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ORIGINAL ARTICLE

Galileo civil signal modulations

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Abstract Spectrum limitations for navigation systems require that the various navigation signals broadcast by the Galileo system must be combined and must utilize bandwidth-efficient modulations. At the L1 band, one of the most important questions is how to combine all the Open Service signals and the Public Regulated Service signal at the payload level, while maintaining good performance at reception. The Interplex modulation, a particular phase-shifted-keyed/phase modulation (PSK/PM), was chosen to transmit these signals because it is a constant-envelope modulation, thereby allowing the use of saturated power amplifiers with limited signal distortion. The Interplex modulation was also taken as baseline at the E6 band to transmit the three channels and the services associated on the same carrier frequency. At the E5 band, the modulation must combine two different services on a same constant envelope composite signal, while keeping the simplicity of a BOC implementation. The constant envelope Alternate Binary Offset Carrier (ALTBOC) modulation was chosen as the solution to transmit the Galileo E5 band signal. The main objective of this paper is to study these Galileo modulations. After the introduction, the E5 band signals are described, followed by the Alternate BOC modulation which has been chosen to transmit them. The second part describes the general formulation of the Interplex modulation and its key parameters for an optimal multiplexing of the Galileo L1 band signals. Since the Galileo Open Service signals at the L1 band are still not yet completely specified, different test cases are considered and their impact on the resulting choice for the Interplex modulation parameters is exposed.

Keywords Galileo · ALTBOC · Interplex · MBOC · CBOC

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Introduction

The development of the Galileo system has led to the study of different modulation techniques both on the E5 and L1 bands in order to obtain the best performance at the reception level. Different structural choices for the signals associated with each service on both bands have been made. Consequently, the desire to coherently transmit all the signals pertaining to each band led to the need of different advanced modulation schemes. One main design driver is the need for a transmitted signal with constant envelope in order to minimize amplifier distortions in the payload.

On the E5 band, the modulation objective is to multiplex three different services, the Open Service (OS), the Commercial Service (CS) and the Safety of Life Service (SoL), included into two Binary Offset Carrier (BOC)-like signals (resulting into four components), while maintaining a constant envelope. The different BOC signals are commonly referred to as BOC(p,q), where the first parameter defines the subcarrier rate as $p \times 1.023$ MHz and the second parameter the spreading code rate as $q \times 1.023$ MHz. The constant envelope Alternate Binary Offset Carrier (ALTBOC) modulation was developed and shown to verify all the aforementioned properties. Consequently, it was chosen to transmit the Galileo E5 band signal.

In the L1 band, the modulation objective is to combine three distinct signals associated to two different services (two signals with the Open Service (OS) and one with the Public Regulated Service (PRS)) into a phase modulated composite signal that keeps a constant envelope. In this case, the Interplex modulation is preferred because it provides the best overall satellite power efficiencies while verifying all the previous objectives.

On the E6 band the modulation scheme is similar to the modulation scheme at the L1 band as shown in Fig. 1. Indeed, the Interplex modulation is also preferred to combine the three distinct channels associated to the two different services.

This paper intends to review the signal multiplexing techniques aforementioned that were proposed to transmit Galileo signals, focusing on civil signals.

In the first part the Galileo E5 signals and its associated ALTBOC modulation are presented. We then describe the modification made on the ''classical'' ALTBOC modulation to obtain a more suitable constant envelope ALTBOC modulation and expose its advantages.

Next, the Galileo L1 signal and the general formulation of the Interplex modulation are presented. Even though the L1 signals are still under investigation, the adaptation of the Interplex application to these signals is studied by considering two cases:

1. The current Galileo baseline: a BOC(1,1) as Data and Pilot Open Service signal
2. A recently proposed Multiplex-BOC (MBOC) (Hein et al. 2006) with either:
   - a BOC(1,1) on the Data OS signal and a Composite BOC (CBOC)(6,1) on the Pilot OS signal (50% of the OS power on each channel), or
   - a CBOC(6,1) on the Data and Pilot OS signal (50% of the OS power on each channel).

The E5 band modulation: the alternate BOC

On the E5 band, the modulation aim is to multiplex two different QPSK-like signals on a same carrier while keeping the properties of an Offset Carrier (OC) signal (with split spectrum properties defining a lower E5a band and an upper E5b band) and a constant envelope.

The Galileo E5 signal consists of four components which transmit two categories of services: the OS on the E5a band, which is divided into a data and a pilot channel, and the SoL service on the E5b band, which is also divided into a data and a pilot channel. These four components have the following characteristics:

- E5a data channel: results from the modulation of the E5a navigation data stream with the E5a data channel PRN tiered code sequence which has a 10.23 Mcps chipping rate.
- E5a pilot (dataless) channel: consists in the E5a pilot channel PRN tiered code sequence which has a 10.23 Mcps chipping rate.
- E5b data channel: results from the modulation of the E5b navigation data stream with the E5b data channel PRN tiered code sequence which has a 10.23 Mcps chipping rate.
- E5b data channel: results from the E5b pilot channel PRN tiered code sequence which has a 10.23 Mcps chipping rate.

It was also desired to use an OC modulation in order to allow possible high accuracy tracking using a very wide bandwidth.

The modulation used to multiplex all these channels is called the constant envelope Alternate Binary Offset

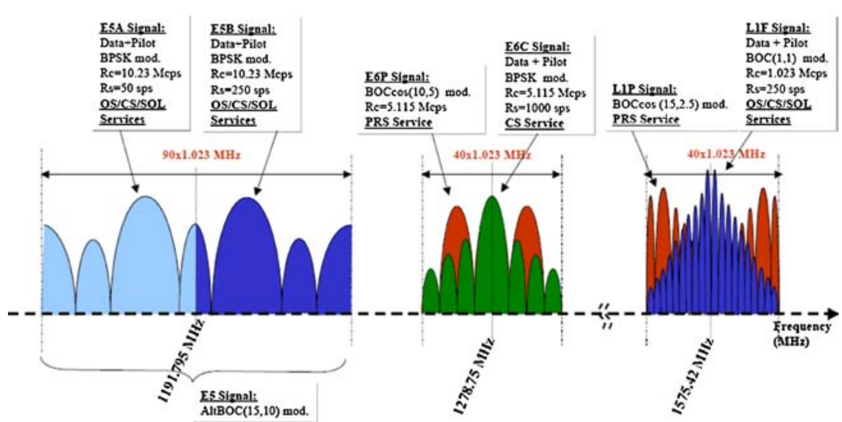

Fig. 1 Galileo frequency spectrum (GJU 2005)

Carrier (ALTBOC) modulation. This modulation is proposed with a code chipping rate of 10.23 Mcps and a subcarrier of 15.345 MHz, leading to an ALTBOC(15,10) configuration.

