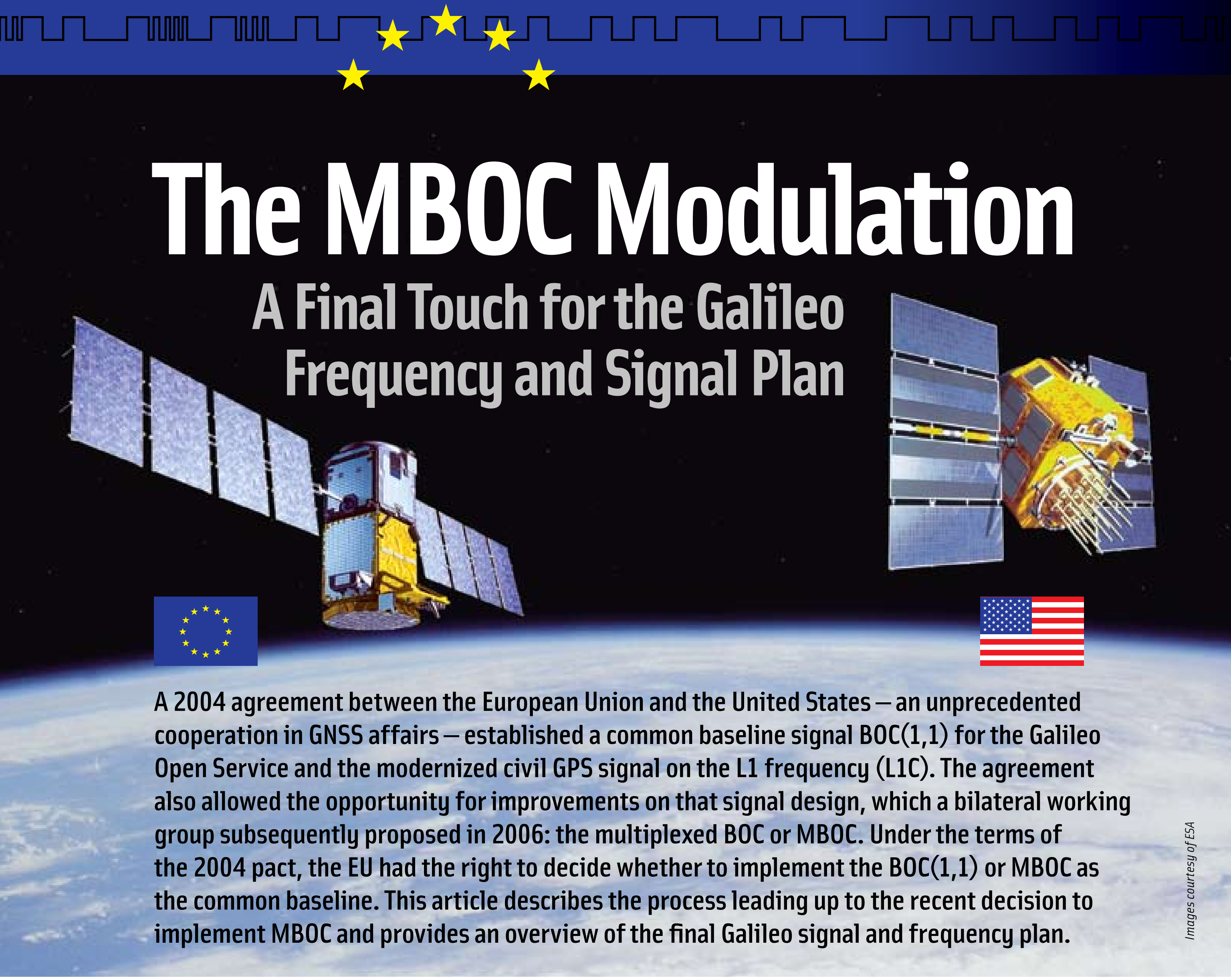

The MBOC Modulation

A Final Touch for the Galileo Frequency and Signal Plan

A 2004 agreement between the European Union and the United States – an unprecedented cooperation in GNSS affairs – established a common baseline signal BOC(1,1) for the Galileo Open Service and the modernized civil GPS signal on the L1 frequency (L1C). The agreement also allowed the opportunity for improvements on that signal design, which a bilateral working group subsequently proposed in 2006: the multiplexed BOC or MBOC. Under the terms of the 2004 pact, the EU had the right to decide whether to implement the BOC(1,1) or MBOC as the common baseline. This article describes the process leading up to the recent decision to implement MBOC and provides an overview of the final Galileo signal and frequency plan.

Images courtesy of ESA

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MEMBERS OF THE GALILEO SIGNAL TASK FORCE OF THE EUROPEAN COMMISSION

As emphasized in the European Commission (EC) "white paper" on European transport policy for 2010, the European Union (EU) needs an independent satellite navigation system. Galileo is Europe's contribution to the global navigation satellite system of systems (GNSS) and has committed itself from the very beginning to developing a signal plan that would provide sufficient independence from GPS, while also being compatible and interoperable with it.

The historic *Agreement on the Promotion, Provision, and Use of Galileo and GPS Satellite-Based Navigation Systems and Related Applications* between the United States and the European Commission (EC) signed in 2004, wherein both parties agreed to work together, affected the originally planned Galileo signals but has intensified the cooperation on interoperability and compatibility issues between Galileo and GPS for the maximum benefit of GNSS users worldwide.

The final touch to the Galileo signal plan was achieved in 2006 when the Working Group on GPS and Galileo compatibility and interoperability, under the auspices of the 2004 agreement, finally settled on a new modulation for the common signal in the E1/L1 frequency, namely the multiplex binary offset carrier, or MBOC for short. This decision was pursuant to efforts mainly driven by the European side and fully recognized by the U.S. representatives.

The journey to the signals Galileo has today for its baseline has been tedious and long, but from the outset the journey has followed a consistent logic. At the very beginning, one of the main challenges that Galileo set for itself was to offer three wideband signals, satisfying at the same time the requirements of the mass market and pushing the potential performance of the navigation signals to their natural limits.

This article will try to shed some light on the long process that has led to the signal baseline we have today. Special care will be placed on describing all the modulations of the final Galileo Signal Plan.

Three Frequencies

It is no surprise that the last signals to be fixed in the Galileo signal plan were those of the E1 band. The E5 and E6 Galileo modulations of today's baseline are basically similar to those announced by members of the Galileo Signal Task Force (STF) in 2002, and only minor changes in the Public Regulated Service (PRS) of E6 have occurred since then.

The wideband AltBOC modulation that Galileo will transmit in E5 was already presented in the baseline of 2002 as the main candidate, and it has remained since then as the best solution until the final baseline. In the case of E6, the PRS has changed the phasing of its BOC(10,5) from sine to cosine, thus increasing the spectral separation with the Commercial Service (CS) – BPSK(5) – and improving in this way its robustness.

Unlike E1, the E5 and E6 frequency bands are not dedicated solely to radionavigation but share the limited frequency resource with other services. Moreover, these latter two bands have never been used before for satellite navigation purposes. This absence of legacy signals turned out to be of benefit, and finding interoperable and compatible signals with the U.S. Global Positioning System was not as difficult as it would prove to be in the case of the E1 band.

Figure 1 presents all the existing and planned navigation signals of the four global navigation systems — GPS, Galileo, Russia's GLONASS, and China's Compass — that are meant to play an important role in the future. As one can recognize E1/L1 shows the highest degree of congestion.

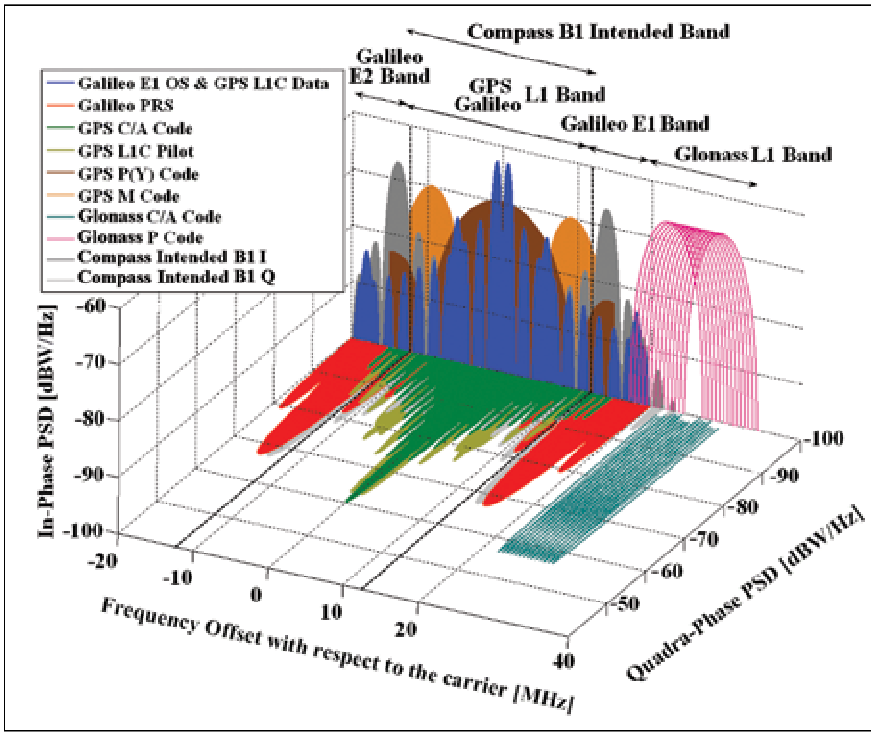

FIGURE 1 Spectra of GPS, Galileo, GLONASS and Compass Intended Signals in E1/L1

Compatibility and Interoperability

From the very beginning, it was clear that being independent, compatible, and interoperable with GPS in E1/L1 would not be an easy task. As we have already underlined, Galileo has pursued from the very first moment the goal of having wideband signals in all its assigned frequency bands — but the complex situation in E1/L1 made it especially difficult.

