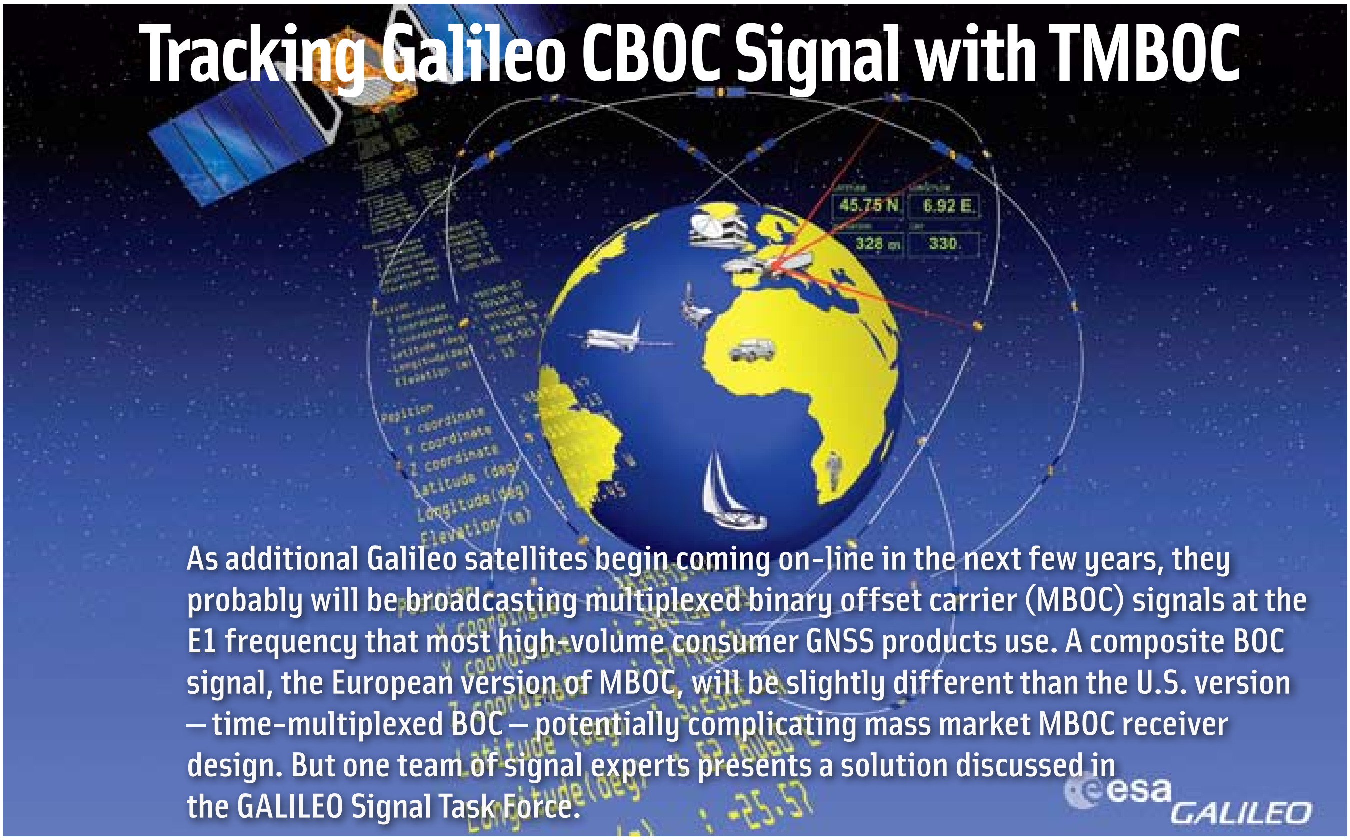
Two for One

Tracking Galileo CBOC Signal with TMBOC



As additional Galileo satellites begin coming on-line in the next few years, they probably will be broadcasting multiplexed binary offset carrier (MBOC) signals at the E1 frequency that most high-volume consumer GNSS products use. A composite BOC signal, the European version of MBOC, will be slightly different than the U.S. version – time-multiplexed BOC – potentially complicating mass market MBOC receiver design. But one team of signal experts presents a solution discussed in the GALILEO Signal Task Force.

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On-going discussions are taking place between U.S. and European Union (EU) experts concerning the future GPSIII L1C and Galileo E1 OS civil signals. An agreement on a common power spectral density (PSD) known as multiplexed binary offset carrier (MBOC) recently emerged as a solid candidate to replace the current baseline: BOC(1,1).

In order to comply with the MBOC PSD, two candidate implementations, known as time-multiplexed BOC (TMBOC) and composite BOC (CBOC) modulations, have been proposed. If fully exploited, these implementations will provide improved performance but require a more complex receiver architecture than a BOC(1,1) receiver.

Increased complexity and associated higher costs, however, might be detrimental for a GNSS receiver manufacturer that would like to use MBOC, but with limited modifications to their receivers — particularly for those companies producing equipment for mass consumer markets. This article aims at evaluating a new CBOC receiver architecture using locally generated TMBOC-like signals that will result in a simpler architecture comparable to a BOC receiver.

The normalized MBOC PSD includes the whole of GPSIII L1C or Galileo E1 OS civil signals, which means both their data and pilot components. Its expression is given by:

$$G_{MBOC}(f) = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f)$$

where $G_{BOC(1,1)}$ and $G_{BOC(6,1)}$ are the BOC(1,1) and BOC (6,1) normalized PSDs.

Because the MBOC is defined only in the frequency domain, a variety of compliant temporal modulations can be used. In the literature, two different modulations were proposed to implement the MBOC:

- TMBOC, which multiplexes in the time domain BOC(1,1) and BOC(6,1) sub-carriers and seems likely to become the main candidate used by the future GPSIII L1C signal, and
- CBOC, which linearly combines BOC(1,1) and BOC(6,1) sub-carriers (both components being present at all times), and appears to be the leading candidate for the Galileo E1 OS signal.

