again underlined in its last meeting on 25/26 March 2002 (where the development phase of Galileo was finally decided) that compatibility and interoperability to GPS should be one of the key drivers for Galileo. With the present Galileo signal plan a maximum of interoperability to GPS is achieved, while still reducing vulnerability when using one system as a back-up of the other. It is obvious to mention that security and market aspects also played an important role.

This paper presents the most recent frequency and signal structure. Its main elements are first outlined. The mapping of Galileo services to signals is discussed. Afterwards detailed considerations (noise and multipath) of the frequency bands are presented. Results from interference analyses are discussed as well as the interoperability and compatibility with GPS in terms of signals structure, geodetic and time reference frame.

THE GALILEO FREQUENCY AND SIGNAL BASELINE – STATUS SEPT. 2002

Galileo will provide 10 navigation signals in Right Hand Circular Polarization (RHCP) in the frequency ranges 1164-1215 MHz (E5a and E5b), 1215-1300 MHz (E6) and 1559-1592 MHz (E2-L1-E1[1]), which are part of the Radio Navigation Satellite Service (RNSS) allocation. An overview is shown in Figure 1, indicating the type of modulation, the chip rate and the data rate for each signal. The carrier frequencies, as well as the frequency bands that are common to GPS or to GLONASS are also highlighted.

All the Galileo satellites will share the same nominal frequency, making use of Code Division Multiple Access (CDMA) compatible with the GPS approach.

Six signals, including three data-less channels, so-called pilot tones (ranging codes not modulated by data), are accessible to all Galileo Users on the E5a, E5b and L1 carrier frequencies for Open Services (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 that gain access through a given Commercial Service (CS) provider. Finally, two signals (one in E6 band and one in E2-L1-E1 band) with encrypted ranging codes and data are accessible to authorized users of the Public Regulated Service (PRS).

A ½ rate Viterbi convolutional coding scheme is used for all the transmitted signals.

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 some 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.
- PRS data, transmitted on E6 and L1 carrier frequencies.

A synthesis of the data mapping on Galileo signals is provided 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 are resulting from a compromise between the following criteria:

- Minimization of the implementation losses in the Galileo satellites, making use of the current state of the art of the related equipments.
- 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 modulation chosen for each of the Galileo carrier frequency is presented in the following subsections. For the E5 band in particular, the trade-off analysis is on going between two alternate solutions that will be both described.

The main modulation parameters for Galileo signals are summarized on the Table 1. The following notation is used:

- $C_X^Y(t)$ is the ranging code on the Y channel ("Y" stands for I or Q for two channels signals, or A, B or C for three channels 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.
- $Sc_X^Y(t)$ is the rectangular subcarrier on the Y channel in the X frequency band.
- m is a modulation index, associated to the modified Hexaphase modulation.

Modulation of the E5 Carrier

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

A. Two 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.
B. One single wideband signal generated following a modified BOC(15,10)[2] modulation called AltBOC(15,10) modulation (see Appendix A). This signal is then amplified through a very wideband amplifier before transmission at the 1191.795 MHz carrier frequencies.

The modulation diagram in case A is given on Figure 2.

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[1] The frequency band E2-L1-E1 is sometimes denoted as L1 for convenience.

[2] BOC(f_s, f_c), denotes a Binary Offset Carrier modulation with a subcarrier frequency f_s and a code rate f_c.