Galileo wanted to be compatible and interoperable with GPS on E1/L1, two concepts defined as follows:

- *Compatibility* refers to the ability of space-based positioning, navigation, and timing (PNT) services to be used separately or together without interfering with each individual service or signal, and without adversely affecting navigation warfare.
- *Interoperability* refers to the ability of civil space-based PNT services to be used together to provide better capabilities at the user level than would be achieved by relying solely on one service or signal.

As we can recognize, being compatible does not necessarily imply that two systems are also interoperable. In any case, Galileo has always pursued both objectives.

While these goals have always been clear in the mind of all STF scientists working on Galileo, it has always been the wish of all the people involved in the development of the Galileo Signal Plan that the Galileo signals, including those in E1/L1, should reach the maximum possible performance offered by the RF bands. As it has been shown in various papers, this could only be possible by occupying higher frequencies.

Finding a signal with increased power at higher frequencies that does not interfere with the GPS M-code and P(Y)-code or the Galileo PRS was anything but trivial and challenged EU and US working teams for long time — until MBOC came along.

It is evident that allocating a wideband signal in E1/L1 without interfering with other existing signals and guaranteeing interoperability with GPS was only possible thanks to the close cooperation that exists between the United States and the European Union since 2004. As a result of strong working relationships, the United States and the European Union announced on July 26, 2007, an agreement for a common GPS-Galileo signal — MBOC — for civilian use. With this decision, the Galileo Signal Plan has been completely frozen for the first generation. In the future, MBOC will allow receivers to track the GPS and/or Galileo signals with higher accuracy, even in challenging environments.

Evolution of the Galileo Signal Plan

MBOC is the culmination of a titanic work and long studies carried out since the Galileo program started. However, because arriving at today's baseline has taken a very long and difficult effort, it is worthwhile to recapitulate and spend some time describing how the signal plan has evolved over the past years.

Square-Root Raised Cosine (SRRC). The square-root raised cosine (SRRC) with roll-off factor of α=0.22 was the first option for the Galileo Signal and Frequency Plan. Much time has passed since the proposal was originally made, but these first works deeply influenced the evolution of the following years. At the time when the first analyses on the future Galileo signals were made the current frequency band assignments had not taken place yet (For details, see *Galileo Signal Validation Development* by R. De Gaudenzi et alia, 2000, cited in the Additional Resources section). Thus, to limit the number of signal and frequency combinations, a set of seven candidate signal structures was identified, each of which could be independently assigned to a particular frequency.

A careful look at *Galileo Signal Validation Development* reveals that all the signals, with a single exception, consist of an in-phase, BPSK-modulated, spread-spectrum signal and an unmodulated quadrature spread-spectrum pilot that uses a different spreading sequence. Another element of interest is the presence of an unmodulated pilot to achieve robust carrier phase tracking [4]. This idea would remain until adoption of the final baseline of Galileo. The SRRC was quickly abandoned due to its limitations, but some original ideas present in the 2000 publication have been kept until today.

Galileo Baseline of 2002. The first tentative Galileo frequency and signal plan alternative to the one described in the previous section was presented by the Galileo STF in two papers: "The Galileo Frequency Structure and Signal Design," (2001) and "Status of Galileo Frequency and Signal Design" (2002), both by G. W. Hein et alia (see Additional Resources for complete citation.) Slowly, this alternative became the baseline for the development of Europe´s satellite navigation system.

By September 2002, the Galileo carrier frequency, modulation scheme, and data rate of all the 10 Galileo navigation signals had experienced very important changes with respect to the first proposals in *Galileo Signal Validation Development*. Moreover, the band frequency assignment was no longer an unknown,

The EU Transport Council in its meeting on March 25–26, 2002, which authorized the development phase of Galileo, underlined that compatibility and interoperability to GPS should be a key drivers for Galileo.

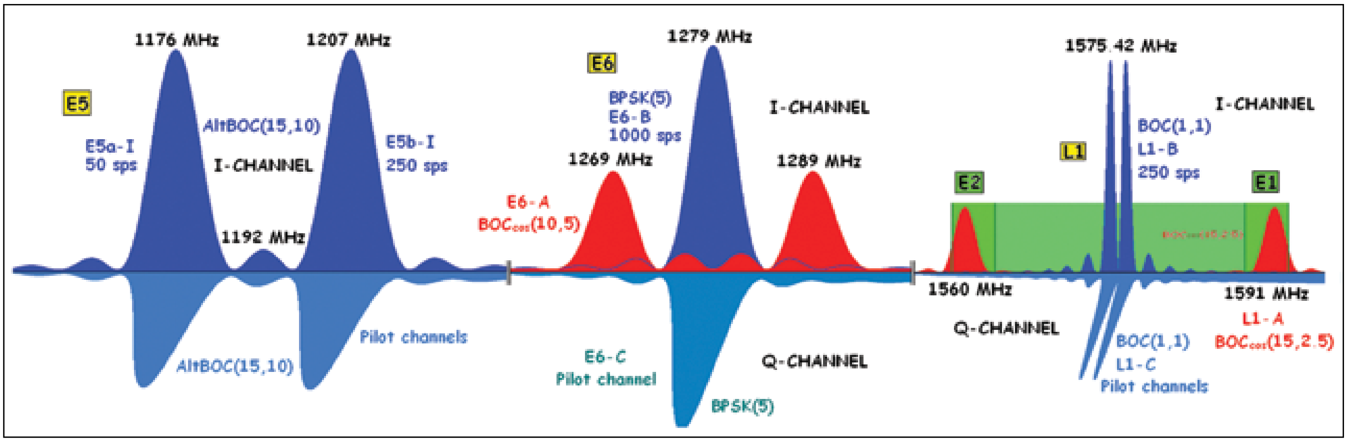

FIGURE 2 Galileo baseline after the Agreement of 2004

and Galileo was developing similar concepts with regards to signal modulation as GPS. The SRRC concept had been definitely abandoned and similar signal structures as those of GPS were now under discussion for Galileo, too. Thus, the status was already in a very mature phase by 2002, and, until the final signal plan, few substantial changes would be required except in the E1/L1 band.

We can summarize these concepts, described in further detail in "The Galileo Frequency Structure and Signal Design," as follows:

- In the lower L-band (i.e., E5a and E5b), the central frequency for E5b was moved to 1207.14 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 would be using chip rates of 10 Mcps. The idea in mind was to have a modulation that allowed processing of 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. As we know, this final wideband signal would be the AltBOC modulation. Furthermore, data rates had also been fixed in the baseline of 2002.
- In the middle (E6) and upper (E2'-L1-E1') L-band, data and chip rates were also defined as well as the search and rescue (SAR) service up- and downlink frequencies. Furthermore, 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. Similar studies were carried out in E6 concerning the mutual interference to/from radars and in the E2-L1-E1 band with regard to the Galileo overlay on GPS L1.

In addition, by 2002 the EC Signal Task Force and ESA had refined criteria for the code selection and had formulated the requirements on each frequency as well. Nonetheless, various code structures were still under investigation.

It is also important to note that the Transport Council of the European Union in its meeting on March 25–26, 2002, where the development phase of Galileo was finally authorized, underlined that compatibility and interoperability to GPS should be one of the key drivers for Galileo. With this signal plan, Galileo presented a good interoperability to GPS but still slight changes would be required.

A Long Way to the Agreement of 2004. The signal plan of 2002 was already very mature in its design and with respect to the baseline of 2004 only small changes can be observed, especially in the E1/L1 band. These can be summarized as follows:

- E6: For the PRS, the BOC(10,5) signal changed from sine-phasing to cosine-phasing. (The parenthetical expressions in these signal designations indicate, first, the sub-carrier frequency and, second, the code rate. Both must be understood as being multiplied by the famous factor 1.023)
- E1: The Open Service (OS) signals changed from BOC(2,2) to BOC(1,1) and the PRS moved from $BOC_{sin}(14,2)$ to $BOC_{cos}(15,2.5)$ in order to fulfill the Agreement of 2004 as we will mention in the next lines.
- E5: AltBOC remained until the end as the wide-band signal of E5.