The Additional Resources section lists papers by G. Hein et al, J. Betz et al, and J.-A. Avila-Rodriguez et al, which introduce and discuss TMBOC and CBOC in detail.

The philosophy behind these two modulations is very different, and, although they would theoretically produce equivalent tracking when used with a TMBOC or CBOC receiver (considering pilot and data channels), they can result in different performances in other configurations (for instance, considering the pilot channel only).

A major difference between the TMBOC and CBOC modulations is that the CBOC sub-carrier, as the weighted sum of two squared-wave sub-carriers, will have four different levels. Consequently, this means that an optimal CBOC receiver has to generate a local replica that also has four levels, resulting in a local replica encoded on more than just one bit. This could complicate the CBOC receiver architecture and might prove detrimental to the widespread use of this modulation for certain types of receiver, if retained as the Galileo E1 OS modulation.

This article describes an innovative technique that only requires a 1-bit local replica, very similar to a TMBOC waveform, to track CBOC signals. This method is particularly interesting because, despite its simple implementation, it has only limited losses in tracking performance with respect to traditional CBOC or TMBOC receivers. Moreover, it shows excellent performance when compared to the previous GPS/Galileo L1 baseline signal, the BOC(1,1).

The first part of this article describes the possible CBOC and TMBOC candidates for Galileo E1 OS and GPS III L1C modulations. The second part looks at the traditional tracking performances of these two modulations in terms of thermal noise and multipath-induced errors.

Finally, we introduce the new 1-bit tracking technique and compare it against optimal CBOC and TMBOC tracking in terms of tracking noise and multipath resistance.

CBOC and TMBOC for Galileo and GPS

As seen in the expression of the MBOC PSD, the power of the BOC(6,1) component has to represent 1/11 of the total OS signal power. Among other parameters, then, the actual implementation of the MBOC will depend upon the power share between the pilot and data channels, as well as the percentage of BOC(6,1) sub-carrier used on each of these channels.

According to the paper by J.-A. Avila-Rodriguez et al, the main candidate implementations are:

- all the BOC(6,1) power is put on the pilot channel and the data channel uses a pure BOC(1,1) sub-carrier channel, or
- the BOC(6,1) power is split between the data and pilot channels.

The latest documents suggest that the first approach is the preferred implementation for the GPS III civil signal, while the second one is a serious candidate for Galileo E1 OS. Indeed, a 75/25 percent power share between pilot and data channels, respectively, has been proposed for GPSIII L1C. On the other hand, a 50/50 share has been recommended for Galileo E1 OS.

Moreover, discussions regarding GPS III appear to lean exclusively towards a TMBOC implementation of the MBOC, while Galileo leans mainly toward a CBOC implementation. In this article we will use these first assumptions to model the signals of interest. This leads to the following models:

- The GPS III L1C case (baseband) can be formulated as:

$$s_{GPS_{L1C}}(t)=\sqrt{\frac{1}{4}}c_D^{GPS}(t)d_{GPS}(t)x(t)+\sqrt{\frac{3}{4}}c_P^{GPS}\,TMBOC(6,1,\,p)(t)$$

where $TMBOC(6,1,\,p)(t)=\begin{cases} x(t) & if \quad t\in S_1 \\ y(t) & if \quad t\in S_2 \end{cases}$

with x and y are the BOC(1,1) and BOC(6,1) sub-carrier waveforms, S_1 is the union of the segments of time when a BOC(1,1) sub-carrier is used within one spreading code length, while S_2, the complement of S_1 within one spreading code length, is the union of the segments of time when a BOC(6,1) sub-carrier is used. Note that a relevant choice of the segments S_1 and S_2 has been shown to potentially reduce the auto and cross-correlation main peak isolation by 1 dB ([4]), $p = length(S_2) = 4/33$ for GPSIII L1C, c_D^{GPS} and c_P^{GPS} are the GPSIII L1C data and pilot channels spreading code sequences, d_{GPS} is the GPSIII L1C navigation message.

Examples of TMBOC sub-carrier are given in the papers listed in the Additional Resources section by G. Hein et al. and J. Betz et al.

The first Galileo E1 OS option (baseband) using CBOC modulation can be written as:

$$s_{Gal_{E1}}(t)=\sqrt{\frac{1}{2}}\left[d_{Gal}(t)c_D^{Gal}(t)CBOC(6,1,\,p,'+')(t)+c_P^{Gal}(t)CBOC(6,1,\,p,'-')(t)\right]$$

where $CBOC(6,1,1/11,'+')(t)=\left(\sqrt{(1-p)}\,x(t)+\sqrt{p}\,y(t)\right)$ and $CBOC(6,1,1/11,'-')(t)=\left(\sqrt{(1-p)}\,x(t)-\sqrt{p}\,y(t)\right)$

with c_D^{Gal} and c_P^{Gal} are the Galileo E1 OS data and pilot channels spreading code sequences, d_{Gal} is the Galileo E1 OS navigation message, and p=1/11 for Galileo E1 OS.

Note that the sign of the BOC(6,1) sub-carrier is different between the data and pilot channels. This is necessary to satisfy the MBOC constraint (removal of cross-terms appearing from the cross-correlation between the BOC(1,1) and BOC(6,1) sub-carriers.