Non-constant envelope ALTBOC modulation

The first idea was to use an OC modulation, but transmitting a different service through each side-lobe of the OC spectrum. One solution was then to multiply the base band signal by a ''complex'' subcarrier. In that way the signal spectrum is not split up, but only shifted to higher or lower frequencies.

Assuming the data channels to be on the in-phase component and the pilot channels on the quadrature component, then the base band signal can be expressed as follow (Ries et al. 2003):

$$x_{\mathrm{ALT\_BOC}}(t) = \left[\left(c_u + j\cdot c_u^{'}\right)\cdot \mathrm{er}(t) + \left(c_L + j\cdot c_L^{'}\right)\cdot \mathrm{er}^*(t)\right] \quad (1)$$

with

$$\begin{aligned} \mathrm{er}(t) &= \mathrm{sign}[\cos(2\pi R_{\mathrm{SC}}t)] + j\cdot \mathrm{sign}[\sin(2\pi R_{\mathrm{SC}}t)] \\ &= c_r(t) + j\cdot s_r(t) \end{aligned} \quad (2)$$

where $\mathrm{er}(t)$ is the ''complex'' subcarrier, R_{SC} the subcarrier frequency, $c_u$the product of the E5a code and the E5a data stream, $c^{'}_u$ the pilot E5a code, c_L the product of the E5b code and the E5b data stream, and $c^{'}_L$ the pilot E5b code.

By developing the previous expression, the ALTBOC signal could also be written as:

$$\begin{aligned} x_{\mathrm{ALT\_BOC}}(t) = \{&\left[\left(c_u + c_L\right)\cdot c_r(t) - \left(c_u^{'} - c_L^{'}\right)\cdot s_r(t)\right] \\ &+ j\cdot\left[\left(c_u^{'} + c_L^{'}\right)\cdot c_r(t) + \left(c_u - c_L\right)\cdot s_r(t)\right]\} \end{aligned} \quad (3)$$

According to the relative signs of the code chips c_u, $c^{'}_u$, c_L, $c^{'}_L$ and the values of the ALTBOC subcarriers, c_r and s_r, the ALTBOC modulation constellation can be deduced and is represented on the next graph:

Figure 2 clearly shows that the ALTBOC modulation envelope is not constant. This would not be optimal considering the non-linearities of the Galileo payload amplifier and thus would distort the broadcast signal. This solution is not suitable and a new modulation, which is based on the same principles, was proposed. This new modulation, called constant envelope ALTBOC modulation, keeps the same properties than the ''classical'' ALTBOC modulation but is obtained with a different process in order to have a constant envelope (Ries et al. 2003).

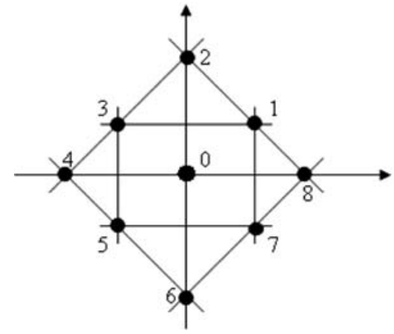

Fig. 2 ALTBOC modulation constellation (Ries et al. 2003)

Constant envelope ALTBOC modulation

The constant envelope ALTBOC modulation is, in fact, based on the modification of the Alternate Linear Offset Carrier (ALTLOC) modulation (Ries et al. 2003). This modulation is similar to the basic ALTBOC modulation presented previously, the only difference being that the subcarrier is not a square-wave subcarrier but a sinusoidal subcarrier.

The constellation plots of the ALTLOC base band signal, as presented in (Ries et al. 2003), can be defined by either Eqs. 4 or 5, depending on the relative signs of the code chips c_u, $c^{'}_u$, c_L, $c^{'}_L$:

$$\begin{aligned} x_{\mathrm{ALT\_LOC}}(t) = 2\Big[&\sin\left(2\pi R_{\mathrm{SC}}t + k_1\frac{\pi}{2}\right) \\ &+ j\cdot k_2\cdot \sin\left(2\pi R_{\mathrm{SC}}t + k_1\frac{\pi}{2}\right)\Big] \end{aligned} \quad (4)$$

$$x_{\mathrm{ALT\_LOC}}(t) = 2\sqrt{2}(j)^{k_1}\cdot\left(\sin\left(2\pi R_{\mathrm{SC}}t + k_2\frac{\pi}{4}\right)\right) \quad (5)$$

where $k_1 \in \{1,2,3,4\}$ and $k_2 = \pm 1$. Note that the k values depend on the values of the different spreading codes chips.

To obtain an ALTBOC with a constant envelope, the idea is to modify the previous equations by changing the sine-wave subcarrier in a square-wave subcarrier by using the following transformation: $\sin(x) \to \frac{\mathrm{sign}(\sin(x))}{\sqrt{2}}$.

So the ALTLOC constellation plots become (Ries et al. 2003):

$$\begin{aligned} x(t) = \sqrt{2}\Big[&\mathrm{sign}\left[\sin\left(2\pi R_{\mathrm{SC}}t + k_1\frac{\pi}{2}\right)\right] \\ &+ j\cdot k_2\cdot \mathrm{sign}\left[\sin\left(2\pi R_{\mathrm{SC}}t + k_1\frac{\pi}{2}\right)\right]\Big] \end{aligned} \quad (6)$$

or

$$x(t) = 2(j)^{k_1} \cdot \mathrm{sign}\left(\sin\left(2\pi R_{\mathrm{SC}} t + k_2 \frac{\pi}{4}\right)\right) \quad (7)$$

with $k_1 \in \{1,2,3,4\}$, $k_2 = \pm 1$

Because the signal takes exactly eight different values the expression for $x(t)$ can be written as

$$x(t) = 2 \cdot \mathrm{e}^{jk\frac{\pi}{4}} \quad k \in \{1,2,3,4,5,6,7,8\} \quad (8)$$

Figure 3 represents the modulation constellation corresponding to Eq. 8. It shows that the signal obtained has a constant envelope, while using a complex square-wave subcarrier. That is why the modulation presented is called constant envelope ALTBOC modulation, introduced by CNES (L. Lestarquit).

This definition of the constant envelope ALTBOC modulation will be used to generate the E5 signal in the Galileo payload. Note that the modulation could easily be implemented using simple look-up tables for the phase assignments.