Let us not rush, though, but rather analyze the changes that took place in a short time frame and with special attention to the most troublesome band: the E1/L1 band.

Changes in the Public Regulated Service of E1. Following the guidelines set up by the Transport Council of the European Union at the beginning of 2004, the negotiations between the European Commission and the United States had clearly intensified with the objective of reaching the much-desired compatibility and interoperability between GPS and Galileo. So far, it seemed clear at the time that, due to reasons of national security, Galileo would have to change its PRS signal from $BOC_{sin}(14,2)$ to another solution. In the previous months, various solutions for the PRS had been thoroughly assessed:

- BPSK(5) at 1594 MHz as the Public Regulated Service instead of $BOC_{sin}(14,2)$.
- BOC(2.5,2.5) at 1594 MHz was another alternative that was subject of this analysis.
- $BOC_{cos}(15,2.5)$ at 1575.42 MHz. This

was indeed the solution ultimately found to be the optimum one for different reasons.

Open Service. From BOC(2,2) to BOC(1,1). Despite common agreement on both the American and European side that the PRS signal had to change from $BOC_{sin}(14,2)$ to $BOC_{cos}(15,2.5)$ to preserve real compatibility and interoperability between GPS and Galileo, the Open Service signal and Civil signal of Galileo and GPS, E1 OS and L1C respectively, were still the object of long discussions. Indeed, together with the BOC(2,2) (proposed in the G. W. Hein et alia papers cited earlier), other signals such as BOC(1.5,1.5) and BOC(1,1) were also studied for the OS service at that time.

Some results on the performance of such solutions have been presented in the following papers: "Criteria for GNSS Multipath Performance Assessment" by M. Irsigler et alia and "Revised Combined Galileo/GPS Frequency and Signal Performance Analysis" by J.-A. Avila-Rodriguez et alia cited in Additional Resources. In addition, other interesting solutions were also being explored such as $BOC_8(2,2)$, also known as the 8-PSK BOC(2,2) discussed in the J.-A. Avila-Rodriguez paper, "On Optimized Signal Waveforms for GNSS," and "Performance of GPS Galileo Receivers Using m-PSK BOC Signals" by A.R. Pratt and J.I.R. Owen (Additional Resources).

Agreement of June 2004: BOC(1,1) - $BOC_{cos}(15, 2.5)$. After many years of fruitful cooperation, the member states of the European Union and the United States signed the agreement on Galileo and GPS satellite-based navigation on June 26, 2004. With it, a new world of possibilities in satellite navigation arose. The agreement fixed BOC(1,1) as the baseline for both Galileo and GPS future OS signals, but at the same time it opened the door to future possible implementations under the following conditions: that they should have the current baseline as the core of potential optimizations and that they would fulfil the NSCC (National Security Compatibility Criteria) with both the GPS M-Code and Galileo PRS. Moreover, the PRS was raised to the same category as the M-code. **Figure 2** shows the resulting baseline as of 2004 (from J.-A. Avila-Rodriguez, "On Optimized Signal Waveforms for GNSS."

The Way to Today's Baseline

Shortly after the agreement of 2004 was signed, experts from both sides of the Atlantic started to work together to find possible alternatives to the common BOC(1,1) modulation that would clearly outperform the Open Service and Civil signals of the baseline while still fulfilling the agreement's requirements on national security. Among the many solutions that were investigated at that time, we underline the following:

- MBOC(5) as the result of multiplexing BOC(1,1) and BOC(5,1)
- *Crazy* BPSK. This signal is a par-

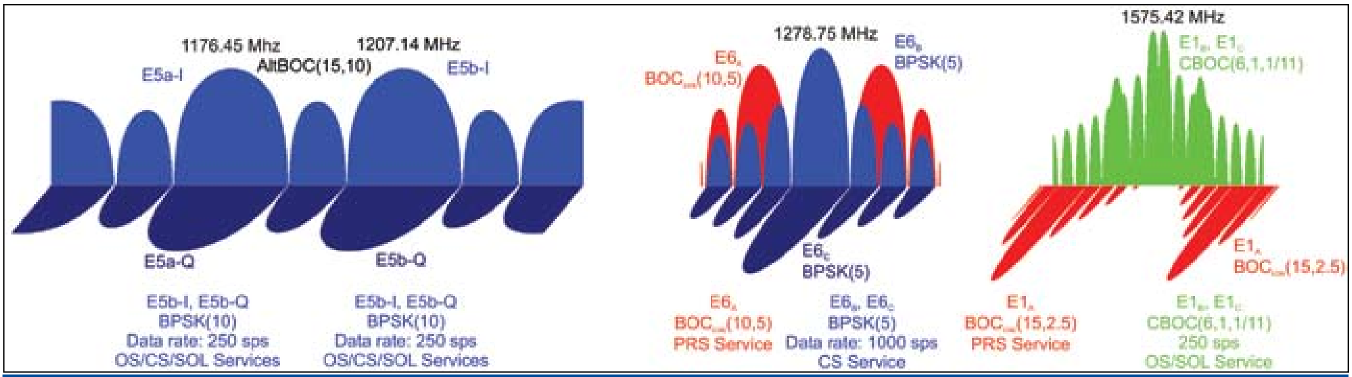

FIGURE 3 Final Galileo baseline (2007)

ticular Binary Coded Symbol (BCS) with 1.5 MHz chip rate and can be described as BCS([15×0,1,4× 0],1.5). Given its great similarity with a BPSK signal, but with an additional quick flip, the signal was baptized as *crazy* BPSK.

- Other BCS signals with chip rates of 1.023 MHz or multiplexed versions of these with BOC(1,1).

CBCS. As we underlined in the preceding section, although the agreement fixed BOC(1,1) as the baseline for both Galileo E1 Open Service and GPS future L1C signals, it also stated that the parties would work together toward achieving optimization of that modulation for their respective systems within the constraints of the agreement. In September 2005, a sophisticated signal known as composite binary coded symbols (CBCS) was presented by members of the EC's Signal Task Force. (See the paper, "A Candidate for the Galileo L1 OS Optimized Signal," by G. W. Hein et alia in Additional Resources.) This signal promised improvement in performance of more than 40 percent in multipath performance with respect to BOC(1,1) (as reported in "Revised Combined Galileo/GPS Frequency and Signal Performance Analysis," by J.-A. Avila-Rodriguez et alia).

CBCS was highly compatible with BOC(1,1) receivers and fulfilled to a high degree the requirements of the 2004 agreement. Moreover, it offered an important improvement in terms of performance.

CBCS*. However, CBCS had some inconvenient properties. Among them, the existence of a tracking bias that could potentially appear due to the cross-correlation between the CBCS signal and BOC(1,1) legacy receivers. This problem could be solved in different manners, the most interesting being that of alternating the BCS sequence. The resulting signal thus received the name CBCS*, where the star refers to the phase-alternation of the BCS component.

MBOC(4,1). Shortly before the optimized signal was selected, one more signal came into the scope of studies as a potential alternative to BOC(1,1). This signal was MBOC(4,1), which results from multiplexing BOC(1,1) and BOC(4,1). Due to its spectral properties, however, it showed a lower degree of growth potential than MBOC(6,1) and was thus abandoned.

MBOC(6,1). Finally, a joint design activity involving experts from the United States and Europe recommended an optimized spreading modulation —MBOC(6,1) — for the L1C signal and the Galileo E1 OS signal. The spreading modulation design places a small amount of additional power at higher frequencies in order to improve signal tracking performance. The signal was found to be satisfactory to both parties and significantly improved BOC(1,1) in many scenarios. Figure 3 shows the final Galileo signal plan as of today. MBOC(6,1) is described in detail in the paper by G. W. Hein et alia, "MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C," listed in Additional Resources.

In the next section, we will present the technical characteristics of the Galileo baseline signals.

GNSS System	Galileo	Galileo	Galileo	Galileo
Service Name	E5a data	E5a pilot	E5b data	E5b pilot
Center Frequency	1191.795 MHz			
Frequency Band	E5			
Access Technique	CDMA			
Spreading modulation	AltBOC(15,10)			
Sub-carrier frequency	15.345 MHz			
Chip rate	10.23 MHz			
Signal Component	Data	Pilot	Data	Pilot
Primary PRN Code length	10230	10230	10230	10230
Code Family	Combination and short-cycling of M-sequences			
Secondary PRN Code length	20	100	4	100
Data rate	50 sps	-	250 sps	-
Minimum Received Power [dBW]	-155 dBW		-155 dBW	
Elevation	10°		10°	

TABLE 1. Galileo E5 signal technical characteristics

Description of Galileo Signals

Now that we have given some insight on how the Galileo plan evolved in the past years, in this section we will describe some aspects of the generation schemes of the baseline signals. Given the novelty of the E1 composite BOC (CBOC) modulation, special attention will be paid to this signal, while for the rest of the bands a brief description will be provided. For a complete description of Galileo E5 and E6 signals, refer to the *Galileo Open Service Signal in Space Interface Control Document (Galileo OS SIS ICD)* listed in Additional Resources.