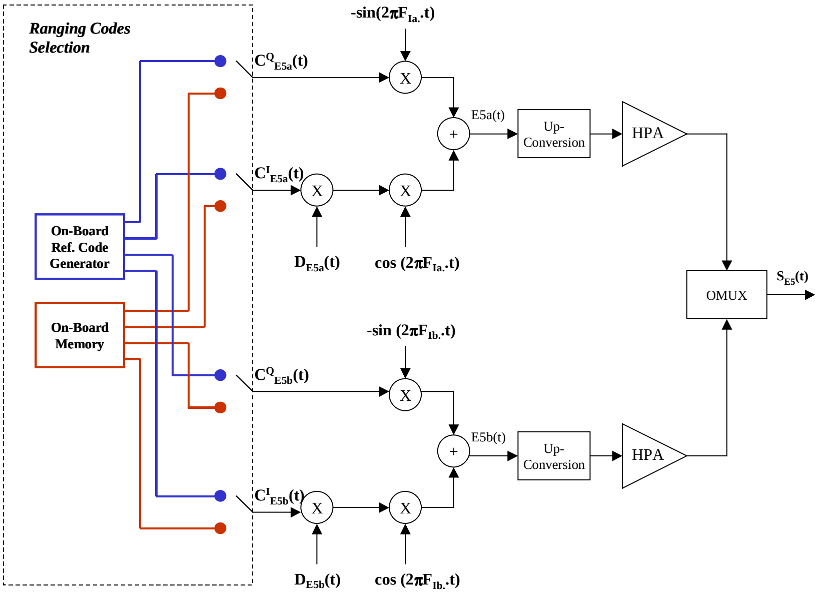
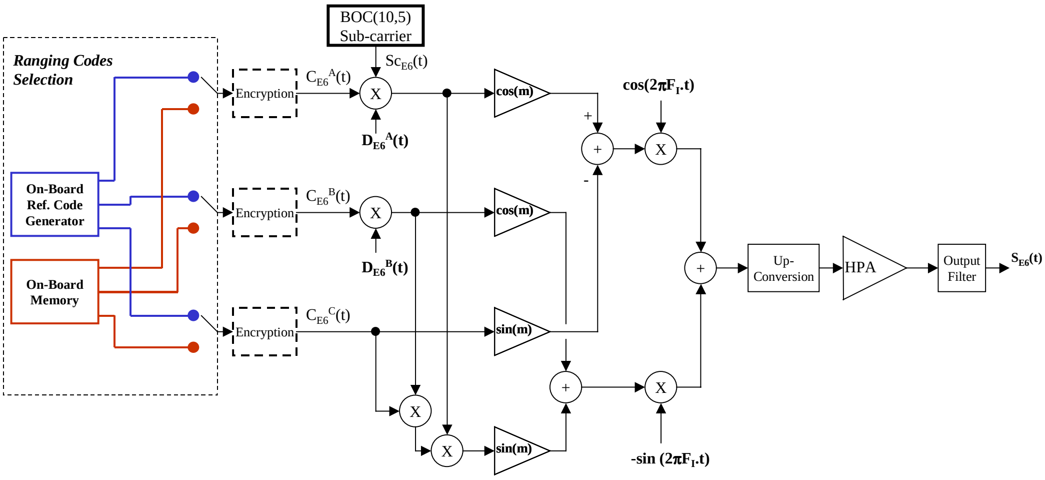
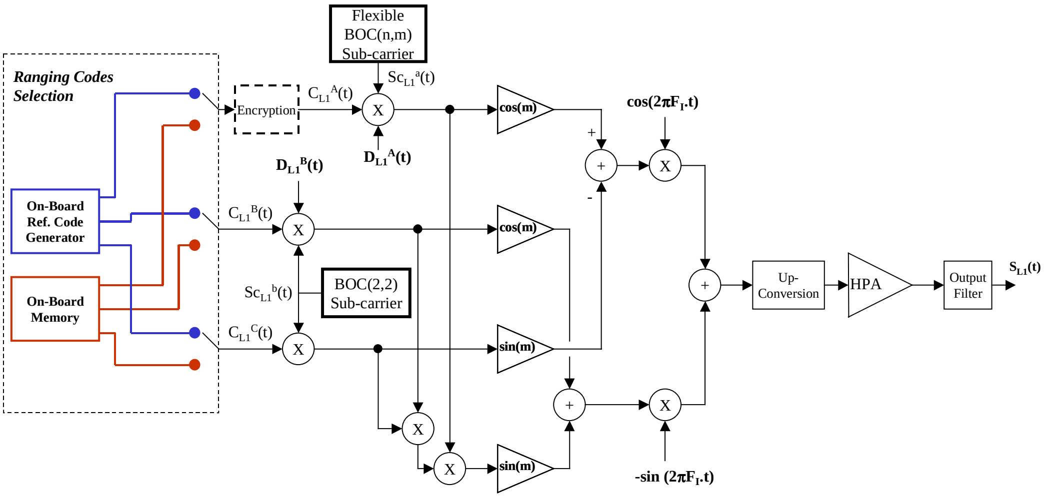


Figure 2: E5 signal modulation diagram in case A



m = modulation index

Figure 3: E6 signal modulation diagram



m = modulation index

Figure 4: E2-L1-E1 signal modulation diagram

In that case the E5 signal can be written:

$$S_{E_5}(t)=\begin{array}{l}\left(C_{E5a}^{I}(t).D_{E5a}^{I}(t)\times\cos\left(2\pi.F_{E5a}.t\right)-C_{E5a}^{Q}(t)\times\sin\left(2\pi.F_{E5a}.t\right)\right)\\+\left(C_{E5b}^{I}(t).D_{E5b}^{I}(t)\times\cos\left(2\pi.F_{E5b}.t\right)-C_{E5b}^{Q}(t)\times\sin\left(2\pi.F_{E5b}.t\right)\right)\end{array}$$

The modulation in case B is a new modulation concept which main interest is that it combines the two signals (E5a and E5b) in 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.

A detailed description of the AltBOC modulation can be found in *(Ries et al., 2002b)* and in Appendix A.

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 on-going.