The temporal expression of the new signal, presented in Soellner and Erhard (2003), is given hereafter and defines the E5 band ALTBOC signal thanks to two subcarriers:

$$x_{\mathrm{ALT\_BOC}}(t) = \begin{cases} \left(c_L + j \cdot c_L^{'}\right) \cdot \left[\mathrm{sc_{as}}(t) - j \cdot \mathrm{sc_{as}}\left(t - \frac{Ts}{4}\right)\right] + \left(c_U + j \cdot c_U^{'}\right) \cdot \left[\mathrm{sc_{as}}(t) + j \cdot \mathrm{sc_{as}}\left(t - \frac{Ts}{4}\right)\right] + \\ \left(\overline{c_L} + j \cdot \overline{c_L^{'}}\right) \cdot \left[\mathrm{sc_{ap}}(t) - j \cdot \mathrm{sc_{ap}}\left(t - \frac{Ts}{4}\right)\right] + \left(\overline{c_U} + j \cdot \overline{c_U^{'}}\right) \cdot \left[\mathrm{sc_{ap}}(t) + j \cdot \mathrm{sc_{ap}}\left(t - \frac{Ts}{4}\right)\right] \end{cases} \quad (9)$$

With

$$\overline{c_L} = c_U c_U^{'} c_L^{'} \quad \overline{c_L^{'}} = c_U c_U^{'} c_L \quad \overline{c_U} = c_L c_U^{'} c_L^{'} \quad \overline{c_u^{'}} = c_U c_L c_L^{'} \quad (10)$$

And

$$\begin{aligned} \mathrm{sc_{as}}(t) &= \left\{\frac{\sqrt{2}}{4}\mathrm{sign}\left(\cos\left(2\pi f_S t - \frac{\pi}{4}\right)\right) + \frac{1}{2}\mathrm{sign}(\cos(2\pi f_S t)) + \frac{\sqrt{2}}{4}\mathrm{sign}\left(\cos\left(2\pi f_S t + \frac{\pi}{4}\right)\right)\right. \\ \mathrm{sc_{ap}}(t) &= \left\{-\frac{\sqrt{2}}{4}\mathrm{sign}\left(\cos\left(2\pi f_S t - \frac{\pi}{4}\right)\right) + \frac{1}{2}\mathrm{sign}(\cos(2\pi f_S t)) - \frac{\sqrt{2}}{4}\mathrm{sign}\left(\cos\left(2\pi f_S t + \frac{\pi}{4}\right)\right)\right. \end{aligned} \quad (11)$$

It can be seen that the first line of Eq. 9 represents the useful signal and is composed, as expected of four channels: the E5a data and pilot channels (on an in-phase/quadra-phase scheme) on the left part, and the E5b data and pilot channels (on an in-phase/quadra-phase scheme) on the right part. It can also been seen that both data channels and both pilot channels are gathered in a BOC-like modulation.

It should be noticed also that the second line of Eq. 9 represent additional terms that are not useful signal but are intermodulation products. They are necessary to keep a constant envelope, they will consume a small portion of the overall power, i.e. will take a small fraction of the available power for the useful signal. It should also to be noted that the presented equations do not take into account the filtering processes which might be applied in the future GALILEO payloads.

The expression of the constant envelope ALTBOC modulation power spectrum density is equal to (Rebeyrol et al. 2005):

$$G_{\mathrm{ALTBOC}}(f) = \frac{4}{\pi^2 f^2 T_c} \frac{\cos^2(\pi f T_c)}{\cos^2\left(\pi f \frac{T_c}{n}\right)} \left[\cos^2\left(\pi f \frac{T_s}{2}\right) - \cos\left(\pi f \frac{T_s}{2}\right) - 2\cos\left(\pi f \frac{T_s}{2}\right)\cos\left(\pi f \frac{T_s}{4}\right) + 2\right] \quad (12)$$

This normalized spectrum is represented in Fig. 4.

Constant envelope ALTBOC signal properties

The innovative constant ALTBOC modulation has many advantages for the users and gives flexibility to

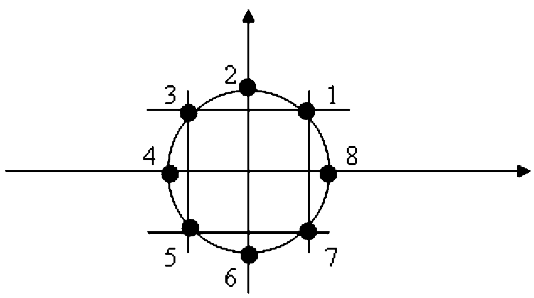

Fig. 3 Constant envelope ALTBOC or ALTBOC 8-PSK modulation constellation

receiver manufacturers to choose between different receiver designs:

- A single wide-band QPSK(10), on E5a or E5b, for a simple receiver.
- A double wide-band QPSK(10), on E5a and E5b independently. Thanks to the ALTBOC modulation, this provides dual frequency measurements, spectral isolation and frequency diversity against interference.
- A BOC(15,10) reduced to its main lobes. This tracking configuration allows a high precision tracking while limiting the susceptibility to interference.
- A BOC(15,10) in an extra wide bandwidth for very high accuracy receivers.

The performances of these different configurations can be found in Ries et al. (2003), Sleewaegen et al. (2005) and Soellner and Erhard (2003).

Fig. 4 Constant envelope ALTBOC(15,10) normalized power spectrum density

As Galileo and GPS are sharing the E5a/L5 band (1176.45 MHz), the inter-system interference between the Galileo ALTBOC signal and the GPS L5 signal should be carefully analyzed. Wallner et al. (2005) has shown that GALILEO E5a interference on GPS L5 is at the maximum about 0.33 dB. However, GPS L5 interference on Galileo E5A is more significant because its maximum value is about 0.63 dB. These two C/N_0 degradation preliminary values are high compared to the 0.25 dB aggregated degradation value generally admitted for GNSS systems. Issler et al. (2003) gives more information on interferences in the E5 band.

The L1 band modulation: Interplex

The problem in the L1 band is different. Indeed, the L1 band modulation should combine three distinct signals associated to two different services into a phase modulated composite signal that keeps a constant envelope on the payload amplifier input in order to optimize the link budget and the power efficiency on-board.

The Galileo L1 signal consists of multiplexing three components that are respectively:

- The L1P channel corresponds to the PRS. For this signal, the carrier is modulated by three components: the L1P navigation data stream, the L1P channel PRN tiered code sequence and the L1P cosine-phased subcarrier. The L1 PRS is a cosine BOC(15,2.5) modulation, introduced by CNES.
- The L1F data channel corresponds to the data OS. For this signal, the carrier is modulated by three components: the L1F navigation data stream, the L1F data channel PRN tiered code sequence and the L1F sine-phased subcarrier.
- The L1F pilot channel corresponds to the pilot OS. For this signal, the carrier is modulated by two components: the L1F pilot channel PRN tiered code sequence and the L1F sine-phased subcarrier.