But first, a brief review of the other signals and frequencies.

E5 Band. The E5 modulation receives the name of AltBOC and is a modified version of a binary offset carrier with a code rate of 10.23 MHz and a sub-carrier frequency of 15.345 MHz. AltBOC(15,10) is a wideband signal that is transmitted at 1191.795 MHz.

The AltBOC multiplexing combines two signals (E5a and E5b) in a composite constant envelope ([5], [16], [17] and [25]), which is then injected through very wideband channel. For further discussion of AltBOC in general, see G. W. Hein et alia "Status of Galileo Frequency and Signal Design" and the papers by J. Godet; M. Soellner and P. Erhard; and L. Ries et alia listed in additional Resources. For more details on the AltBOC multiplexing refer to the paper by J.-A. Avila-Rodriguez and the *Galileo OS SIS ICD.*

As shown in the papers by J.-A. Avila-Rodriguez and by E. Rebeyrol et alia, the power spectral density for the modified AltBOC(15,10) modulation with constant envelope is shown to adopt the form:

$$G_{AltBOC}^{\Phi_{odd,c}}(f) = \frac{4 f_c}{\pi^2 f^2} \frac{\cos^2(\pi f T_c)}{\cos^2\left(\pi f \frac{T_c}{n}\right)} \left[\cos^2\left(\frac{\pi f}{2 f_s}\right) - \cos\left(\frac{\pi f}{2 f_s}\right) - 2\cos\left(\frac{\pi f}{2 f_s}\right)\cos\left(\frac{\pi f}{4 f_s}\right) + 2 \right] \qquad [1]$$

As we can recognize, this corresponds to the odd case, which is the one Galileo presents given the ratio between the sub-carrier and chipping rate. To conclude, the spectrum of the Galileo E5 signal modulation is shown in **Figure 4**.

It is interesting to note that the AltBOC(15,10) modulation is very similar to two BPSK(10) signals shifted by 15 MHz to the left and right of the carrier frequency. Indeed, because a very wide bandwidth is necessary to acquire all the main lobes of the modulation, many receivers might operate correlating the AltBOC signal with a BPSK(10) replica on either lobe.

E5 Open Service Codes. The E5 primary codes can be considered as memory stored binary sequences or can be generated with shift registers. Indeed, the outputs of two parallel registers are modulo-two added to generate the primary codes. For more details on the start values of the primary codes and the corresponding secondary codes of each satellite, refer to the *Galileo OS SIS ICD.*

E5 Main Signal Parameters. Table 1 summarizes the main technical characteristics of the Galileo E5 signals.

E6 Band. The Galileo E6 signal contains three channels that are transmitted at 1278.75 MHz. The resulting spectra are further shown to adopt the form illustrated in Figure 5.

E6 Commercial Service Codes. The E6 Commercial Service (CS) codes are *random* codes, also known as *memory* codes in the literature. As described in the patent held by J. Winkel (see Additional Resources), the main idea behind random codes is to generate a family of codes that fulfils the properties of randomness as well as possible for a given code length.

The codes can be driven to fulfill special properties such as balance and weakened balance, where the probability of 0's and 1's must not be identical but within a well-defined range, or to realize the autocorrelation sidelobe zero (ASZ) property. This latter property guarantees that the autocorrelation values of every code correlate to zero with a delayed version of itself, shifted by one chip. For more details on the properties and generation of the random codes refer to the paper by S. Wallner et alia, "Galileo E1 OS and GPS L1C Pseudo Random Noise Codes - Requirements, Generation, Optimization and Comparison."

E6 Main Signal Parameters. Table 2 summarizes the main technical characteristics of the E6 signal.

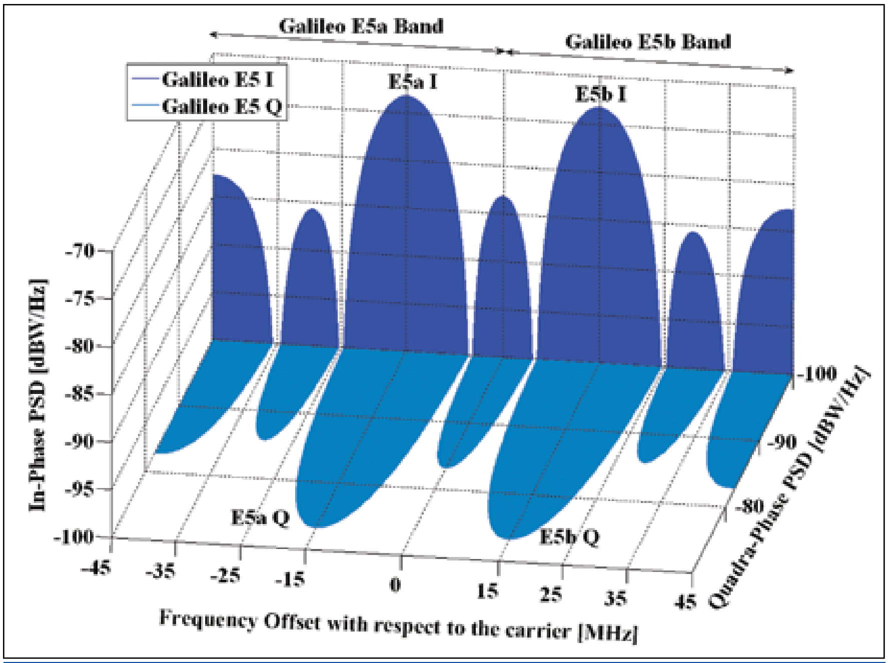

FIGURE 4 Spectra of Galileo Signals in E5 [4]

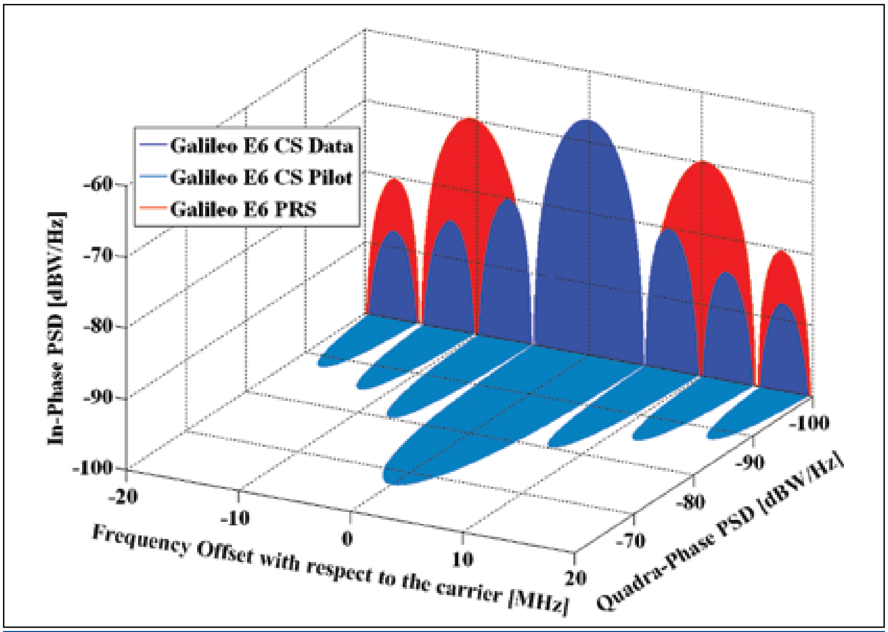

FIGURE 5 Spectra of Galileo Signals in E6

E1 & CBOC

The E1 Open Service (OS) modulation, CBOC (Composite Binary Offset Carrier), is a particular implementation of MBOC (multiplexed BOC). MBOC(6,1,1/11) is the result of multiplexing a wideband signal, BOC(6,1), with a narrow-band signal, BOC(1,1), in such a way that 1/11 of the power is allocated, on average, to the high frequency component. MBOC is transmitted at 1575.42 MHz with constant envelope. This signal was the last to be defined, and the next version of the public Galileo SIS ICD will contain its description.