Modulation of the E6 Carrier

The E6 signal contains three channels that are transmitted at the same E6 carrier frequency. The multiplexing scheme between the three carriers is a major point under consideration today, which shall be carefully optimized. This optimization process shall take into account payload and receivers implementation complexity and associated performances (including compatibility aspects).

The investigated solutions are time multiplexing and a modified Hexaphase modulation (so-called Interplex modulation). The modified Hexaphase is taken as baseline but the final selection process is on going between those two potential solutions.

Figure 3 presents the modulation diagram of the modified Hexaphase. A QPSK signal resulting from the combination of two channels is phase modulated with the third channel. The modulation index is used to set the relative power between the three channels.

With this current assumption, the E6 signal can be written:

$$S_{E6}(t)=\begin{array}{r}\left[C_{E6}^{A}(t).D_{E6}^{A}(t).Sc_{E6}(t).\cos(m)-C_{E6}^{C}(t).\sin(m))\right]\times\cos(2\pi.F_{E6}.t)\\-\left[C_{E6}^{B}(t).D_{E6}^{B}(t).\cos(m)+C_{E6}^{A}(t).C_{E6}^{B}(t).C_{E6}^{C}(t).Sc_{E6}(t).\sin(m))\right]\times\sin(2\pi.F_{E6}.t)\end{array}$$

To be consistent with the relative powers required between 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 than 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.

Figure 4 presents the modulation diagram of the E2-L1-E1 signal, with the baseline modified Hexaphase based solution.

The E2-L1-E1 signal can be written:

$$S_{L1}(t)=\begin{array}{r}\left[C_{L1}^{A}(t).D_{L1}^{A}(t).Sc_{L1}^{a}(t).\cos(m)-C_{L1}^{C}(t).Sc_{L1}^{b}(t)\sin(m))\right]\times\cos(2\pi.F_{L1}.t)\\-\left[C_{L1}^{B}(t).D_{L1}^{B}(t).Sc_{L1}^{b}(t)\cos(m)+C_{L1}^{A}(t).C_{L1}^{B}(t).C_{L1}^{C}(t).Sc_{L1}^{a}(t).\sin(m))\right]\times\sin(2\pi.F_{L1}.t)\end{array}$$

The same modulation index of m=0.6155 is used.

GALILEO SPREADING CODES

The pseudo random noise (PRN) code sequences used for the Galileo navigation signals determine important properties of the system. Therefore a careful selection of Galileo code design parameters is necessary. These parameters include the code length and its relation to the data rate and the auto- and cross-correlation properties of the code sequences. The performance of the Galileo codes is also given by the cold start acquisition time.

A first set of reference codes is being retained that offer a good compromise between acquisition time and protection against interference. These codes are based on shift-registered codes, which will be generated on-board.

Table 1: Main Galileo navigation signal parameters

freq. 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[3]]				A → BOC(10,5) B → BPSK[4](5) C → BPSK(5)			A → flexible BOC(n,m) B → BOC(2,2) C → 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 min. received power at 10^o elevation	-158 dBW	-158 dBW	-158 dBW	-158 dBW	-155 dBW	-158 dBW	-158 dBW	-155 dBW	-158 dBW	-158 dBW

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[3] Quadrature Phase Shift Keying

[4] Binary Phase Shift Keying

The reference ranging codes are constructed tiered codes, consisting in 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 a 100.

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

Code Length

The code length for Galileo channels carrying a navigation data message shall fit within one symbol in order to have no code ambiguity. The resulting code lengths are shown in Table 2.

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	8184	-
$E6_C$	no data	100 ms	10230	50
$L1_A$	PRS	TBD	-	-
$L1_B$	OS/CS/SoL	4 ms	8184	-
$L1_C$	OS/CS/SoL		8124	25

For the data-less channels, the basic approach is to consider long codes of 20 ms length. Alternate solutions are however being investigated. The first 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 0.7 s 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 Properties

The cross-correlation properties (interference) are partly determined by the actual code sequences as will be discussed below. 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 is highly dependent on the applied receiver acquisition technique, but generally 30-50 s for cold acquisition time is envisaged for simple receivers on the E5 signals. For the CS on E6 a acquisition time of 30 s is planned if it is considered as a single frequency product. If not, there will be no specific requirement of the E6 acquisition time. Similar consideration applies for the E2-L1-E1 signal. Again it should be stressed that acquisition time performance is highly dependent on affordable receiver complexity.

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 too much 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 be a result of a trade-off of market analysis 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.

The 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 $E2\text{-}L1\text{-}E1_B$ and $E2\text{-}L1\text{-}E1_C$ 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 result by using additionally signal $E5b_I$ and $E5b_Q$.