In this case, the preferred modulation chosen to transmit all these channels is called Interplex modulation.

Formulation

The Interplex modulation is a phase-shifted-keyed/phase modulation (PSK/PM), combining multiple signals into a phase modulated composite signal. The general form of the Interplex phase-modulated signal, as presented in Butman and Timor (1972), is:

$$s(t) = \sqrt{2P}\cos\left(2\pi f_c \cdot t + \theta(t) + \varphi\right) \tag{13}$$

where P is the total average power, f_c the carrier frequency, $\theta(t)$ the phase modulation and φ a random phase.

In the case of GNSS applications, in particular in the case of the Galileo System, the phase modulation is defined as:

$$\theta(t) = \beta_1 s_1(t) + \sum_{n=2}^{N} \beta_n \cdot s_1(t) \cdot s_n(t) \tag{14}$$

with

$$s_n(t) = \pm 1 \tag{15}$$

where

- N is the number of signals
- β_n is the modulation angle or modulation index.

The value of the modulation indexes β_n determines the power allocation for each signal component.

As already mentioned in the first section, on the Galileo L1 band, three signals are multiplexed on the same carrier. Without losing generality, it can assume that:

- one signal will be in the quadrature channel, s_1
- two signals will be in the in-phase channel, s_2 and s_3

Thus, the general formula of a three components Interplex signal can be expressed as:

$$\begin{aligned} s(t) = \sqrt{2P}\cos\Big(&2\pi f_c \cdot t - \frac{\pi}{2} \cdot s_1(t) + \beta_2 \cdot s_1(t) \cdot s_2(t) \\ &+\beta_3 \cdot s_1(t) \cdot s_3(t) + \varphi\Big) \end{aligned} \tag{16}$$

Note that β_1 is taken equal to $-\pi/2$ because the signal s_1 has been chosen in quadrature with the two others signals.

By developing Eq. 16, it can be shown that:

$$s(t) = \sqrt{2P}\left[\begin{array}{l} (s_2(t) \cdot \sin(\beta_2)\cos(\beta_3) + s_3(t) \cdot \cos(\beta_2)\sin(\beta_3)) \cdot \cos(2\pi f_c \cdot t + \varphi) \\ + (s_1(t) \cdot \cos(\beta_2)\cos(\beta_3) - s_1(t) \cdot s_2(t) \cdot s_3(t) \cdot \sin(\beta_2)\sin(\beta_3)) \cdot \sin(2\pi f_c \cdot t + \varphi) \end{array}\right] \tag{17}$$

From Eq. 17 it can be noticed that the first three terms correspond to the desired useful signal terms s_1, s_2, s_3; the fourth term is an undesired intermodulation (IM) term.

This IM term is equal to the product of the three desired signals balanced by the modulation indexes β_2 and β_3. This term, as in the case of the constant ALTBOC modulation, even if it permits to obtain a constant envelope, consumes a small fraction of the total transmitted power available for the three desired signals. Thus, a small part of the transmitted power is used through this IM component. However, in contrast to the ALTBOC modulation, the modulation indexes allow the minimization of the power consumed by the IM component. This can be shown when looking at the expressions of the power of each component:

$$\begin{aligned} P_1 &= P \cdot \cos^2(\beta_2) \cdot \cos^2(\beta_3) \\ P_2 &= P \cdot \sin^2(\beta_2) \cdot \cos^2(\beta_3) \\ P_3 &= P \cdot \cos^2(\beta_2) \cdot \sin^2(\beta_3) \\ P_{\mathrm{IM}} &= P \cdot \sin^2(\beta_2) \cdot \sin^2(\beta_3) \end{aligned} \tag{18}$$

These equations show that a trade-off must be made in order to have sufficient power on the desired signals and non-disadvantageous power on the IM signal. According to the Galileo L1 signals, it can be imagined that the IM signal will have more or less influence.

In the following, different test cases, representing the current investigations on the Galileo L1 OS signal modulation are exposed. Note that the L1 PRS cosine-phased BOC(15, 2.5) signal is represented by s_1 in the following sections.

Galileo L1 OS BOC(1,1) signal

While the L1 OS signals are still under investigation, the current Galileo L1 OS base line (GJU 2005) signals are, at the time of writing:

- For the data OS signal: a BOC(1,1) signal s_2.
- For the pilot OS signal: a BOC(1,1) signal s_3.

In this case, as referred in GJU (2005), one possibility is that the total power should be equally divided into the in-phase component and the quadrature component. Moreover, the power of the data OS component should be equal to the power of the pilot OS component. Consequently, the parameters β_2 and β_3 are constrained by the following relationships:

$$\begin{cases} P_1 = P \cdot \cos^2(\beta_2) \cdot \cos^2(\beta_3) = 2 \cdot P \cdot \sin^2(\beta_2) \cdot \cos^2(\beta_3) \\ P_2 = P_3 = P \cdot \sin^2(\beta_2) \cdot \cos^2(\beta_3) \end{cases} \tag{19}$$

This system leads to $\beta_2 = -\beta_3 = m = 0.6155$ radians. Consequently, the expression of the transmitted signal is:

$$s(t) = \sqrt{2P}\cos\left(2\pi f_c \cdot t - \frac{\pi}{2} \cdot s_1(t) + m \cdot s_1(t) \cdot s_2(t) - m \cdot s_1(t) \cdot s_3(t) + \varphi\right) \tag{20}$$

or

$$s(t) = \sqrt{2P}\left[\begin{array}{l}(s_2(t) \cdot \sin(m)\cos(m) - s_3(t) \cdot \cos(m)\sin(m)) \cdot \cos(2\pi f_c \cdot t + \varphi) \\ + \left(s_1(t) \cdot \cos^2(m) + s_1(t) \cdot s_2(t) \cdot s_3(t) \cdot \sin^2(m)\right) \cdot \sin(2\pi f_c \cdot t + \varphi)\end{array}\right] \tag{21}$$

The IM term is the product of the signals s_1, s_2 and s_3 as foreseen. So in this case it is a BOC(15,2.5) as PRS signal. The power used for the IM is –9.54 dB below the total L1 power.

Figure 5 shows that the modulation constellation is only composed of six plots. This is due to the fact that the signals s_2 and s_3 are both BOC(1,1) subcarrier and thus the constellation plot goes through two points twice.