The normalized (unit power) power spectral density, specified without the effect of band-limiting filters and payload imperfections, is given by

$$G_{MBOC(6,1,1/11)}(f)=\frac{10}{11}G_{BOC(1,1)}(f)+\frac{1}{11}G_{BOC(6,1)}(f) \quad [2]$$

Figure 6 shows a generic view of the generation of the Galileo CBOC implementation of MBOC. As we can recognize, the E1 CBOC signal components are generated as follows:

- $e_{E1\text{-}B}(t)$ from the I/NAV navigation data stream $D_{E1\text{-}B}(t)$ and the ranging code $C_{E1\text{-}B}(t)$, then modulated with the sub-carriers $sc_{E1\text{-}BOC(1,1)}(t)$ and $sc_{E1\text{-}BOC(6,1)}(t)$ of BOC(1,1) and BOC(6,1) respectively.
- $e_{E1\text{-}C}(t)$ (pilot component) from the ranging code $C_{E1\text{-}C}(t)$ including its secondary code, then modulated with the sub-carriers $sc_{E1\text{-}BOC(1,1)}(t)$ and $sc_{E1\text{-}BOC(6,1)}(t)$ in antiphase.

Equation (3) provides the mathematical description of these components. Furthermore, the Galileo satellites transmit the E1 signal components with the ranging codes chip rates and symbol rates according to Table 3 where:

$$e_{\text{E1-B}}(t)=\sum_{i=-\infty}^{+\infty}\left[c_{\text{E1-B},|i|_{L_{E1-B}}}\,D_{\text{E1-B},[i]_{DC_{\text{E1-B}}}}\,\text{rect}_{T_{c,\text{E1-B}}}\left(t-iT_{c,\text{E1-B}}\right)\right]$$
$$e_{\text{E1-C}}(t)=\sum_{i=-\infty}^{+\infty}\left[c_{\text{E1-C},|i|_{L_{E1-C}}}\,\text{rect}_{T_{c,\text{E1-C}}}\left(t-iT_{c,\text{E1-C}}\right)\right] \quad [3]$$

GNSS System	Galileo	Galileo	Galileo
Service Name	E6 CS data	E6 CS pilot	E6 PRS
Center Frequency	1278.75 MHz		
Frequency Band	E6		
Access Technique	CDMA		
Spreading modulation	BPSK(5)	BPSK(5)	BOCcos(10,5)
Sub-carrier frequency	-	-	10.23 MHz
Chip rate	5.115 MHz		
Signal Component	Data	Pilot	N/A
Primary PRN Code length	5115	5115	N/A
Code Family	Memory codes		N/A
Secondary PRN Code length	-	100	N/A
Data rate	1000 sps	-	N/A
Minimum Received Power [dBW]	-155		N/A
Elevation	10°		N/A

TABLE 2. Galileo E6 signal technical charactertistics

- $X\text{-}Y$ indicates the carrier X and component Y
- $L_{X\text{-}Y}$ is the ranging code repetition period
- $T_{C,X\text{-}Y}$ is the ranging code chip length
- $R_{C,X\text{-}Y} = 1/T_{C,X\text{-}Y}$ is the code chip rate
- $R_{S,X\text{-}Y}$ is the inverse of the sub-carrier frequency
- $|i|_L$ indicates i modulo L
- $[i]_{DC}$ indicates the integer part of i/DC
- $DC_{X\text{-}Y}$ is number of code chips per symbol
- $c_{X\text{-}Y,k}$ is the k^{th} chip of the ranging code
- $\text{rect}_T(t)$ is the rectangle function which is equal to 1 for $0<t<T$ and equal to 0 elsewhere

The navigation data message stream, after channel encoding, is transmitted with the symbol rate as stated in Table 4.

The E1 OS composite signal is then generated according to equation (4), with the binary signal components $e_{E1\text{-}B}(t)$ and $e_{E1\text{-}C}(t)$. Note that, as for E6, both pilot and data components are modulated onto the same carrier component, with a power sharing of 50 percent.

$$s_{E1}(t)=\frac{1}{\sqrt{2}}\left\{\begin{array}{l}e_{E1-B}(t)\left[P\,sc_{E1-BOC(1,1)}(t)+Q\,sc_{E1-BOC(6,1)}(t)\right]\\-\,e_{E1-C}(t)\left[P\,sc_{E1-BOC(1,1)}(t)-Q\,sc_{E1-BOC(6,1)}(t)\right]\end{array}\right\} \quad [4]$$

The parameters P and Q are chosen such that the combined power of the BOC(1,1) and the BOC(6,1) sub-carrier compo-

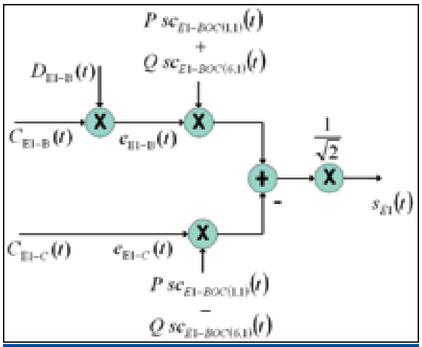

FIGURE 6 Modulation scheme of Galileo E1 signals

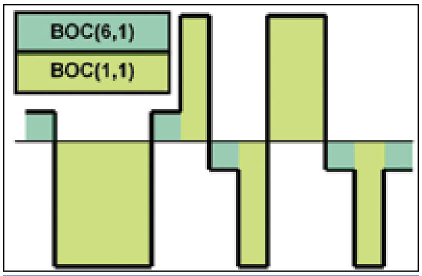

FIGURE 7 Pseudo-random time multiplexing of BOC(6,1) and BOC(1,1) in the CBOC solution

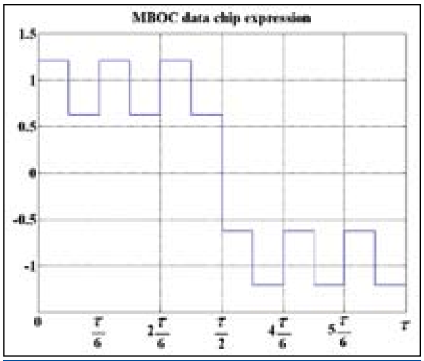

FIGURE 8 Data CBOC data chip with BOC(1,1) and BOC(6,1) in-phase

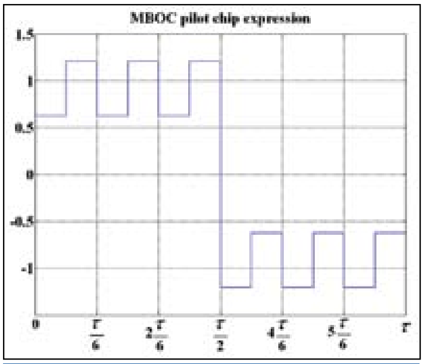

FIGURE 9 Pilot CBOC pilot chip with BOC(1,1) and BOC(6,1) in anti-phase

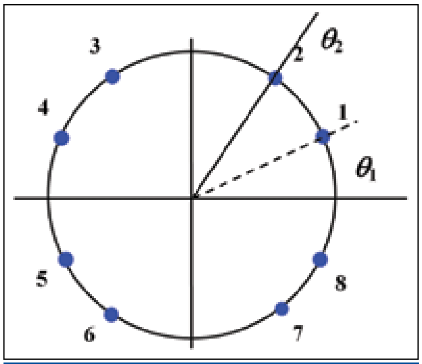

FIGURE 10 Modified 8-PSK modulation with constant envelope for the optimized signal

nents equals 1/11 of the total power of $e_{E1-B}(t)$ and $e_{E1-C}(t)$, before application of any bandwidth limitation. This yields:

$$P = \sqrt{\frac{10}{11}} \qquad Q = \sqrt{\frac{1}{11}} \qquad [5]$$

The CBOC signal adopted for Galileo is based on the approach presented in the papers by G. W. Hein et alia, "MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C" and "A Candidate for the Galileo L1 OS Optimized Signal," and the paper by J.-A. Avila-Rodriguez, "On Optimized signal Waveforms for GNSS." This approach uses four-level spreading symbols formed by the weighted sum of BOC(1,1) and BOC(6,1) symbols on both data and pilot. A time domain representation of a CBOC implementation is shown in **Figure 7**.

If we take a careful look at equation (4), we can recognize that CBOC has data and pilot channels in anti-phase. This is clearly shown in the next figures. **Figure 8** shows the MBOC data chip expression.

Equally, the pilot channel would present the shape for a chip shown in **Figure 9**.

As a result of the slight difference in the time domain definition, slight differences are also observed in the performance of the data and pilot channels. However, despite that factor, the CBOC implementation always performs better than its BOC(1,1) predecessor.

The phase points of the resulting CBOC constellation are shown in **Figure 10**.

It is important to mention that CBOC is a particular case of the CBCS multiplexing scheme that was presented in "A Candidate for the Galileo L1 OS Optimized Signal," where the particular BCS sequence is in this case BOC(6,1). This means that all the theory derived in this paper and that by J.-A. Avila-Rodriguez is also valid for describing the CBOC case. One only has to substitute in the equations of the generic BCS case the particular BOC(6,1) sequence and the power of 1/11. We must note that, despite CBOC being a four-levels signal, it can also be tracked with good performances with 2-level signals, that is one-bit signals, as shown in the paper by O. Julien et alia referenced in Additional Resources.