The 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 $E2\text{-}L1\text{-}E1_B$ and $E2\text{-}L1\text{-}E1_C$ and additional CS encrypted data messages and ranging codes on the signal $E6_B$ and $E6_C$. The Multi Carrier (MC) Differential Application CS could use in addition the OS ranging codes and navigation data messages on the signal E5a and E5b.

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 $E2\text{-}L1\text{-}E1_A$.

Table 3. Galileo services mapped to signals

Id	OS SF	OS DF	OS IA	SoL	CS VA	CS MC	PRS
$E5a_{I,Q}$		🟩	🟩	🟩		🟩	
$E5b_{I,Q}$			🟩	🟩		🟩	
$E6_A$							🟩
$E6_{B,C}$					🟩	🟩	
$L1_A$							🟩
$L1_{B,C}$	🟩	🟩	🟩	🟩	🟩	🟩	

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

SEARCH AND RESCUE

The SAR distress messages (from distress emitting beacons to SAR operators), will be detected by the Galileo satellites in the 406-406.1 MHz band and then broadcasted 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). The SAR data, from SAR operators to distress emitting beacons, will be used for alert acknowledgement and coordination of rescue teams and will be embedded in the OS data of the signal transmitted in the E2-L1-E1 carrier frequency

SOME PERFORMANCE PARAMETERS

Overall performance evaluation of Galileo signals is currently investigated. A major difference of Galileo signals to the currently emitted GPS signals is the BOC (resp. AltBOC) modulation scheme and the large bandwidth employed for most of the signals.

An important parameter in this context is the pseudorange code measurement error due to thermal noise. Table 4 shows the Cramer-Rao lower bound *(Spilker, 1996)* for this value of all Galileo signals and the GPS C/A and L5 signal. A receiver DLL bandwidth of 1 Hz is assumed and a value of –205 dBWs is used to convert the minimum received power to a typical carrier to noise density value. The power of the of the processed signals in one frequency and service (i.e. data and pilot channels) are combined.

From Table 4 it is evident 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.

Table 4. Code accuracy due to thermal noise

processed signals	modulation	power [dBW]	bandw. [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

This also implies that the autocorrelation function of BOC signals shows several peaks and dedicated algorithms must be implemented in the 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 if BOC and BPSK signals are compared as shown in Figure 5 and Figure 6. For these figures a coherent early minus late code discriminator is used. A common discriminator spacing of d=1/14 is chosen to allow for visual comparisons of all signals and to track the central peak of the BOC(14,2) signal. The multipath signal is -3 dB weaker than the direct signal. Note that typical multipath amplitudes are in the range between -7 and -10 dB.

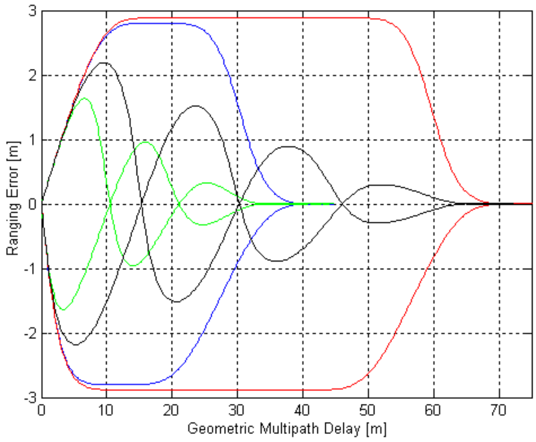

Figure 5. Multipath error envelope, green: BOC(15,10)[5], black: BOC(10,5), blue: BPSK(10), red: BPSK(5).

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[5] A standard BOC modulation scheme was used.

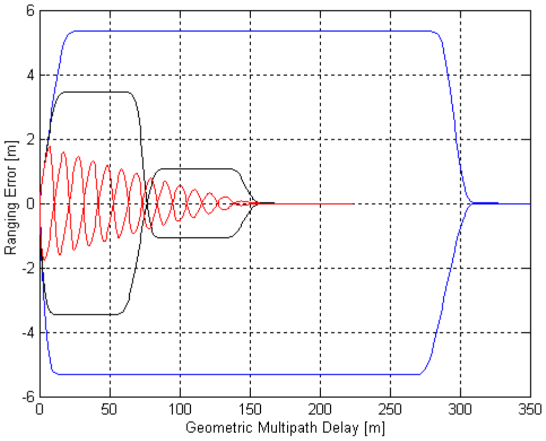

Figure 6. Multipath error envelope, black: BOC(2,2), red: BOC(14,2), blue: BPSK(1).

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

If E5a and E5b are tracked coherently, this results in an extremely low code tracking error due to thermal noise (cf. 3rd line 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 (i.e. averaging of E5a and E5b pseudoranges) the performance gain is much less (cf. 2nd line of Table 4).