Figure 6 represents the power spectrum density of the Galileo L1 signal using the Interplex modulation (Rebeyrol et al. 2006).

Galileo L1 OS MBOC signal

Recently, a new optimized spreading modulation called Multiplex-BOC (MBOC) was recommended in Hein et al. (2006) for Galileo L1 OS signal. The MBOC power spectrum density recommended in Hein et al. (2006) is the power spectrum density of the entire signal (pilot and data components together), denoted MBOC(6,1,1/11), and given by:

$$S_{\mathrm{OS}}(f) = \frac{10}{11} S_{\mathrm{BOC}(1,1)}(f) + \frac{1}{11} S_{\mathrm{BOC}(6,1)} \tag{22}$$

where $S_{\mathrm{BOC}}(n,m)$ is the unit-power power spectrum density of a sine-phased BOC spreading modulation. A BOC(6,1) signal is introduced to improve the OS signal tracking performance. The MBOC spectrum is represented on (Fig. 7):

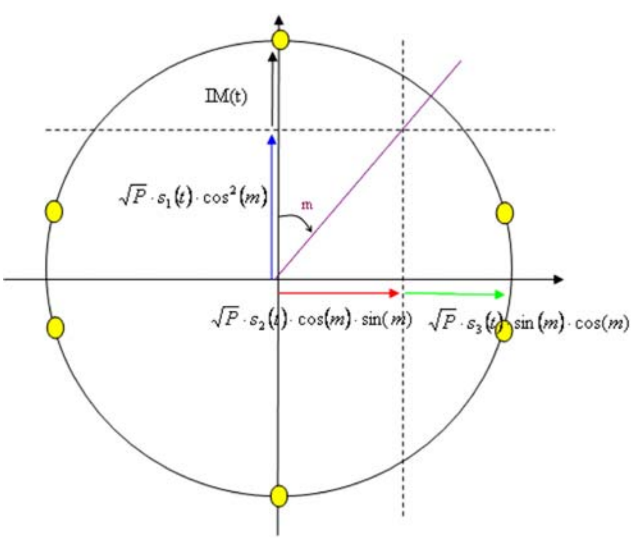

Fig. 5 BOC(1,1) L1 band Interplex modulation constellation

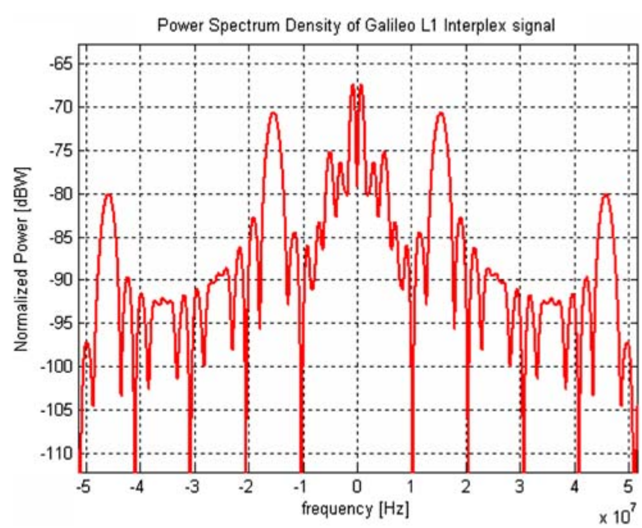

Fig. 6 Galileo L1 Interplex signal normalized power spectrum density

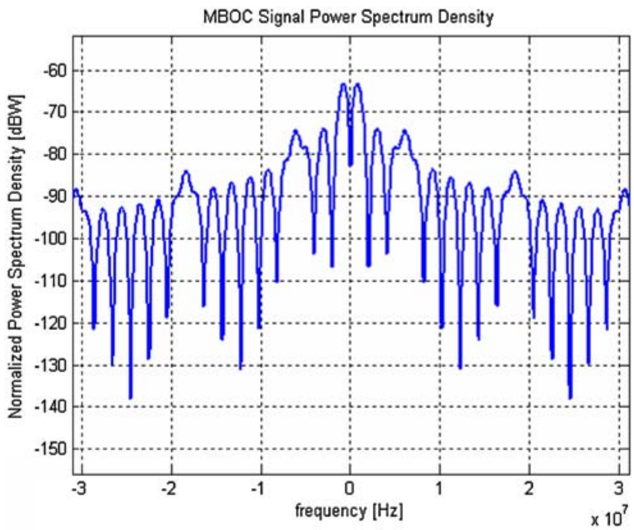

Fig. 7 MBOC signal power spectrum density

In order to fulfill this power spectrum density constraint, one proposed option is to use a Composite BOC (CBOC) subcarrier modulating the PRN code. This subcarrier is obtained from a linear combination of a BOC(1,1) subcarrier and a BOC(6,1) subcarrier. The CBOC(6,1) was introduced publicly for the first time in Hein et al. (2005), and more recently in Avila-Rodriguez et al. (2006). An optimal reception of this modulation uses a correlation between the incoming CBOC signal and a locally generated replica of this CBOC waveform. However, due to the linear combination of the BOC(1,1) and BOC(6,1), this CBOC replica has four levels and should thus be coded on at least 2 bits. This would significantly complicate the receiver architecture. To decrease the receiver complexity, that could represent a drawback for the use of this signal in general GNSS receivers, two CBOC tracking techniques, which need only a local subcarrier that can be coded on 1 bit, are proposed:

1. The first technique uses parallel correlations:
   - A correlation between the incoming CBOC signal and a local replica of the BOC(1,1) component of the CBOC
   - A correlation between the incoming CBOC code and a local replica of the BOC(6,1) component of the CBOC

   The resulting correlation values are then linearly combined to form the optimal CBOC correlation value. The resulting acquisition and tracking performances equal the optimal CBOC tracking. The drawback, however, is the need to use twice as many correlators as in the nominal case.
2. A second method was proposed to reduce the number of required correlators. It uses, for the correlation process, a local replica of the incoming spreading code modulated by a subcarrier that is composed of an alternating succession of segments with pure BOC(1,1) and pure BOC(6,1) waveforms. This multiplexing allows capturing part of the BOC(1,1) and BOC(6,1) components present in the CBOC signal to improve the signal reception. However, since the resulting local waveform differs from the incoming CBOC waveform, the correlation process is degraded and losses in the signal reception and processing are expected. The relative time duration of the BOC(1,1) and BOC(6,1) local subcarriers will affect the relative contribution of the BOC(1,1) and BOC(6,1) autocorrelations in the resulting correlation values. It can be optimized and changed according to different performance parameters such as multipath rejection, tracking in thermal noise or correlation loss.
3. Others simple and efficient CBOC tracking techniques are also under investigation (Julien et al. 2006).