- The second Galileo E1 OS option (baseband) using TMBOC modulation can be written as:

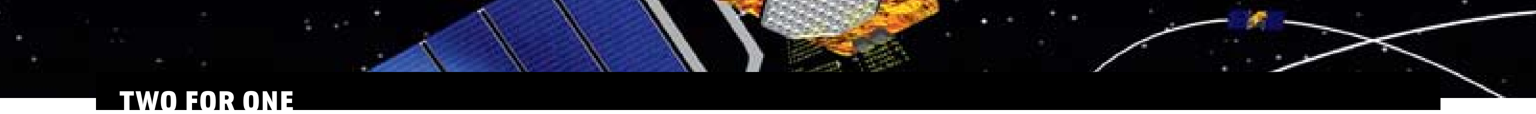
$$s_{Gal_{E1}}(t)=\sqrt{\frac{1}{2}}\left[d_{Gal}(t)TMBOC(6,1,\,p)+TMBOC(6,1,p)(t)\right]$$

where p=1/11 for Galileo E1 OS.

Finally, we presume that receiver manufacturers will probably try to minimize their tracking architecture complexity, and thus will track future signals using only their pilot channel.

L1/E1 Pilot: Achievable Performance

Traditional tracking of spread spectrum signals uses the correlation of the incoming signal with the same local replica as the useful incoming signal. Thus, most of the tracking performances depend upon the autocorrelation of the useful signal.



The autocorrelation functions of the previously defined modernized waveforms (the data channel is shown for completeness) presented in the previous section are given by:

$$R_{CBOC\,('-')}(\tau)=\left(\left(1-p\right)R_x(\tau)+pR_y(\tau)-2\sqrt{\left(p\left(1-p\right)\right)}R_{x/y}(\tau)\right)$$

$$R_{CBOC\,('+')}(\tau)=\left(\left(1-p\right)R_x(\tau)+pR_y(\tau)+2\sqrt{\left(p\left(1-p\right)\right)}R_{x/y}(\tau)\right)$$

$$R_{TMBOC}(\tau)=\left(\left(1-p\right)R_x(\tau)+pR_y(\tau)\right)$$

where R_x and R_y are the BOC(1,1) and BOC(6,1) autocorrelation functions respectively.

Figure 1 shows the normalized autocorrelation functions of each of the considered modernized signals:

- The percentage of BOC(6,1) power in the signal channel shapes the autocorrelation function. The higher the percentage of BOC(6,1), the narrower the autocorrelation function main peak will become.
- The sign of the BOC(6,1) component will also shape the correlation function on the CBOC: with a negative sign, the main peak of the autocorrelation function is narrower. We would then expect that CBOC('+') and CBOC('-') will have different tracking performances.
- The shape of the normalized autocorrelation function shows that the addition of a BOC(6,1) component most likely will not create extra false-lock points compared to BOC(1,1) tracking. Indeed, no real peak is visible. However, we need to recognize that the presence of the undulations on CBOC and TMBOC autocorrelation functions will shorten the admissible range of values for the early-late correlators compared to the BOC(1,1) case. (This goes with the necessary larger front-end bandwidth required and the expected better tracking performances.)

In terms of tracking performances, we will examine two main criteria here: (1) the code tracking noise induced by thermal noise, and (2) the multipath-induced code tracking error. Moreover, we will only investigate the dot-product (DP) discriminator as the reference discriminator here because it is a commonly used due to its low squaring losses (See studies by A.J Van Dierendonck and E. Kaplan, for instance, in Additional Resources). Its expression is given by:

$$D_{DP}=\left(I_E-I_L\right)I_P+\left(Q_E-Q_L\right)Q_P$$

where I_x and Q_x represent the in-phase and quadra-phase correlators' output where X=E for the early correlator, X=P for the prompt correlator, and X=L for the late correlator.

Thermal Noise-Induced Code Tracking Error

Assuming a DP discriminator, the theoretical thermal noise-induced tracking error variance is given by:

$$\sigma_{DP}^2=\frac{B_L\left(1-0.5B_LT_I\right)\left(\tilde{R}_{CBOC}(0)-\tilde{R}_{CBOC}(d)\right)}{\dfrac{P}{2N_0}\left(\left.\dfrac{d\tilde{\tilde{R}}_{CBOC}(x)}{dx}\right|_{x=\frac{d}{2}}\right)^2}\times\left(1+\frac{\tilde{R}_{CBOC}(0)}{\dfrac{PT_I}{N_0}\tilde{\tilde{R}}^2_{CBOC}(0)}\right)$$

where B_L is the DLL loop bandwidth, T_I is the coherent integration time, d is the early-late spacing, P is the incoming useful signal power (in a single channel), N_0 is the thermal noise PSD level, $\tilde{R}_{CBOC}$ is the filtered correlator output noise correlation function, and $\tilde{\tilde{R}}_{CBOC}$ is the filtered correlation function of the incoming signal.