RECENT RESULTS OF INTERFERENCE STUDIES

The use of the frequency range 960-1215 MHz, containing the lower L-band E5a and E5b, by aeronautical radionavigation services 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.

Discussion on interference assessment of DME/TACAN, JTIDS/MIDS and radar out of band radiation over L5, E5a and E5b have been conducted since several years. Interference due to these ground-based sources increases with altitude since more interfering signals are received.

The sensitive parameter in this context is the acquisition threshold having limited margins to cope with interference of 5.8 dB for GPS L5, 4.8 dB for E5a and 3.3 dB for E5b. Tracking threshold and data demodulation threshold values are a few dB higher. A standard time domain pulse blanking receiver and advanced signal processing is assumed to be used *(Hegarty et al., 2000)*. It should be noted that in contrast to the US, Europe does not plan at present to re-allocate certain DMEs to circumvent this problem.

COMPATIBILITY/INTEROPERABILITY OF GALILEO-GPS

Galileo shall be designed and developed using time, geodesy and signal structure standards interoperable and compatible with civil GPS and its augmentations.

Compatibility is in this context understood as the assurance that Galileo or GPS will not degrade the stand-alone service of the other system. Interoperability is the ability for the combined use of both GNSS to improve upon accuracy, integrity, availability and reliability through the use of a single common receiver design.

Signal-in-Space

The Galileo/GPS interoperability is realized by a partial frequency overlap with different signal structures and/or different code sequences. At E5a (resp. L5) and E2-L1-E1 (resp. L1) Galileo and GPS signals are broadcasted using identical carrier frequencies. At L1 spectral separation of GPS and Galileo signals is given by the 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 frontend design at the cost of mutual interference of both systems. This so-called inter-system interference adds to the interference of navigation signals belonging to the same system, called intra-system interference. Only the sum of both types of interference is relevant for determining the receiver performance.

Interference has been described in *(Hein et al., 2001, de Mateo et al., 2002 and Ries et al., 2002a)* and a brief overview plus update shall be given in the following. For details we refer to *(Godet et al., 2002),* where satellite orbital parameters, antenna diagrams, user locations, signal characteristics are described. It can be shown that the C/N_0 degradation of GPS C/A code signals due to Galileo BOC(2,2) signals is never above 0.2 dB over the world at any time. For the International Space Station it is 0.22 dB. The maximum C/N_0 degradation as a function of geographical coordinates is shown in Figure 7.

The maximum GPS C/A code intra-system interference computed is below 2.7 dB. This represents the maximum self-interference that GPS C/A codes are currently suffering and explains that GPS C/A real power is about 3 dB above specifications.

The maximum inter-system interference (0.2 dB) cannot occur at the same time nor at the same space than 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 yields a degradation of current GPS C/A code worst case link budget by only 0.05 dB[6].

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[6] By modifying the GPS constellation (number of satellites and power), this value can go up to 0.08 dB, cf. *(Godet et al., 2002)*

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

GPS L5 signal C/N_0 degradation due to Galileo E5a as a function of geographical coordinates is shown in Figure 8. Galileo signal degradation due to GPS signals has also been investigated and a summary is shown in Table 5.

From Table 5 it is evident that reciprocal interference levels are very low on L1. They are more significant in E5a/L5. We noted in the last section that DME interference of E5a and L5 signal 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.

Table 5. Reciprocal level of interference (worst case link budget degradation / inter-system C/N_0 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

Geodetic Coordinate Reference Frame

For the Galileo coordinate reference system international civilian standards will be adopted. However, for various reasons the realization of the Galileo coordinate and time reference frame should be based on stations and clocks different from those of GPS. These reasons include 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 ITRF is based on a set of station coordinates and velocities derived from observations of VLBI, LLR, SLR, GPS and DORIS. A reduction of the individual coordinates to a common reference epoch considering their station velocity models is performed using fixed plate motion models or estimated velocity fields.

GPS uses WGS84 as coordinate reference frame, practically also a realization of the ITRS, realized by the coordinates of the GPS control stations. The differences between WGS84 and the GTRF are expected to be only a few cm.

This implies for the interoperability of both GNSS systems that the WGS84 and GTRF will be identical within the accuracy of both realizations (i.e. coordinate reference frames are compatible). This accuracy is sufficient for navigation and most other user requirements and the remaining discrepancies in the 2 cm level are only of interest for research in geosciences. Transformation parameters can be provided by a Galileo external Geodetic Reference Service Provider – if needed at all. At the moment it is not foreseen to put such information in the navigation data message.

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. In that context the European satellite gravity missions GOCE and CHAMP as well as the American mission GRACE are of importance.

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 ns. The GST limits, expressed as a time offset relative to TAI, 95% of the time over any yearly time interval, should be 50 ns. The difference between GST and TAI and between GST and UTC(Pred) shall be broadcasted to the users via the signal-in-space of each service.