Hein et al. (2006) proposes different possible implementations to obtain the MBOC modulation on the OS signal using a CBOC waveform, and particularly proposes to transmit:

1. a data BOC(1,1) component and a pilot CBOC(6,1) component, or
2. a data and pilot CBOC(6,1) component.

This section will focus on the application of the Interplex modulation to these two particular cases because these two cases are somewhat different compared to the BOC(1,1) case, previously studied.

Indeed, in the MBOC case, the Interplex modulation multiplexes five signal components:

- the data BOC(1,1) OS component: $D_D C_D x(t)$
- the pilot BOC(1,1) OS component: $C_P x(t)$
- the data BOC(6,1) OS component: $D_D C_D y(t)$
- the pilot BOC(6,1) OS component: $C_P y(t)$
- the PRS component: $D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t)$

where D_D, D_{PRS} represent respectively the OS and PRS data stream, C_D, C_P, C_{PRS} the data OS, pilot OS and PRS codes, $x(t)$ a sine-phased BOC(1,1) subcarrier, $y(t)$ a sine-phased BOC(6,1) subcarrier, and $z(t)$ a cosine-phased BOC(15,2.5) subcarrier.

So the general expression of the Interplex is:

$$s(t) = \cos\left(\begin{array}{l} 2\pi f_s t - \frac{\pi}{2} D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) + \beta_1 \cdot D_D C_D x(t) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \\ + \beta_2 \cdot C_P x(t) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) + \beta_3 \cdot C_P y(t) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \\ + \beta_4 \cdot D_D C_D y(t) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \end{array}\right) \tag{23}$$

By developing Eq. 23 we obtain:

$$\begin{aligned} s(t) = & \left\{\begin{array}{l} (\sin(\beta_1)\cos(\beta_2)\cos(\beta_3)\cos(\beta_4) - \cos(\beta_1)\sin(\beta_2)\sin(\beta_3)\sin(\beta_4)) \cdot C_P x(t) \\ + (\cos(\beta_1)\sin(\beta_2)\cos(\beta_3)\cos(\beta_4) - \sin(\beta_1)\cos(\beta_2)\sin(\beta_3)\sin(\beta_4)) \cdot D_D C_D x(t) \\ + (\cos(\beta_1)\cos(\beta_2)\sin(\beta_3)\cos(\beta_4) - \sin(\beta_1)\sin(\beta_2)\cos(\beta_3)\sin(\beta_4)) \cdot C_P y(t) \\ + (\cos(\beta_1)\cos(\beta_2)\cos(\beta_3)\sin(\beta_4) - \sin(\beta_1)\sin(\beta_2)\sin(\beta_3)\cos(\beta_4)) \cdot D_D C_D y(t) \end{array}\right\} \cos(2\pi f_s t) \\ & + \left\{\begin{array}{l} (\cos(\beta_1)\cos(\beta_2)\cos(\beta_3)\cos(\beta_4) + \sin(\beta_1)\sin(\beta_2)\sin(\beta_3)\sin(\beta_4)) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \\ - (\cos(\beta_1)\cos(\beta_2)\sin(\beta_3)\sin(\beta_4) + \sin(\beta_1)\sin(\beta_2)\cos(\beta_3)\cos(\beta_4)) \cdot D_D C_D C_p D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \\ - (\sin(\beta_1)\cos(\beta_2)\sin(\beta_3)\cos(\beta_4) + \cos(\beta_1)\sin(\beta_2)\cos(\beta_3)\sin(\beta_4)) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) x(t) y(t) \\ - (\sin(\beta_1)\cos(\beta_2)\cos(\beta_3)\sin(\beta_4) + \cos(\beta_1)\sin(\beta_2)\sin(\beta_3)\cos(\beta_4)) \cdot D_D C_D C_p D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) x(t) y(t) \end{array}\right\} \sin(2\pi f_s t) \end{aligned} \tag{24}$$

The intermodulation term (IM) is then equal to:

$$\mathrm{IM}(t) = \left\{\begin{array}{l} - \left(\begin{array}{l} \cos(\beta_1)\cos(\beta_2)\sin(\beta_3)\sin(\beta_4) \\ + \sin(\beta_1)\sin(\beta_2)\cos(\beta_3)\cos(\beta_4) \end{array}\right) \cdot D_D C_D C_p D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) \\ - \left(\begin{array}{l} \sin(\beta_1)\cos(\beta_2)\sin(\beta_3)\cos(\beta_4) \\ + \cos(\beta_1)\sin(\beta_2)\cos(\beta_3)\sin(\beta_4) \end{array}\right) \cdot D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) x(t) y(t) \\ - \left(\begin{array}{l} \sin(\beta_1)\cos(\beta_2)\cos(\beta_3)\sin(\beta_4) \\ + \cos(\beta_1)\sin(\beta_2)\sin(\beta_3)\cos(\beta_4) \end{array}\right) \cdot D_D C_D C_p D_{\mathrm{PRS}} C_{\mathrm{PRS}} z(t) x(t) y(t) \end{array}\right. \tag{25}$$

The values of the modulation indexes are defined thanks to conditions put on the amplitude of each signal. Two different cases will be considered:

- case 1: a CBOC(6,1) on the data and pilot OS component. Equal power on data and pilot, and 1/11 of the total power in the BOC(6, 1) component are considered.
- case 2: a CBOC(6,1) on the pilot OS component and a BOC(1,1) on the data OS component. Equal power on data and pilot, 1/11 of the total power in the BOC(6,1) component are also considered.