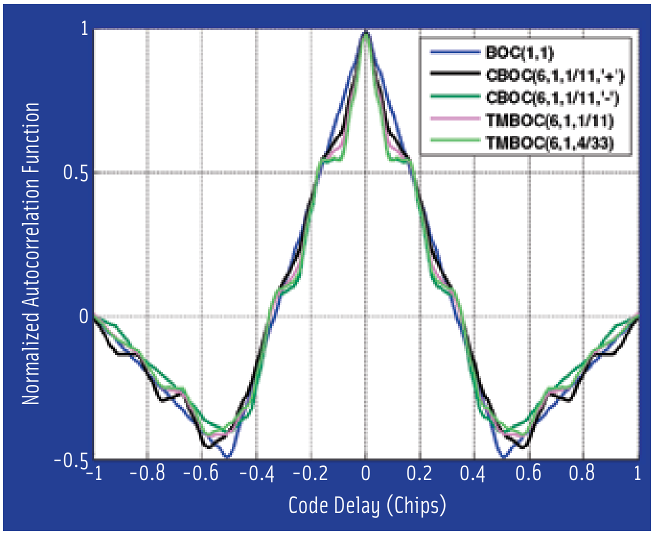


FIGURE 1 CBOC and TMBOC Autocorrelation Functions

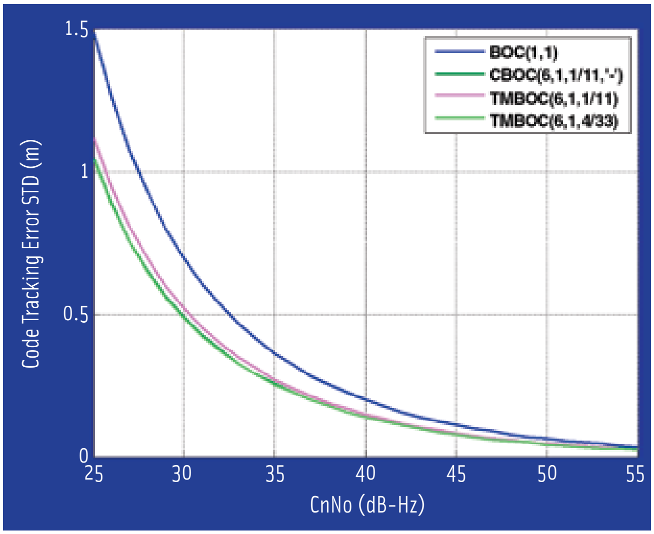


FIGURE 2 BOC(1,1), CBOC and TMBOC code tracking performance. Computations assume a DP discriminator, a 1 Hz loop bandwidth, a 1/12 chip early-late spacing, a 4 millisecond integration time, and a 12 MHz one-sided filter (Note: CBOC(6,1,1/11,'-') and TMBOC(6,1,4/33) are overlapping in graph.)

Figure 2 shows the theoretical code tracking noise using a DP discriminator for the different considered pilot signals assuming a 1 Hz DLL loop bandwidth, a 1/12 of a chip early-late spacing, a 4-ms integration time, and a 12 MHz front-end filter. The use of a pure BOC(1,1) as the incoming signal (with equivalent power) is also shown as a reference because it remains the current Galileo E1 baseline signal.

Figure 2 indicates that all currently considered, modernized pilot channels would significantly improve the resistance of the code tracking loop to thermal noise compared to

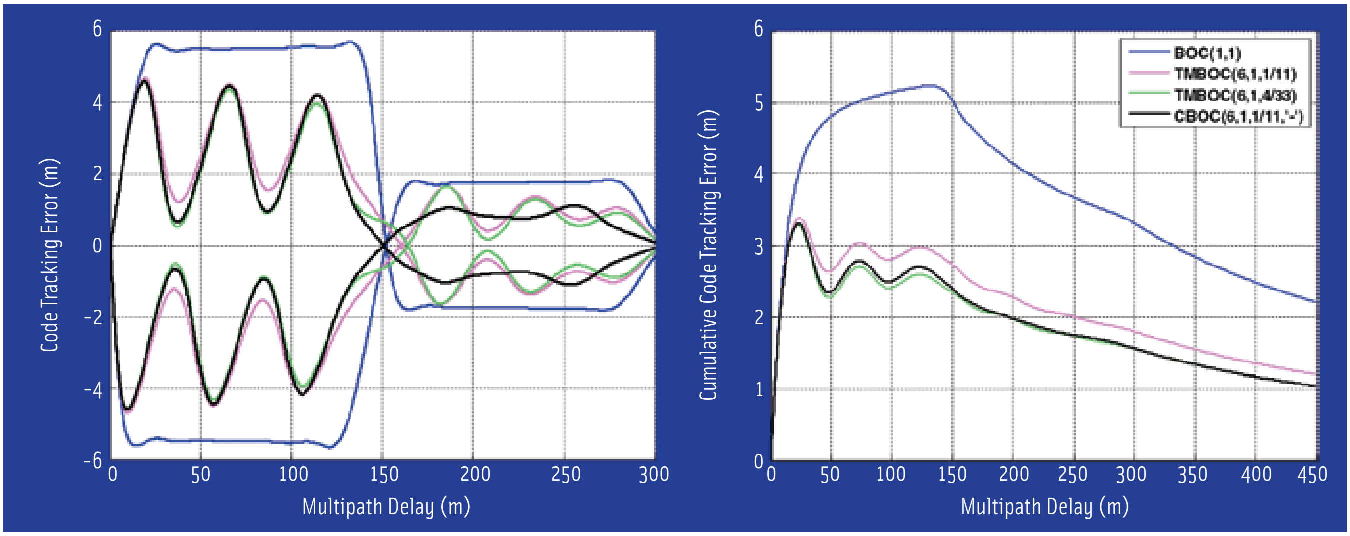


FIGURE 3 CBOC and TMBOC Multipath Running Average Error (Right) and Multipath Envelope (Left) Assuming a 1/12 Chip Early-Late Spacing, a SMAR of 3 dBs and a 12 MHz One-Sided Filter

BOC(1,1) tracking. The improvement is in line with the sharpness of the autocorrelation main peak seen in Figure 1.

This improvement in terms of equivalent carrier-to-noise (C/N_0) ranges from 2.4 dBs for TMBOC(6,1,1/11) tracking to 3 dBs for TMBOC(6,1,4/33) or CBOC(6,1,1/11,'-') tracking. This is very significant when one thinks that only a very small amount of BOC(6,1) has been added.

Multipath-Induced Tracking Error

Multipath-induced tracking errors are also dependent upon the autocorrelation function shape. So, comparing the performance of the different MBOC candidates against multipath offers an interesting approach.

In undertaking this comparison, a common figure of merit is the multipath running average error introduced in the 2006 ION/PLANS paper by G. Hein et al. This running average error is plotted in **Figure 3** beside the more traditional multipath envelopes for an early-late spacing of 1/12 chips, a one-sided front-end filter of 12 MHz, and a Signal-to-Multipath Amplitude Ratio (SMAR) of 3 dBs.