Figure 11 illustrates the normalized autocorrelation function of the CBOC(6,1,1/11) spread-spectrum time series along with the autocorrelation function for BOC(1,1). Observe that CBOC(6,1,1/11)'s correlation function main peak is narrower than that of BOC(1,1), while the widths at values of 0.5 and at the zero crossing are virtually the same.

This is a very desirable property, since the steeper the main peak of the autocorrelation function, the better will be the potential performance of the signal. In fact, the potential to mitigate multipath

Component (Parameter Y)	Sub-carrier Type	Sub-carrier Rate		Ranging Code Chip-Rate $R_{C,E1-Y}$ (MChip/s)
		$R_{S,E1-Y,a}$ (MHz)	$R_{S,E1-Y,b}$ (MHz)	
B	CBOC, in-phase	1.023	6.138	1.023
C	CBOC, anti-phase	1.023	6.138	1.023

TABLE 3. E1 Safety of Life (SoL) CBOC chip- and sub-carrier rates

Component (Parameter Y)	Symbol Rate $R_{D,E1-Y}$ (symbols/s)
B	250
C	No data

TABLE 4. E1 Open Service (OS) Symbol Rates

that a signal possesses is closely related to the slope of the autocorrelation around the main peak. For more details on the performance of the MBOC modulation refer to G. W. Hein et alia, "MBOC: The New Optimized Spreading Modulation Recommended for GALILEO L1 OS and GPS L1C," and the paper by J.-A. Avila-Rodriguez, "On Optimized signal Waveforms for GNSS."

The spectra of the Galileo signals in E1 are shown to adopt the form illustrated in **Figure 12**.

It is important to mention that for a long time the actual E1 band received the name of L1 band in analogy with GPS, and it was not until the publication of the Galileo OS SIS ICD that L1 changed to the current E1. The E1 band is made of the 24 MHz of the L1 band centred at 1575,42 MHz, and of the E2' and E1' slots apart L1, slots for which Galileo filed first at the ITU, like for E6 and E5 bands, having also a European anteriority.

E1 OS Codes. The E1 Open Service (OS) codes and the E6 CS codes are also random codes. As shown in the paper by S. Wallner et alia, "Galileo E1 OS and GPS L1C Pseudo Random Noise Codes - Requirements, Generation, Optimization and Comparison," the plain number of choices to set the 0's and 1's for the whole code family is enormous, and consequently special algorithms have to be applied to generate random codes efficiently. One possible implementation is the use of *genetic algorithms* as was done during the optimization of all random codes of Galileo.

Random codes, also known as *memory* codes, are — despite their promising name — not truly random. However, because they aspire to reach the best possible pseudorandom behavior for a given length, the term "random" is not completely wrong.

E1 Main Signal Parameters. Finally, the technical characteristics of all the Galileo signals in E1 can be summarized in **Table 5**.

MBOC Performance

Given the capital role that the E1 OS optimization has played since the US/EU agreement of 2004 was signed, we show in the next paragraphs some performance figures that clearly speak for the selected modulation. For comparison, the E1 OS baseline of 2002, namely BOC(2,2), the baseline of 2004, namely BOC(1,1) and a very high frequency signal, as is BPSK(10), will be compared with the MBOC modulation ultimately selected.

As we can recognize, MBOC performs very close to BOC(2,2), being sometimes even superior. Furthermore, for the particular case of 14 MHz and a chip spacing of 0.05 chips, MBOC seems to even outperform BPSK(10) for short multipath. This puts in clear evidence the wideband character that MBOC presents. Indeed, as we have underlined in several parts of this paper, the main goal in the E1 OS optimization has been to design a wideband signal also for E1/L1. This signal should serve users that will demand wider bandwidths in the future.

In addition, this signal should also possess "mass market" characteristics. This has been fully achieved with MBOC where one can choose whether to make use of the low frequency component – BOC(1,1) – or also use the wideband BOC(6,1) part. The associated code tracking noise (**Figure 13**), multipath envelopes (**Figure 14**), the running average error (which is another way of expressing the multipath envelopes, **Figure 15**), and root mean square

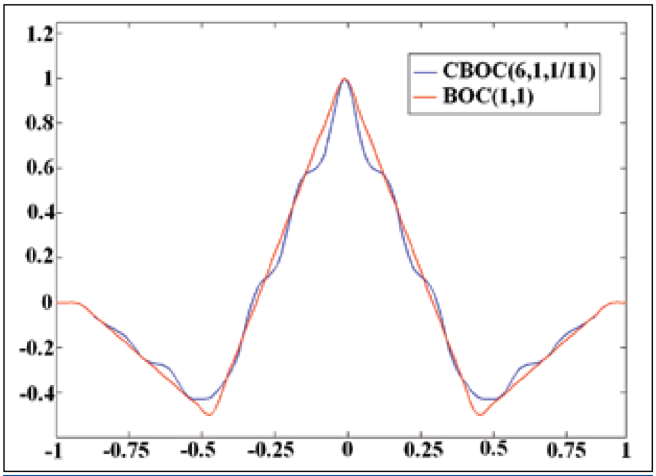

FIGURE 11 Normalized autocorrelation functions computed over ±15 MHz bandwidth

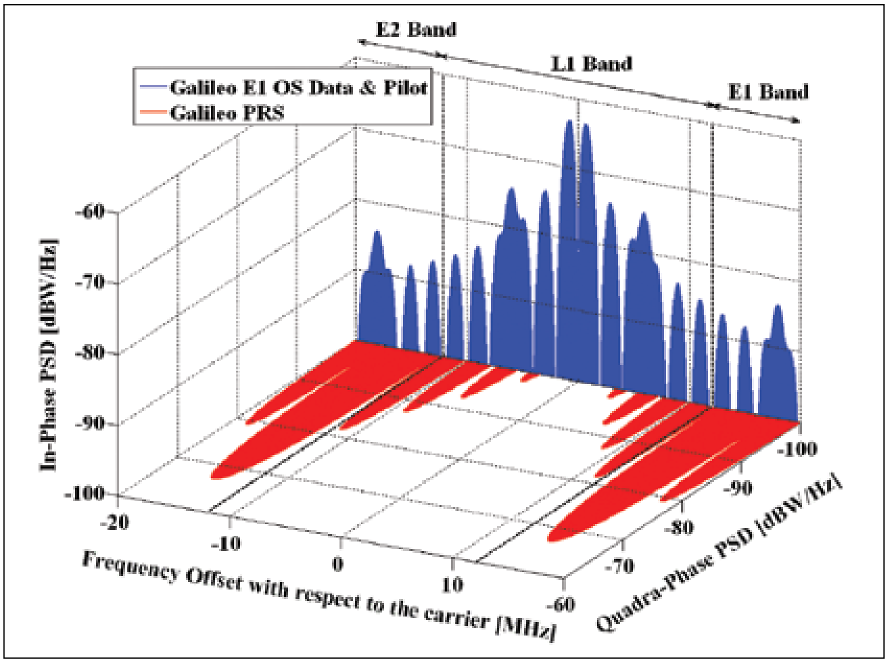

FIGURE 12 Spectra of Galileo Signals in E1

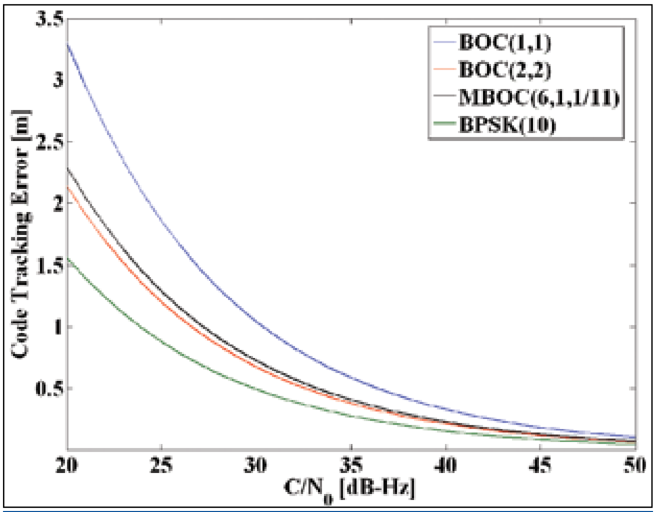

FIGURE 13 BOC(1,1), BOC(2,2), MBOC and BPSK(10) Cramer Rao Lower Bound, BW = 14 MHz