Case 1

In this case the base band expression of the signal is:

$$s(t) = D_D C_D\{Px(t) + Qy(t)\} + C_P\{Px(t) - Qy(t)\} + j\{D_{\text{PRS}} C_{\text{PRS}} R \cdot z(t) + IM(t)\} \tag{26}$$

Consequently, to obtain Eq. 26 from the general Eq. 24, the following system should be solved:

$$\begin{cases} \sin(\beta_1)\cos(\beta_2)\cos(\beta_3)\cos(\beta_4) - \cos(\beta_1)\sin(\beta_2)\sin(\beta_3)\sin(\beta_4) = P \\ \cos(\beta_1)\sin(\beta_2)\cos(\beta_3)\cos(\beta_4) - \sin(\beta_1)\cos(\beta_2)\sin(\beta_3)\sin(\beta_4) = P \\ \cos(\beta_1)\cos(\beta_2)\sin(\beta_3)\cos(\beta_4) - \sin(\beta_1)\sin(\beta_2)\cos(\beta_3)\sin(\beta_4) = -Q \\ \cos(\beta_1)\cos(\beta_2)\cos(\beta_3)\sin(\beta_4) - \sin(\beta_1)\sin(\beta_2)\sin(\beta_3)\cos(\beta_4) = Q \end{cases} \tag{27}$$

This system leads to:

$$\begin{cases} \beta_1 = \beta_2 \\ \beta_4 = -\beta_3 \end{cases} \quad \text{and} \quad \begin{cases} P = \dfrac{\sin(2\beta_1)}{2} \\ Q = \dfrac{\sin(2\beta_3)}{2} \\ R = \dfrac{(\cos(2\beta_1) + \cos(2\beta_3))}{2} \\ \quad = \dfrac{\sqrt{1-4P^2} + \sqrt{1-4Q^2}}{2} \end{cases} \tag{28}$$

Finally, Eq. 24 becomes in this case:

$$s(t) = \left\{\frac{\sin(2\beta_1)}{2}[C_P + D_D C_D]\cdot x(t) + \frac{\sin(2\beta_3)}{2}[-C_P + D_D C_D]\cdot y(t)\right\}\cos(2\pi f_s t) + \left\{\frac{(\cos(2\beta_1) + \cos(2\beta_3))}{2}\cdot D_{\text{PRS}} C_{\text{PRS}} z(t) + \frac{(\cos(2\beta_1) - \cos(2\beta_3))}{2}\cdot D_D C_D C_p D_{\text{PRS}} C_{\text{PRS}} z(t)\right\}\sin(2\pi f_s t) \tag{29}$$

Equation 29 shows that the IM only depends on the OS codes, data and on the PRS component (Fig. 8).

Hein et al. (2006) proposes that the percentage of BOC(6,1) power represents 2/11 of the pilot OS power. This condition involves

$$\begin{matrix} P = 0.383998 \\ Q = 0.121431 \\ R = 0.805258 \end{matrix} \quad \text{and} \quad \begin{matrix} \beta_1 = \beta_2 = 0.43785 \\ \beta_3 = -\beta_4 = 0.122657 \end{matrix} \tag{30}$$

considering the case of equal power on data and pilot and the PRS component being 3 dB above the OS component.

As regards the intermodulation term, the values chosen for the percentage of BOC(6,1) induce a IM power equal to 15.6 dB below the total signal power.

Case 2

In the other case, the CBOC(6,1) is only present on the pilot OS component, so the base band expression of the signal is:

$$s(t) = D_D C_D P x(t) + C_P\{Rx(t) - Qy(t)\} + j\{D_{\text{PRS}} C_{\text{PRS}} S \cdot z(t) + \text{IM}(t)\} \tag{31}$$

Consequently, to obtain Eq. 31 from the general Eq. 24, the following system should be resolved:

$$\begin{cases} \sin(\beta_1)\cos(\beta_2)\cos(\beta_3)\cos(\beta_4) - \cos(\beta_1)\sin(\beta_2)\sin(\beta_3)\sin(\beta_4) = R \\ \cos(\beta_1)\sin(\beta_2)\cos(\beta_3)\cos(\beta_4) - \sin(\beta_1)\cos(\beta_2)\sin(\beta_3)\sin(\beta_4) = P \\ \cos(\beta_1)\cos(\beta_2)\sin(\beta_3)\cos(\beta_4) - \sin(\beta_1)\sin(\beta_2)\cos(\beta_3)\sin(\beta_4) = -Q \\ \cos(\beta_1)\cos(\beta_2)\cos(\beta_3)\sin(\beta_4) - \sin(\beta_1)\sin(\beta_2)\sin(\beta_3)\cos(\beta_4) = 0 \end{cases} \tag{32}$$

If the modulation indexes verify Eq. 32, the PRS amplitude and the IM amplitude could be expressed as a function of P, Q and R. The expressions obtained are:

$$S = \frac{\sqrt{1-(R+Q+P)^2} + \sqrt{1-(R-Q+P)^2} + \sqrt{1-(R+Q-P)^2} + \sqrt{1-(R-Q-P)^2}}{4} \tag{33}$$

$$\mathrm{IM}(t) = \frac{1}{4} z(t) \left\{ \begin{array}{l} x(t)y(t)C_P D_D C_D \left(\begin{array}{l} -\sqrt{1-(R-Q-P)^2} + \sqrt{1-(R+Q-P)^2} \\ +\sqrt{1-(R-Q+P)^2} - \sqrt{1-(R+Q+P)^2} \end{array} \right) \\ +x(t)y(t) \left(\begin{array}{l} \sqrt{1-(R-Q-P)^2} - \sqrt{1-(R+Q-P)^2} \\ +\sqrt{1-(R-Q+P)^2} - \sqrt{1-(R+Q+P)^2} \end{array} \right) \\ +C_P D_D C_D \left(\begin{array}{l} -\sqrt{1-(R-Q-P)^2} - \sqrt{1-(R+Q-P)^2} \\ -\sqrt{1-(R-Q+P)^2} + \sqrt{1-(R+Q+P)^2} \end{array} \right) \end{array} \right\} \tag{34}$$

The IM takes eight different values, so the modulation is no longer an 8-PSK modulation as previously seen, it is a 16-PSK modulation as presented on Fig. 9.

As previously, Hein et al. (2006) proposes that the percentage of BOC(6,1) power represents 2/11 of the pilot OS power. This condition involves:

$$\begin{array}{ll} R = 0.358235 & \beta_1 = 0.43121 \\ Q = 0.168874 & \beta_2 = 0.746958 \\ P = 0.396044 & \beta_3 = -0.22261 \\ S = 0.79124 & \beta_4 = -0.0528 \end{array} \quad \text{and} \tag{35}$$

considering the case of equal power on data and pilot and the PRS component being 3 dB above the OS component.

Regarding the IM term, the values chosen for the percentage of BOC(6,1) induce an IM power 12.2 dB below the total signal power considering that the IM term have zero cross-correlation with $z(t)$. This value is weaker than the one obtained if the data and pilot OS are a BOC(1,1), but it is higher than the value obtained in the case 1. Therefore, considering an optimization of the power wasted, the case 1 with a CBOC(6,1) on the data and the pilot OS component is better.