Once again, we can observe that the CBOC(6,1,1/11,' -') and TMBOC(6,1,1/11) have the best performances. This is mostly due to the narrow peaks constituting their autocorrelation function. It is important to see that all these CBOC and TMBOC multipath results are much better than for pure BOC(1,1) tracking.

Please note that the performance shown in Figure 3 is a measure of the inherent capability of the modulation to mitigate multipath using a standard receiver configuration. It does not represent an advanced multipath mitigation tool that could be compared to techniques used on C/A code such as double-delta, MMT (developed by L. R. Weil and others) or MEDLL (a proprietary technique patented by NovAtel Inc.).

In a more general way, the multipath rejection capability of CBOC or TMBOC signals is dependent upon their autocorrelation function shape, and thus upon the ratio *p* between the weights of the BOC(1,1) and BOC(6,1) autocorrelation functions. Although constrained by the MBOC PSD, and thus currently not changeable, a more optimal multipath mitigation capability (according to the multipath running average envelope figure of merit) could be obtained for higher values of *p*, as shown in the paper by O. Julien et al. presented at the ION NTM 2007.

Conclusions on Traditional CBOC and TMBOC Tracking

The foregoing CBOC and TMBOC performance analysis has outlined the potential improvement in terms of thermal noise and multipath mitigation of MBOC-compliant signals with respect to BOC(1,1) modulation.

In particular, we have shown that a receiver tracking the GPSIII L1C or Galileo E1 OS pilot candidates would significantly improve its inherent multipath rejection capability and gain between 2.4 and 3 dBs in terms of equivalent C/N_0 in thermal noise. This improvement comes, of course, at the expense of implementing a required wider front-end bandwidth, but we should note that a receiver with a narrower front-end filter can still track only the BOC(1,1) part of the MBOC without significant loss (below 0.6 dBs).

However, from a receiver architecture point-of-view, the reception and processing of CBOC and TMBOC is more challenging than BOC(1,1) reception. As already mentioned, ranging signal reception is traditionally done using a locally generated replica of the incoming signal. This means that a TMBOC receiver will have to implement time-multiplexing of BOC(1,1) and BOC(6,1) sub-carriers.

Because its sub-carrier is a linear combination of two synchronized square sub-carriers, a CBOC receiver has more than two levels. This means that the local replica has to be encoded on several bits, which implies a potential need for more complex receiver architectures. This could reduce some uses of this signal, which leads us to look at techniques that would only use local replicas encoded on 1-bit, while maintaining the attractive CBOC tracking performances.

An example of such a method involves the use of two separate correlations of the incoming CBOC signal with, on one side, a pure BOC(1,1) replica and, separately, a pure BOC(6,1) replica. Because the correlation operation is linear, a simple linear combination of these two correlation values would result in the exact same output as traditional CBOC autocorrelation and, thus, eventually the exact same tracking performances.

However, this processing requires twice as many correlators as traditional CBOC tracking and thus extra complexity. The following section, therefore, introduces a new CBOC tracking technique that intends to deal with that problem.

Tracking CBOC with TMBOC

The idea behind the proposed 1-bit CBOC processing is that both the BOC(1,1) and BOC(6,1) components should be present in the locally generated signal in order to use their properties:

- Most of the incoming power is in the BOC(1,1) component.
- The narrow BOC(6,1) autocorrelation function implies excellent tracking performances.

Then, one way to achieve this is to locally generate a signal close to a TMBOC modulation, with an alternating sequence of BOC(1,1) and BOC(6,1) sub-carriers modulating the PRN sequence. However, in order to avoid confusion between the proposed TMBOC modulation and this local replica (used here to track a CBOC signal), it will be referred to as TM61 replica. By extension, we also refer to the tracking technique as TM61.

The local replica can then be expressed as:

$$TM61(\alpha)(t)=c_P^{Gal}(t)\begin{cases} x(t) & if \quad t\in S_3 \\ \pm\, y(t) & if \quad t\in S_4 \end{cases}$$

where S_3 is the union of the segments of time when a BOC(1,1) sub-carrier is used, while S_4, the complement of S_3 in the time domain, is the union of the segments of time when a BOC(6,1) sub-carrier is used, and α represents the percentage of time when the BOC(6,1) sub-carrier is used.

The choice upon the sign of the BOC(6,1) sub-carrier in the TM61 local replica depends upon the associated sign of the BOC(6,1) sub-carrier in the incoming CBOC signal. If a CBOC('-') signal is received, the BOC(6,1) sub-carrier in the TM61 replica will have a negative sign.

The resulting correlation function between the TM61 and an incoming CBOC('-') — which is easy to extrapolate to a CBOC('+') — is then given by:

$$R_{CBOC('-')/TM61(\alpha)}(\tau)=\Big((1-\alpha)\sqrt{(1-p)}R_x(\tau)+\alpha\sqrt{p}R_y(\tau)-\big((1-\alpha)\sqrt{p}+\alpha\sqrt{(1-p)}\big)R_{x/y}(\tau)\Big)$$

We can see that this cross-correlation function is also a linear combination of the BOC(1,1) autocorrelation function, the BOC(6,1) autocorrelation function, and the BOC(1,1)/BOC(6,1) cross-correlation function. However, in this case the ratio between these three components is dependent upon the parameter α and is thus controlled by the receiver design.