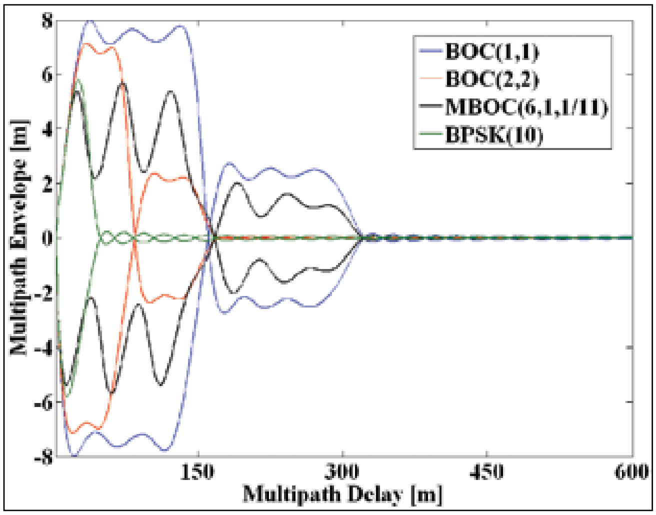

FIGURE 14 Multipath Error Envelope for noncoherent early-late processing (NELP), BW=14 MHz (Ideal filter), d=0.05 chips

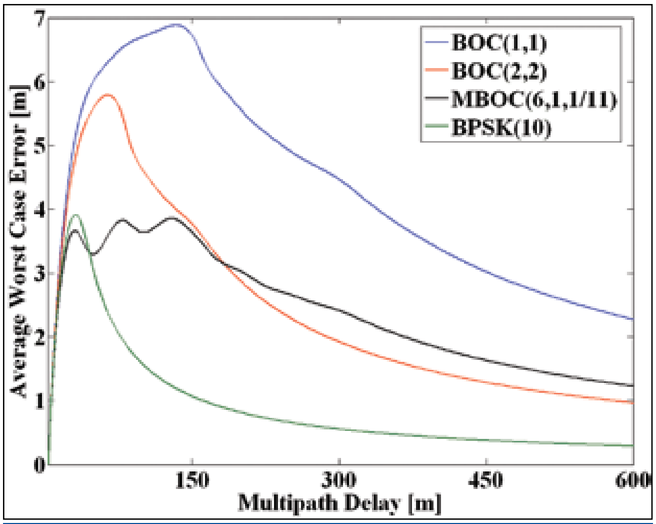

FIGURE 15 Average error for noncoherent early-late processing (NELP), BW=14 MHz (Ideal Brickwall filter), d=0.05 chips

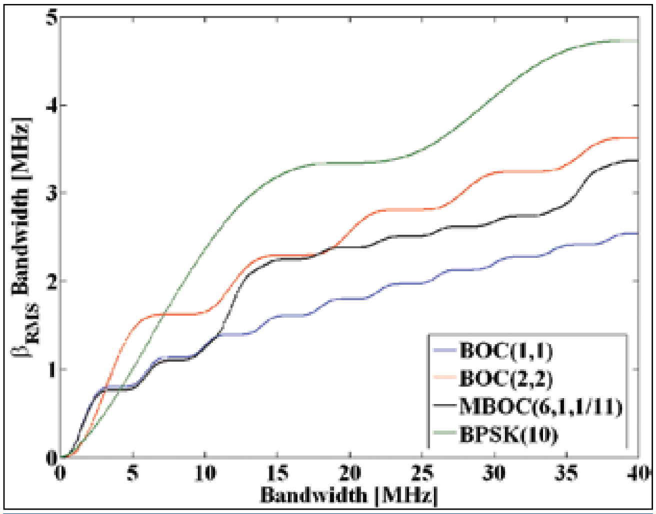

FIGURE 16 RMS bandwidth vs. two-sided receiver bandwidth (Ideal Brick-wall filter)

(RMS) bandwidth figures (**Figure 16**) are shown next.

MBOC: Improved Compatibility and Interoperability. Compatibility and interoperability have been hot topics from the very moment Galileo was planned. Indeed, as more and more systems join the select club of countries with their own navigation system, the more importance the idea gains.

MBOC brings additional reduction of interference between GPS L1C/L1-C/A and Galileo OS, and this is a direct consequence of the better spectral separation coefficients (SSC) of the signal. This underlines the great importance of using this figure to assess the degradation and overlapping among different signals. In **Figure 17** we show the reduction of the maximum C/N_0 degradation that results from changing the baseline from BOC(1,1) to MBOC(6,1,1/11), based on calculations presented in the paper by S. Wallner et alia, "Interference Computations between GPS and Galileo." .

C-Band. During the World Radio Conference 2000 (WRC-2000), the Galileo program obtained authorization to use C-band frequencies. At that time, a dedicated portion of the C-band had been assigned for radionavigation, but technical complexities made it impossible for the first generation of Galileo to take advantage of it. It is, however, a serious candidate for one or several additional signals of the next generation of Galileo, assumed to be backward-compatible with the first generation for which investments are currently being made.

Indeed, phase noise problems, the higher free space attenuation, and the strong signal attenuation due to rain and the in-door environment knocked down all the proposed solutions, discussed in the article by M. Irsigler et alia, "Use of C-Band Frequencies for Satellite Navigation: Benefits and Drawbacks" (see Additional Resources). But, in the future, things could have changed, and C-band may be a possible alternative among other new frequency bands to study.

Galileo Services

The Galileo signals will be assigned to provide the service categories which are summarized in Table 6.

Open Service (OS). The single-frequency (SF) OS will be provided by each of the three signals: E1, E5a and E5b. The dual-frequency (DF) OS will be provided by the following dual-frequency signal combinations:

- E1(B&C) - E5a
- E1(B&C) - E5b

Commercial Service (CS). The CS will be provided by the E6(B&C) signal plus the OS signals (E1(B&C), E5a, and E5b). The E6(B&C) signal contains the value-added data and is combined with OS signals for improved performance.

Safety of Life (SoL). The mono-frequency SoL will be provided by each of the two signals: E1(B&C) and E5b. The dual-frequency SoL will be provided by the following dual-frequency signal combination: E1(B&C) - E5b. It has to be noted that the Galileo safety-of-life frequencies are in the Aeronautical RadioNavigation Service (ARNS) bands allocated for GNSS, that is E5a, E5b, and E1. The integrity broadcast and the protection provided in the ARNS bands are two important features of the GALILEO SoL.

A third important value-added safety-of-life feature provided by Galileo is the frequency diversity offered by the three mentioned ARNS Galileo bands, making the SoL Galileo or Galileo/GPS receivers, for instance, E5a, E5b, and E1 receivers. Using a probabilistic theory related to involuntary jamming of GNSS receivers (as discussed in the paper by J.-L. Issler et alia cited in Additional Resources), the probability of losing the dual frequency navigation function has been assessed and computed to be approximately 15,000 times lower in the case where a tri-frequency single system receiver is used instead of a dual-frequency single system receiver, making this event an improbable case. This result is particularly important for safety of life applications, such as civil aviation. Therefore, frequency diversity has an enormous potential as a simple interference mitigation means.

Public Regulated Service (PRS). The PRS service will be provided by the E1-A and E6-A signals. These will use encrypted PRS ranging codes, navigation data messages, and sub-carriers improving signal processing performances (as discussed in the paper by A. de Latour).

Search And Rescue (SAR). The SAR distress messages 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, transmitted from SAR operators to distress-emitting beacons, will be used for

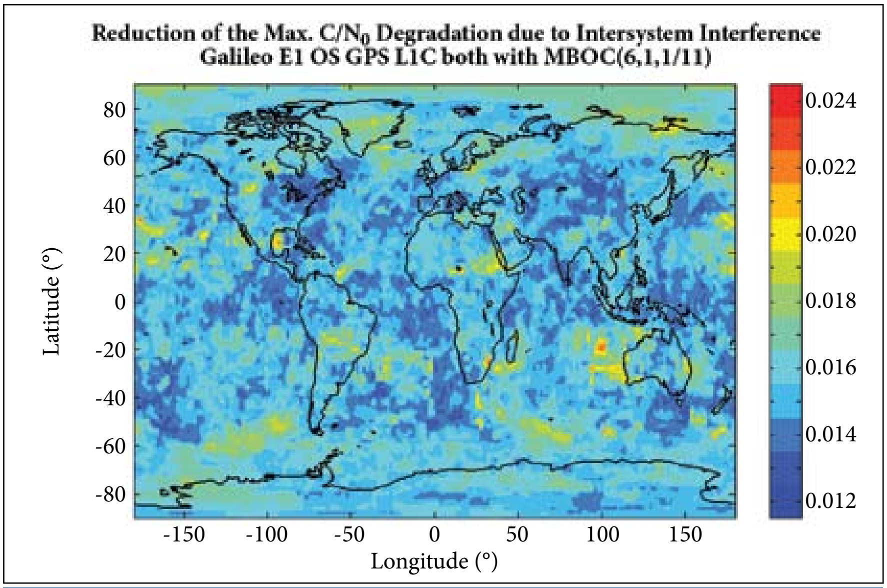

FIGURE 17 Reduction of the maximum C/N0 Degradation due to Intersystem Interference when MBOC is used instead of BOC(1,1) [19]. Minimum: 0.016 dB and maximum 0.023 dB