However, in this case the OS power spectrum density does not verify exactly the PSD constraint expressed by Eq. 22 because of the apparition of a cross-correlation term between the BOC(1,1) and the BOC(6,1). Indeed, the power spectrum density of the OS signal in the present case is equal to:

$$S_{\mathrm{OS}}(f) = \left[\left(R^2 + P^2\right) \cdot S_{\mathrm{BOC}(1,1)} + Q^2 \cdot S_{\mathrm{BOC}(6,1)} - \frac{2RQ}{T_C} \cdot \mathrm{Re}\{FT(x) \cdot FT^*(y)\} \right] \tag{36}$$

where FT represents the Fourier transformation.

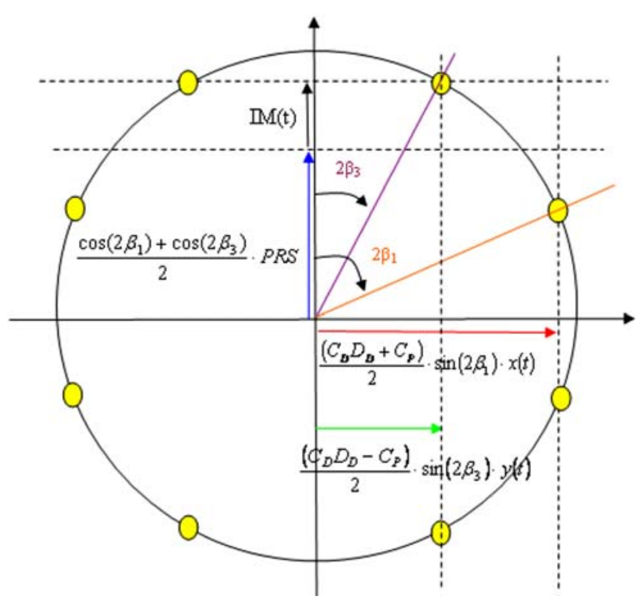

Fig. 8 CBOC(6,1) on data and pilot OS component modulation constellation

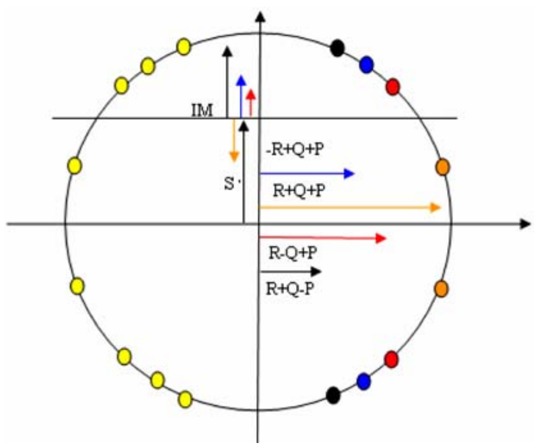

Fig. 9 CBOC(6,1) on pilot OS component and BOC(1,1) on data OS component modulation constellation

However, the cross-correlation term represents only a power of 0.2 dBW, consequently this spectrum could be considered similar to the Eq. 22 spectrum. Moreover, the cross-correlation term can be zeroed by alternating the relative polarity of the BOC(1,1) and BOC(6,1) signals. This means there is an alternation between "in phase" CBOC(6,1) (where the first part of the chip is of the same polarity) and "antiphase" CBOC(6,1) (where the first part of the chip is of opposite polarity).

As already mentioned, for the case 2 the modulation constellation is a 16-PSK modulation, so the number of constellation plots is higher than in the case 1. This means that each plot is closer to another one, and that this modulation is more likely to suffer from distortions created by the payload and receiver phase noise. For this reason, CBOC filtering should be minimized in the payload.

Finally, as Galileo and GPS are sharing the L1 band, the inter-system interference between the two systems should be analyzed. Wallner et al. (2005) has shown that the baseline L1 OS BOC(1,1) presents interference values on GPS C/A that are at their maximum still below the generally admitted degradation of 0.25 dB. Moreover, the candidate for the GALILEO L1 OS optimized signal (CBOC) would bring an additional improvement in this respect for the percentage of BOC(6,1) proposed. Indeed, the calculation of the Spectral Separation Coefficient between the GPS L1 C/A signal and the Galileo L1 OS signal shows (Table 1) that the CBOC signal presents an even better spectral isolation with GPS C/A code than the BOC(1,1) baseline.

The SSCs, presented in Table 1, are computed thanks to the following equation:

$$\mathrm{SSC}_{\mathrm{OS/CA}} = \int\limits_{\mathrm{BW}_R} S'_{\mathrm{OS}}(f) \cdot S'_{\mathrm{C/A}}(f)\,\mathrm{d}f \qquad (37)$$

The two power spectrum densities are considered normalized in their transmission bands (40.92 MHz for the OS signal and 30.69 MHz for the GPS C/A signal). The integration is made in a receiver bandwidth considered equal to 24 MHz. The calculation uses the continuous spectrum approximation which is not always valid for interference computations. But the C/A spectral isolation with CBOC(6,1)is always better than with BOC(1,1).

Conclusion

The signals on the L1 and E5 bands are different enough to require different modulation schemes in order to broadcast a coherent and synchronized composite signal with the constrained of maintaining a constant envelope. Different proposed modulations to transmit the Galileo civil signals have been presented:

- a constant envelope ALTBOC for the E5 band, and
- an Interplex for the L1 band (and like the E6 band).

On the E5 band it has been shown how the constant envelope ALTBOC modulation succeeds in multiplexing the two different services (OS and SoL) associated to the four transmitted signals into two Binary Offset Carrier (BOC)-like signals. Moreover, the flexibility of use for receiver manufacturers that can choose between different receiver designs has been presented.

The Interplex modulation used to transmit the L1 band signal have also been specified. The general formulation of the Interplex modulation and its application to a L1 signal with the baseline BOC(1,1)-modulated Open Service component have been explained. Different options, resulting from the potential optimization of the L1 OS have been discussed. The case of an OS signal using an MBOC modulation has been studied as a test case. It has also been shown that the Interplex modulation implies intermodulation (IM) terms in order to obtain a constant envelope, and thus wastes part of the transmitted power through this IM

Table 1 SSC of the BOC(1,1) baseline and the CBOC(6,1) signal with the GPS C/A code

Galileo OS signal	SSC with GPS C/A code (dB/Hz)
BOC(1,1) baseline	–67.78
CBOC(6,1)	–68.15

component. Finally, the modulation constellations and the intermodulation term powers obtained for the different configurations of the Open Service signal were compared. It has been shown that a CBOC(6,1) as data and pilot Open Service signal is the best solution to limit the waste of power in the intermodulation term. Moreover this configuration is the most suitable as regards to the modulation constellation plots because it is less likely to suffer from distortions created by the payload and receiver phase noise.

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