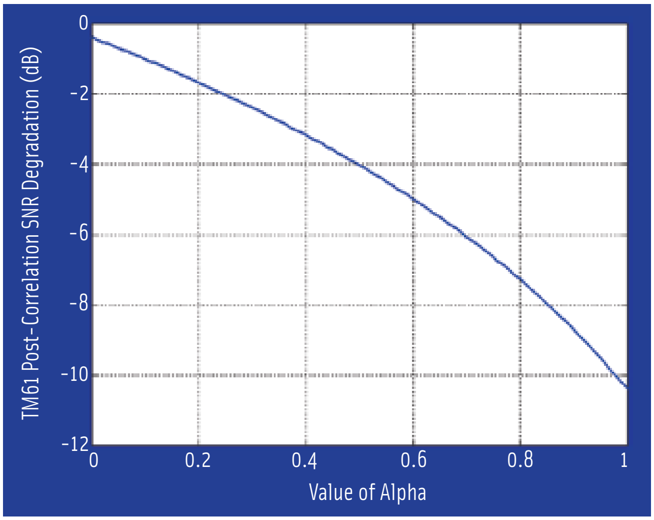


FIGURE 4 TM61-Induced Post-Correlation SNR Degradation for CBOC(6,1,1/11)

One-Sided Bandwidth (MHz)	Post-Correlation SNR Degradation (dB)
8	-0.35
9	-0.35
10	-0.35
11	-0.35
12	-0.35

TABLE 1. Post-correlation SNR degradation for a CBOC(6,1,1/11,'-') as a function of the front-end filter bandwidth

Effects on Signal-to-Noise Ratio

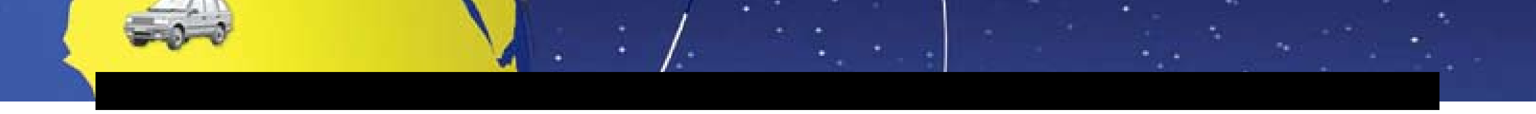
Because a local replica different from the incoming signal is used, we need to quantify the associated post-correlation losses. In the presence of thermal noise only, the noise power at the correlator output is the same using a CBOC local replica, a TMBOC local replica, or a TM61 local replica. Thus, the post-correlation signal-to-noise ratio (SNR) can be quantified, assuming infinite front-end filter, as:

$$\deg_{Post-Cort\_SNR}=\left(\frac{R_{CBOC/TM61(\alpha)}(0)}{R_{CBOC}(0)}\right)^2=$$
$$=\left(\sqrt{(1-p)}+\alpha\left(\sqrt{p}-\sqrt{(1-p)}\right)\right)^2$$

This post-correlation SNR degradation due to the use of a TM61 local replica is represented in **Figure 4** for the CBOC(6,1,1/11). Choosing a small value for α allows a minimization of the correlation losses, as expected. A low post-correlation SNR degradation at the correlator outputs has important consequences on the receiver performance at several stages:

- phase tracking performances that uses the in-phase and quadra-phase prompt correlator outputs,
- code tracking,
- data demodulation if used on the data channel.

However, choosing a small value for α also means that the TM61/CBOC correlation function will be close to a BOC(1,1)



autocorrelation function, and the tracking performance will thus be significantly degraded compared to traditional CBOC tracking. Because phase tracking and data demodulation are done using the prompt correlator outputs only, it might be interesting to use different TM61 local replicas for the prompt correlator and the early and late correlators to have a more flexible tracking architecture. Thus, a new DP discriminator is defined using:

$$D_{DP}^{TM61}=\left(I_{E}^{TM61(\alpha)}-I_{L}^{TM61(\alpha)}\right)I_{P}^{TM61(\alpha')}+\left(Q_{E}^{TM61(\alpha)}-Q_{L}^{TM61(\alpha)}\right)Q_{P}^{TM61(\alpha')}$$

where *α* corresponds to the TM61 local replica used for the early and late correlators, and *α´* corresponds to the TM61 local replica used for the prompt correlator.

Using that discriminator, and assuming that all the correlation functions are symmetric, the theoretical tracking noise standard deviation can be written equal to:

$$\sigma_{DP,TM61(\alpha)}^{2}=\frac{B_L\left(1-0.5B_LT_I\right)\left(\tilde{R}_{TM61_{E,L}(\alpha)}(0)-\tilde{R}_{TM61_{E,L}(\alpha)}(d)\right)}{\frac{P}{2N_0}\left(\left.\frac{d\tilde{\tilde{R}}_{CBOC\,/TM61_{E,L}(\alpha)}(x)}{dx}\right|_{x=\frac{d}{2}}\right)^{2}}\times\left(1+\frac{\tilde{R}_{TM61_P(\alpha')}(0)}{\frac{PT_I}{N_0}\tilde{\tilde{R}}_{CBOC\,/TM61_P(\alpha')}^{2}(0)}\right)$$

Here we see that the separation of the early and late TM61 replicas from the prompt TM61 local replicas leads to these very interesting conclusions:

- the squaring losses only depend upon the prompt TM61 local replica
- the asymptotical variance (when squaring losses are not present) depends upon the early and late TM61 local replicas only.

Thus, in order to minimize the squaring losses, it is important to have minimal correlation losses for the prompt correlator. Consequently, from now on, the local TM61 replica used for the prompt correlator will use α´=0, which means that it is a pure BOC(1,1) local replica. This implies that the correlation losses are minimal (about 0.35 dBs for CBOC(6,1,1/11) as shown in **Table 1**) which makes it very suitable for data demodulation and phase tracking purposes.

On the other hand, the asymptotical tracking variance depends upon the TM61(*α*) autocorrelation values (obtained from the early and late TM61 replicas) in 0 and *d*, and the TM61(*α*)/CBOC cross-correlation slope in *d*/2. Thus, a more thorough analysis has to be undertaken.