The offset of the GST with respect to the GPS system time is monitored in the Galileo ground segment and the offset is eventually broadcasted to the user.

The offset might also be estimated in the user receiver with very high accuracy by spending just one satellite observation – the accuracy is (probably) higher than that one (eventually) broadcasted. Thus, broadcasting might be not necessary for the general navigation user.

Interoperability Summary

The Galileo system follows international recommendations for steering of its time and coordinate references (UTC and ITRF). This itself enables a possible high level of interoperability in case GPS follows the same, very reasonable, rules.

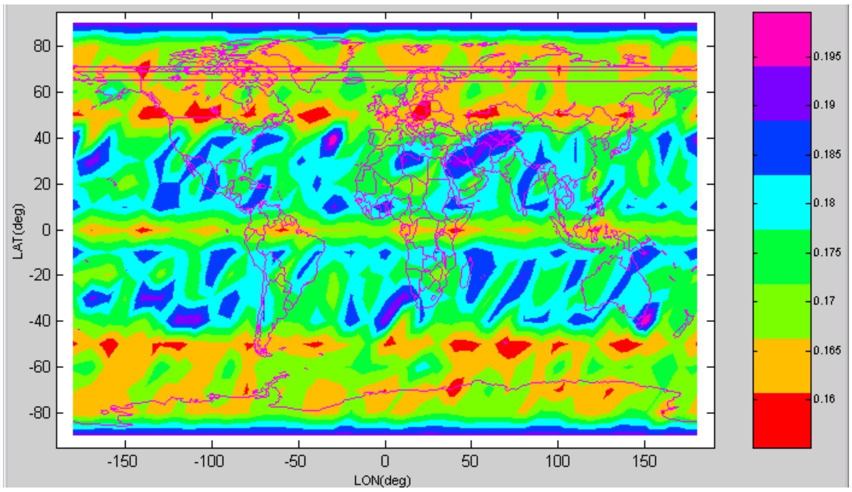


Figure 7. Maximum GPS C/A code C/N_0 degradation in [dB] due to inter-system interference from a Galileo BOC(2,2) signal on E2-L1-E1.

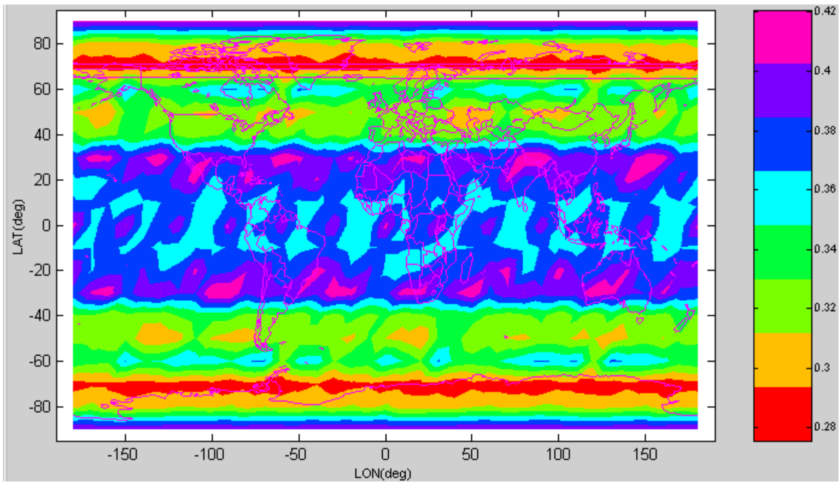


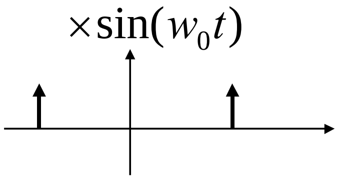
Figure 8. Maximum GPS L5 C/N_0 degradation in [dB] due to inter-system interference from Galileo E5a

APPENDIX A
ALTERNATE BOC MODULATION

This appendix introduces basic principles of the alternate BOC modulation scheme to outline the general idea of this new technique. More details, as well as a possible implementation on E5 can be found in *(Ries et al., 2002b).*

The alternate BOC modulation scheme aims at generating a single subcarrier signal adopting a source coding similarly to the one involved in the classical BOC. The process allows to keep the BOC implementation simplicity and a constant envelope while permitting to differentiate the lobe. The method will be briefly outlined in the following using the notations listed Table 6.

The standard BOC modulation is a square subcarrier modulation, illustrated in Figure 9. The signal *s(t)* is multiplied by the rectangular subcarrier of frequency f_s which splits the spectrum of the signal into two parts (symbolized as two bold arrows in Figure 9), located at the left and right side of the carrier frequency.