GNSS System	Galileo	Galileo	Galileo
Service Name	E1 OS		PRS
Center Frequency	1575.42 MHz		
Frequency Band	E1		
Access Technique	CDMA		
Spreading modulation	CBOC(6,1,1/11)		BOC_{cos}(15,2.5)
Sub-carrier frequency	1.023 and 6.138 MHz (Two sub-carriers)		15.345 MHz
Chip rate	1.023 MHz		2.5575 MHz
Signal Component	Data	Pilot	N/A
Primary PRN Code length	4092		N/A
Code Family	Random Codes		N/A
Secondary PRN Code length	-	25	N/A
Data rate	250 sps	-	N/A
Minimum Received Power [dBW]	-157	N/A	
Elevation	10°		N/A

TABLE 5. Galileo E1 signal technical characteristics

Id	OS	SoL	CS	PRS	SAR
E5a	●		●		
E5b	●	●	●		
E6A				●	
E6B,C			●		
L6					●
E1A				●	
E1B,C	●	●	●		

TABLE 6. Galileo Services mapped to signals

acknowledgement of distress alerts and coordination of rescue teams. The data will be embedded in the OS data of the signal transmitted in the E1 carrier frequency.

Conclusions

Galileo has finalized its frequency and signal plan. As this paper has evidenced, the way to today´s baseline has been long and difficult, but with MBOC the objective of providing wideband signals in all the assigned frequencies has been achieved.

After briefly recounting the evolution of the Galileo Signal Plan in the past years, an overview of the technical characteristics of all the baseline modulations has been provided by this article. Special attention was paid to the MBOC modulation that has recently been adopted as baseline for the Galileo E1 Open Service and GPS L1 Civil (L1C). Performance figures were also provided for MBOC, and we concluded the article with a discussion of the services that Galileo is planning to provide.

Acknowledgments

The work of the European Commission Signal Task Force was supported by many European national space agencies such as, e. g., Deutsches Zentrum für Luft- und Raumfahrt (DLR, Germany), Centre National d´Etudes Spatiales (France), and Defence Science and Technology Laboratory (United Kingdom). Many other members of the European Commission Galileo Signal Task Force have also contributed to this work.

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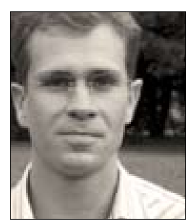
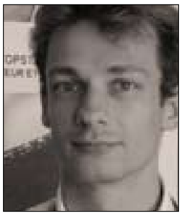
Guenter W. Hein is Full Professor and Director of the Institute of Geodesy and Navigation at the University FAF Munich. He is responsible for research and teaching in the fields of high-precision GNSS positioning and navigation, physical geodesy and satellite methods. He has been working in the field of GPS since 1984 and is author of numerous papers on kinematic positioning and navigation as well as sensor integration. In 2002 he received the prestigious "Johannes Kepler Award" from the U.S. Institute of Navigation (ION) for "sustained and significant contributions to satellite navigation." Presently he is heavily involved in the Galileo program.



Stefan Wallner studied at the Technical University of Munich and graduated with a diploma in techno-mathematics. He is now a research associate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Germany in Munich. His main topics of interests are the spreading codes and the signal structure of Galileo together with radio frequency compatibility of GNSS.

Jean-Luc Issler is head of the Transmission Techniques and Signal Processing Department of CNES (the French Space Agency), whose main tasks are signal processing, air interfaces and equipment in radionavigation; tracking, telemetry, and control; propagation, and spectrum survey. He has been involved in the development of several spaceborne receivers in Europe, as well as in studies on the European radionavigation projects, such as GALILEO and pseudolite networks. With the Direction de la Recherche et des Affaires Scientifiques et Techniques (DRAST), he represents

France in the Galileo Signal Task Force of the European Commission. In 2004, with Lionel Ries and Laurent Lestarquit, he received the Astronautic Prize of the AAAF (French aeronautical and space association) for his technical work on Galileo signals and spaceborne GNSS equipment.



Lionel Ries has been a navigation engineer in the Transmission Techniques and Signal Processing Department at CNES since June 2000. He is responsible for research activities on GNSS2 signal, including BOC modulations and GPS IIF L5, and software receivers. He is involved in the Galileo program in which he supports the European Space Agency, the European Commission, and the Galileo Joint Undertaking through the Galileo Signal Task Force. He graduated from the Ecole Polytechnique de Bruxelles, at Brussels Free University (Belgium) and received an M.S. degree from the Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (SUPAERO) in Toulouse (France).

Laurent Lestarquit graduated from the Ecole Polytechnique of Paris and then specialized in space telecommunication systems at the Ecole Nationale de l'Aéronautique et de l'Espace (SUPAERO) in Toulouse, France. Since 1996, he has been collaborating on several projects related to GPS space receivers (HETE2 and STENTOR). He is now involved in the Galileo program and supports the EC and ESA through the Galileo Signal Task Force. He invented the AltBOC 8 PSK signal proposed for Galileo on the E5 frequency. From now on he will be involved in Galileo orbit determination and time synchronization.

Antoine de Latour has been a navigation engineer in the CNES Transmission Techniques and Signal Processing Department since 2003. He is involved in the Galileo Program in which he supports the European Space Agency and the European Commission. Delatour is involved in the design of the Galileo signals, in the use of GNSS for space applications, in the GPS/Galileo radio frequency compatibility assessment, and in the development of a GNSS RF signal simulator. In particular, he studied in depth the CBOC Galileo signal definition and the PRS signal. Delatour proposed new tracking signal techniques for generic receivers and spaceborne receivers. He was graduated from the Ecole Supérieure d´Electricité (Supélec) in Paris and obtained a masters´s degree from the University of Stuttgart.

Jérémie Godet is the chairman of the Galileo Signal Task Force and has security and frequency responsibility in the Galileo Unit of the European Commission. He is in charge of compatibility and interoperability discussions with GPS, GLONASS, and QZSS for the Galileo program. He graduated from the Ecole Nationale Supérieure des Télécommunications de Bretagne (Télécom Bretagne, France) and received an M.S. degree from the International Space University.

Frédéric Bastide is working at the European GNSS Supervisory Authority (GSA) where he is in charge of Galileo signals. He is also involved in coordination activities with other GNSSes. He graduated as an electronics engineer at the ENAC in 2001 and obtained a Ph.D. in GNSS studies from the Institut National Polytechnique de Toulouse.

Tony (A. R.) 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, Indian Institute of Technology (IIT) New Delhi and at the University of Copenhagen. 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 the Galileo satellite system.

John I. R. Owen is Leader of Navigation Systems, Air Systems Department, Dstl. He is a Dstl senior fellow, a fellow of the Royal Institute of Navigation. He gained a BSc (Hons) in electrical and electronic engineering, Loughborough University, and joined the Royal Aircraft Establishment to research aspects of aircraft antennas. He helped develop the first GPS adaptive antenna system. He moved to the satellite navigation research group in 1982 and was responsible for the technical development of GPS receivers, antenna systems, and simulators in the UK. He is technical adviser to tjhe UK Government Departments for GPS and the European Galileo program, where he is active on the Signal Working Group, the Security Board, and the European Space Agency Program Board for Navigation. He chairs the ICAO Global Navigation Satellite Systems spectrum subgroup.

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spacecraft, the first of which — GIOVE-A — has been in orbit since its December 27, 2005, launch. A GPS IIIA launch is not currently expected before 2013. The larger GIOVE-B satellite, which more closely matches the fully operational Galileo spacecraft design, is scheduled for launch in the final days of this year.

On September 3 the spacecraft — built by as production team, led by prime contractor Thales Alenia Space and including Telespazio, EADS Astrium, and ESA — began its journey from the Thales Alenia plant in Rome to the ESA-ESTEC facility in Noordwijk, The Netherlands.

GIOVE-B has successfully passed all preliminary tests, including the thermal-vacuum test that duplicates the satellite's in-orbit environment, and will undergo further tests in The Netherlands before being sent to the Baikonur cosmodrome to start launch preparations.

Building on 2004 Pact

Building on the historic cooperative agreement on GPS and Galileo signed between the two parties in June 2004, a joint working group overcame technical challenges to design interoperable optimized civil signals that will also protect common security interests.

Incorporating MBOC into both GPS and Galileo is expected to enhance commercial opportunities for the development of new GNSS products and services.

The cooperative agreement reflects a marked turnaround in U.S. attitudes toward Galileo. In the early years of the Bush administration, numerous attempts were made to forestall implementation of what was then seen as a rival to GPS.