Table 2 shows the TM61(α) tracking noise standard deviation degradation of CBOC(6,1,1/11,'-') for the different possible values of α compared to the optimal tracking noise standard deviation of the candidate CBOC and TMBOC signals on the pilot channel. Please note that the prompt local replica is assumed to be a pure BOC(1,1) and consequently the values of α only affect the TM61(α) early and late local replicas.

Several conclusions can be drawn from these results:

- For a CBOC(6,1,1/11,'-'), the optimal value for α (for the early and late TM61 local replicas) seems to be either 0 or 1. Interestingly, these extreme cases mean that only a pure BOC(1,1) or a pure BOC(6,1) could be generated locally for the early and late correlators, which would significantly reduce receiver architecture complexity, because in this case neither multi-bit nor time-multiplexed sub-carriers are necessary.
- The use of the TM61 tracking technique for CBOC(6,1,1/11,'-') exhibits a degradation of approximately 2.5dBs with respect to traditional CBOC(6,1,1/11,'-') tracking. This is the drawback inherent to the simplification of the receiver architecture. However, when compared to the TMBOC(6,1,1/11) case, which is the other option of Galileo E1 OS pilot signal, this degradation drops to 1.9 dBs.
- The TM61 outperforms traditional BOC(1,1) tracking. This is an excellent result since it means that with a simple receiver architecture, we can obtain better performance than would have been obtained with the current Galileo baseline.

TM61 and Code Noise Tracking

The last criterion studied to assess the TM61 tracking technique is its inherent resistance to multipath. As in the optimal tracking case, we will investigate this criterion in terms of the average multipath envelope error.

Figure 5 shows the multipath resistance of the TM61 technique for different values of α used for the early and late local replicas (once again, the prompt replica uses a pure BOC(1,1) sub-carrier) assuming an incoming CBOC(6,1,1/11,'-') signal. Among these, the case when α equals 0 has, by far, the worst performance. This is as expected because in this case the TM61/CBOC correlation function is close to a pure BOC(1,1) one.

The case α=0.5 seems to be optimal, although when α=1 the performance is comparable. This result is intriguing and corroborates what was foreseen with tradi-

Value of α for Early and Late TM61(α) Local Replicas	TM61(α) Tracking Error Degradation of CBOC(6,1,1/11,'-') in Terms of Equivalent C/N0 (dB)		
	vs TMBOC(6,1,1/11)	vs TMBOC(6,1,4/33) or CBOC(6,1,1/11,'-')	vs BOC(1,1)
0	2	2.6	-0.4
0.2	2.9	3.5	0.5
0.4	2.8	3.4	0.4
0.6	2.6	3.2	0.2
0.8	2.3	2.9	-0.1
1	1.9	2.5	-0.6

TABLE 2. TM61(α) Tracking error degradation vs TMBOC in terms of equivalent C/N_0 for an early-late spacing of 1/12 chips, a 12 MHz double-sided front-end filter, and a 4-ms integration

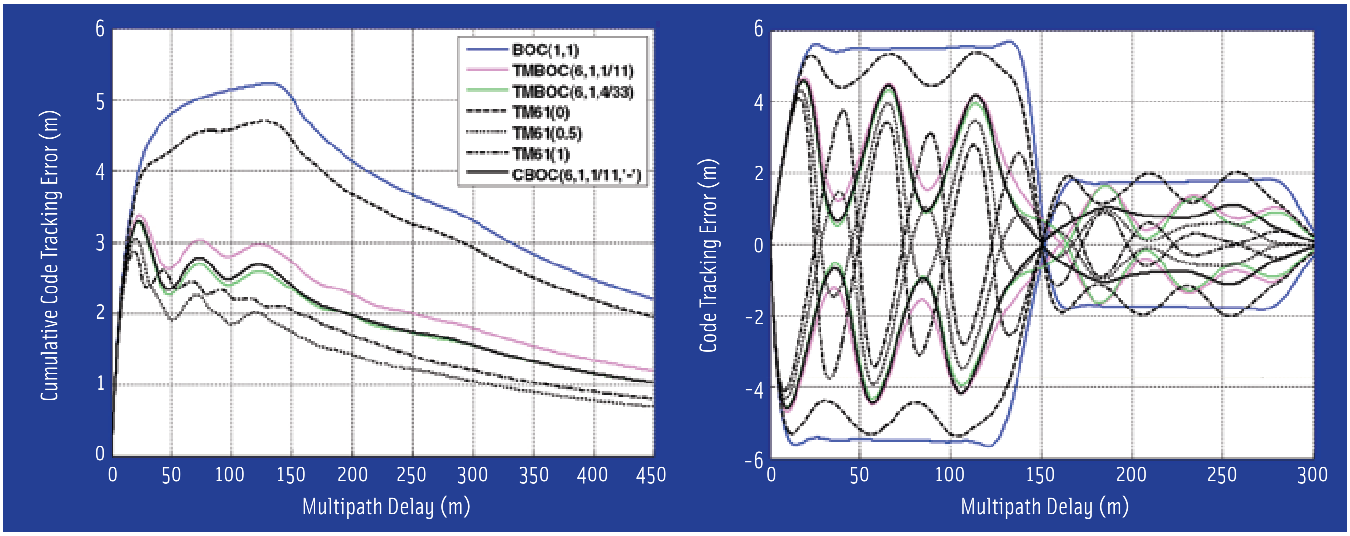


FIGURE 5 **Running Average Multipath Error using TM61 Tracking Technique for a CBOC(6,1,1/11,'-') (Left) and Envelope (Right) for an Early-Late Spacing of 1/12 Chips and a 12 MHz Double-Sided Front-End Filter**

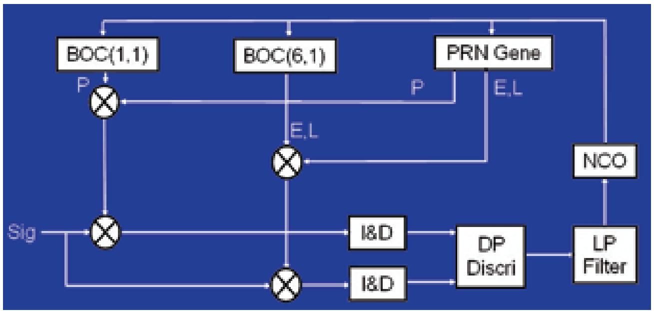


FIGURE 6 **TM61 Tracking Architecture to Track a CBOC Signal**

tional CBOC tracking: an optimum (in terms of running average multipath error) can be reached for a certain ratio between the weights attached to the BOC(1,1) and BOC(6,1) autocorrelation functions. Since, unlike in the traditional CBOC tracking case, the TM61 allows setting this ratio to any value (through the parameter α), this optimum can be reached using the new proposed method.