Square sub carrier or BOC

$$s_s(t) = s(t) * sign(\sin(2\pi f_s t))$$

$$S_s(f) \approx \alpha\, S(f) \otimes (\delta(f - f_s) - \delta(f + f_s))$$

Figure 9. Standard BOC modulation scheme

Table 6. Notations for alternate BOC modulation

symbol	description	numerical value
f_0		1.023 MHz
f_{E5}	medium carrier frequency between E5a and E5b	1191.795 MHz
w_0	$2\pi f_s$	
f_c	code rate of Galileo signals in E5a and E5b	$10 f_0 =$ 10.23 MHz
f_s	frequency offset of E5a or E5b to F_{E5}	$15 f_0 =$ 15.345 MHz
T_s	$1/f_s$	
t	time	
$cr(t)$	$\mathrm{sign}(\cos(2\pi f_s t))$	
$sr(t)$	$\mathrm{sign}(\sin(2\pi f_s t))$	
er	$er=cr+j\,sr$	
c_a	PRN code in E5a (data channel)	
c_b	PRN code in E5b (data channel)	
d_a	data flow in E5a	
d_b	data flow in E5b	
c'_a	PRN code in E5a (dataless channel)	
c'_b	PRN code in E5b (dataless channel)	

The idea of alternate (or baseband) BOC modulation is to perform the same process but multiplying the base band signal by a 'complex' rectangular subcarrier following the scheme shown in Figure 10. In that way the signal spectrum is not split up, but only shifted to higher frequencies. Shifting to lower frequencies is obviously also possible. A different signal *s(t),* containing a different ranging code and navigation data message, can be used for shifting to the lower and upper frequency range. By this principle the two side lobes of a BOC signal can carry different information.

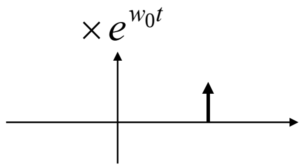
The signal is of constant envelope as will be shown in the following. The alternate BOC signal can be expressed as

$$x(t)=c_a(t)\cdot er(t)+c_b(t)\cdot er^*(t).$$

The signal spectrum comprises a main line which is the same as the line for the ideal (sinusoidal) complex exponential with the same frequency f_s and minor harmonics spaced every $4f_s$.

It is equivalent to modulate the data flow c_a+c_b by the waveform c_r and to add in quadrature the data flow c_a-c_b modulated by the waveform s_r, because the alternate signal expression can be arranged as

$$x(t)=[c_a(t)+c_b(t)]cr(t)+j[c_a(t)-c_b(t)]sr(t).$$



Alternate BOC

$$s_s(t)=s(t)*sign(\cos(2\pi f_s t)+j sign(\sin(2\pi f_s t)))$$

$$S_s(f)\approx\alpha\, S(f)\otimes(\delta(f-f_s))$$

Figure 10. Alternate BOC modulation scheme

As c_r and s_r yield BOC signals, we have two BOC signals in quadrature. For a BOC(15,10) signal, we remind that if T_c is the duration of a chip and T_s the subcarrier period, we have

$$T_s = T_c/1.5\,.$$

Therefore, during the length of one chip, the subcarrier phase values (i.e. the argument of c_r and s_r) cycle 1.5 times through a full period.

Since the data flows c_a and c_b can assume only values of +1 and –1, the signal *x(t)* can be written as

$$x(t)=2e^{jk\frac{\pi}{2}} \qquad k\in\{1,2,3,4\}.$$

The value of k is determined from the values of c_a and c_b and from the values of $c_r(t)$ and $s_r(t)$.

Thus, we verified that the amplitude of the I and Q channels is constant.

The limitation of this basic concept lies in the fact that each signal in E5a and E5b must be a BPSK signal and no QPSK signals, to include pilot channels, are allowed if the good constant envelope characteristics are to be kept, because some portions of the alternate signal will be at null power.

If the data channels are on I and the pilot channels are on Q, then the base-band signal can be expressed as follows.

$$x(t)=\{[c_a(t)d_a(t)+c_b(t)d_b(t)]cr(t)-[c'_a(t)-c'_b(t)]sr(t)\}$$
$$+j\{[c'_a(t)+c'_b(t)]cr(t)+[c_a(t)d_a(t)-c_b(t)d_b(t)]sr(t)\}$$

This signal can take 9 different values, which can be written by the following formula.

$$\begin{cases} x(t)=A_k\cdot e^{jk\frac{\pi}{4}} & k=\{0,1,2,3,4,5,6,7,8\} \\ with \begin{cases} A_k=0 & for\, k=0 \\ A_k=2\sqrt{2} & k\ odd \\ A_k=4 & k\, even \end{cases} \end{cases}$$

It is clearly seen that the resulting modulation won't be a constant envelope modulation. The I and Q channels can even be zero at the same time. The non-constant envelope imposes limitation on the high power amplifier shall not be considered further.