The TM61 multipath resistance improvement is particularly important when a CBOC(6,1,1/11) signal is used. It is also interesting to see that TM61(1) tracking provides an improvement for very short multipath over all other configurations.

Conclusions about TM61

From the previous analysis, it appears that a preferred implementation for the TM61 tracking method is to locally generate a pure BOC(1,1) replica for the prompt correlator, and a pure BOC(6,1) replica for the early and late correlators. This would result in a very simple tracking architecture, as represented in **Figure 6**.

A 2.5 dBs degradation in terms of equivalent C/N_0 is observed for the code tracking noise, but we might expect that for many applications tracking noise is not the main source of error. On the other hand, the preferred TM61 configuration implies an increased multipath rejection capability with respect to all traditional tracking of CBOC and TMBOC. This is important because multipath is always present and a main source of errors.

Finally, the TM61 tracking technique of a CBOC signal significantly outperforms the use of a BOC(1,1) signal, the current Galileo/GPS baseline, with the same receiver complexity

The use of the preferred implementation of the TM61 tracking technique implies that the actual TM61/CBOC correlation function generated by the early and late correlators will look like a BOC(6,1) autocorrelation function. Thus, special care has to be taken with the appearance of false tracking locks.

We also must point out that the TM61 tracking technique is important in case the CBOC modulation will be chosen for Galileo. Indeed, it has been seen that the traditional performance of the CBOC(6,1,p,'-') was slightly better than TMBOC(6,1,p) for traditional tracking performance (although, as already mentioned, TMBOC might offer better cross-correlation properties).

Now, in case a receiver manufacturer would like to limit the complexity of their receiver design to track the Galileo E1 OS, the TM61 offers the simplest implementation with almost no degradation on phase tracking and excellent multipath mitigation capabilities.

Because of the simplicity of the TM61 tracking technique architecture, it would be interesting to try to expand its use to TMBOC reception. However, a direct implementation would not be successful since the correlation of a pure BOC(1,1) or BOC(6,1) replica with a TMBOC signal is not optimal. This has already been explained in [3] and [4].

Indeed, the orthogonal property of the BOC(1,1) and BOC(6,1) waveforms leads to only a partial correlation process that further degrades the post-SNR correlation. In particular, the BOC(6,1)/TMBOC(6,1,4/33) leads to a degradation of 18 dBs.

One way to solve this issue is, during the correlation process, to blank the part of the TMBOC signal that does not use a BOC(6,1) sub-carrier (when correlated with a BOC(6,1)). The post-correlation SNR degradation is then strongly reduced.

However, including a blanking process in the TMBOC tracking makes the receiver architecture more complex. Moreover, in this case, the correlation result is only a partial correlation that might significantly degrade the spreading code properties.

Conclusions

Following the US/EU MBOC agreement, the current main candidates for the GPSIII L1C and Galileo E1 OS have been introduced. In particular, the pilot channels have been analyzed with their use of the new CBOC and TMBOC modulations.

Although adding a very small amount of BOC(6,1) to the previous BOC(1,1) baseline, it has been shown that the tracking performances of these future signals are significantly improved compared to pure BOC(1,1) tracking. In particular, tracking noise is reduced by 2.4 to 3 dBs in terms of equivalent C/N0, and multipath mitigation is significantly improved.

Focusing on the CBOC modulation, its multi-level waveform could result in more challenging receiver architecture. In order to keep a simple receiver design to receive a CBOC signal, a new tracking technique, referred to as TM61, has been proposed to allow tracking of the CBOC modulation with a 1-bit only locally generated replica. This method uses time-multiplexing of BOC(1,1) and BOC(6,1) sub-carrier on the same model as the TMBOC modulation.

A preferred implementation of TM61 is the use of a pure BOC(1,1) sub-carrier for the prompt correlators and a pure BOC(6,1) sub-carrier for the early and late correlators (a DP discriminator being assumed). This yields a much simpler receiver architecture since it requires only pure sub-carriers with no-multiplexing (different from TMBOC receivers), 1-bit local replicas (unlike a CBOC local replica) and a minimum of correlators. Please note it is also possible to use another implementation of the TM61 tracking methods with time-multiplexing.

In its preferred implementation, TM61 brings only a slight post-correlation SNR degradation (about 0.35 dBs for the selected CBOC main candidate for Galileo pilot channel), enabling good phase tracking. TM61 code tracking noise performance is degraded with respect to traditional CBOC tracking by approximately 2.4 dBs. However, this has to be put into perspective considering the substantial reduction in receiver complexity with TM61 and the fact that thermal noise might not be the main source of error for many applications.

Finally, the TM61 tracking technique has been demonstrated to provide, in its preferred implementation, a better multipath resistance compared to traditional CBOC tracking. In any case, the use of TM61 to receive a CBOC signal has been shown to significantly outperform the traditional reception of a pure BOC(1,1) with equivalent power, thus supporting the use of the modernized CBOC signal. Consequently, it seems to be a very good tracking technique for implementation in future CBOC receivers.

Additional Resources

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