Other Alternate BOC Modulation Schemes

The idea of using a sinusoidal modulating signal instead of a rectangular one has been also studied, but this variant still doesn't provide a signal with a constant envelope.

Another BOC variant, preferred in Galileo signal design, allows to generate the four E5 signals with a constant envelope. In this case, the generated signal is a classical 8-PSK modulation. An optimal use of the high power amplifier can be guaranteed. The modulation spectrum of the signal is presented in Figure 11 and further details can be found in *(Ries et al., 2002b).*

Alternate BOC Summary

The generation of combined E5a and E5b signals presents several advantages:

- correlation losses are low
- gain in precision due to the possibility to transmit many side-lobes, in a wide band coherent signal
- optimization of the use of E5a and E5b: simple/low-cost receivers can use a single band whereas more complex receivers can operate in dual mode single band mode (non-coherent reception of E5a and E5b) or in a coherent dual band mode and thus get advantages in term of performance.
- it allows some flexibility for the service definition, since a service can be dedicated to one band only while the second one could in certain conditions use both.
- the payload baseband generator and the E5 radio frequency channel are simplified and the high power amplifier/output multiplexer subsystem as well.

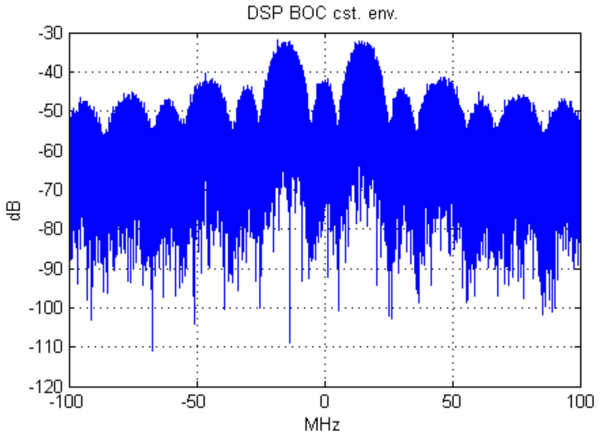


Figure 11. Modulation spectrum of the constant envelope AltBOC(15,10) signal

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REFERENCES

Betz, J. (1999): The Offset Carrier Modulation for GPS Modernization, Proc. of ION 1999 National Technical Meeting, San Diego, January 1999.

Godet, J., J.C. de Mateo, P. Erhard and O. Nouvel (2002): Assessing the Radio Frequency Compatibility between GPS and Galileo, Proc. of ION GPS 2002, Portland, September 2002.

Hegarty, C., A. J. Van Dierendonck, D. Bobyn, M. Tran, T. Kim and J. Grabowski (2000): Suppression of Pulsed Interference through Blanking, Proc. of IAIN World Congress in Association with the U.S. ION 56th Annual Meeting, San Diego, June 2000, p. 399.

Hein, G. W., J. Godet, J.-L. Issler, J.-Chr. Martin, R. Lucas-Rodriguez and T. Pratt (2001): The Galileo Frequency Structure and Signal Design, Proc. of ION GPS 2001, Salt Lake City, September 2001, pp. 1273-1282.

de Mateo Garcia, J., P. Erhard and J. Godet (2002): GPS/Galileo Interference Study, Proc. of ENC-GNSS 2002, Copenhagen, May 2002.

Pany, T., M. Irsigler, B. Eissfeller and J. Winkel (2002): Code and Carrier Phase Tracking Performance of a Future Galileo RTK Receiver, Proc. of ENC-GNSS 2002, Copenhagen, May 2002.

Pratt, T. (2002): A New Class of Spreading Codes Exhibiting Low Cross-Correlation Properties, Proc. of ION GPS 2002, Portland, September 2002.

Ries L., Q. Jeandel, O. Nouvel, C. Macabiau, V.Calmette, W. Vigneau, J-L. Issler and J-C. Martin (2002a): A Software Receiver for GPSIIF-L5 Signal, Proc. of ION GPS 2002, Portland, September 2002.

Ries L., L. Lestarquit, P. Erhard, F. Legrand, C. Maccabiau, Q. Jeandel and C. Bourgat (2002b): Software Simulation Tools for GNSS2 BOC Signal Analysis, Proc. of ION GPS 2002, Portland, September 2002.

Spilker J. (1996): GPS Signal Structure and Theoretical Performance, In: W. Parkinson and J. Spilker: GPS Positioning System Theory and Applications Vol., Progress in Astronautics and Aeronautics Vol. 163. American Institute of Aeoronautics and Astronautics., pp. 57-120.

Winkel, J. (2002): Modeling and Simulating Generic GNSS Signal Structures and Receiver in a Multipath Environment, Ph.D. Thesis, University FAF Munich, Neubiberg.