Analysis and Performance of Tracking Schemes for the Galileo MBOC signal

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BIOGRAPHY

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INTRODUCTION

MBOC (Multiplex Binary Offset Carrier) modulation has been selected for future Galileo E1 OS and GPS L1C signals. The power spectral density function of the new MBOC modulation is formed as the sum of the 10/11 normalized BOC(1,1) and 1/11 normalized BOC(6,1) signal spectrum, given as:

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

MBOC is defined in the frequency domain, and two different implementations have been defined for Galileo and GPS, known as ***CBOC*** and ***TMBOC,*** respectively. Indeed, the GPS L1C signal will have a pure BOC(1,1) data channel carrying 25% of the total signal power, while the pilot signal will use a TMBOC modulation with 75% of the total signal power. TMBOC consists of time-multiplexed subcarriers, such that 29/33 chips of the spreading code are modulated by a BOC(1,1) subcarrier, and remaining 4/33 modulated by BOC(6,1) subcarrier. On the other hand, Galileo E1 will share its power equally between data and pilot channels, and both channels will use a CBOC modulation with the BOC(6,1) subcarrier. The CBOC signal is based on the four-level sub-carrier formed by the weighed sum of BOC(1,1) and BOC(6,1) on both data and pilot channels. The BOC(6,1) component is added to BOC(1,1) in phase (‘+’) for the data channel, and in antiphase (‘-’) for the pilot channel [1].

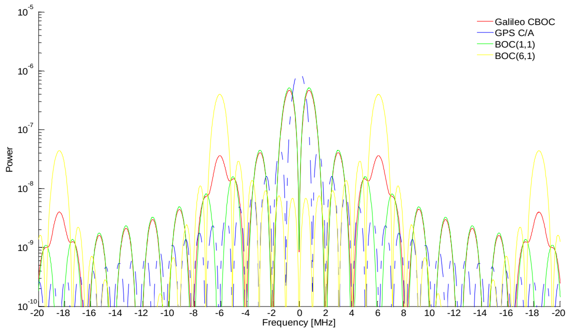

Figure 1 – Power spectral density comparison for new MBOC signals, BOC(1,1) and BPSK(1)

The power spectral density of the MBOC signal is shown on the Figure 1. We can notice the presence of the BOC(6,1) high power component on higher frequencies. This improves the tracking properties bandwidth, minimum 14 MHz, as can be seen from Figure 1.

The main purpose of tracking is to refine the values for the estimated frequency and code phase $[(\Delta f_i, \Delta \phi_i)]$ obtained during the acquisition process, track them, and demodulate navigation messages. Traditional tracking assumes the local replication of the incoming satellite signal expected to arrive in the receiver, for computing the autocorrelation function necessary to perform the tracking, [4]. The autocorrelation function of the MBOC signal has a narrower correlation peak as compared to BOC(1,1), as we can observe from Figure 2, where the different MBOC modulation options are presented and compared to BOC(1,1) for a front-end bandwidth of 25 MHz. We note that some shapes of the autocorrelation functions provide better tracking properties, but also the possibility of making false lock points.

Tracking of the CBOC and TMBOC signal can be best described using different metrics and characteristics of the signal that can provide relevant information about the tracking and quantify it somehow. In this paper, we will analyze different MBOC tracking algorithms recently proposed, and compare them with respect to the amplitude of the autocorrelation's main peak, multipath error envelopes, code tracking errors and receiver architectures.

TRACKING PERFORMANCE METRICS

Performance of tracking loops is measured by comparing the code and phase delays tracked by the receiver and the actual code and phase delays at the entrance of the tracking loops. **DLL** (Delay Lock Loop) is the code tracking loop giving the estimation of the code tracking error, while PLL (Phase Lock Loop) is the carrier tracking loop, providing estimation of the frequency offset,[4].

Three main characteristics are important regarding tracking performance: ***Biased tracking*** influenced by the existence of false lock points; ***code tracking error*** induced by the thermal noise, and ***multipath*** that influences code tracking error. User performance expectations with respect to tracking can be divided into three main points (see,e.g., [7]):

Tracking sensitivity **–** can be defined as the minimum pre-correlation SNR that insures correct signal tracking, as given in [7]. Increasing the post-correlation SNR as much as possible can improve tracking sensitivity. Increasing the coherent integration time will increase the sensitivity, but attention should be driven to the bit transitions if a data channel is used for tracking. AGPS in the form of the signal, but requires a larger front-end of an additional ground link can also help and increase sensitivity.

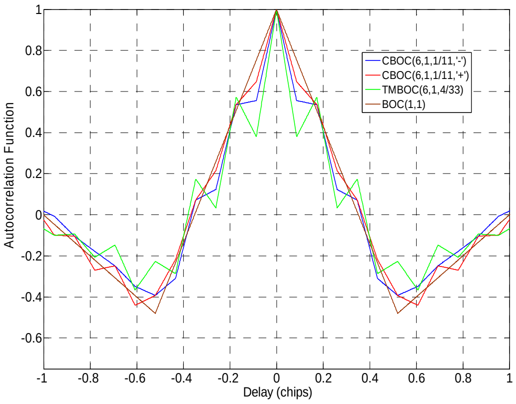

Figure 2– Autocorrelation functions for three different MBOC options: CBOC in phase and anti-phase and TMBOC compared to BOC(1,1) for 25 MHz of bandwidth

Tracking robustness **–** can be defined as the ability of the tracking loop to maintain the lock on the main autocorrelation peak [7]. The main parameter is the loop stability region (pull-in region). When the SNR drops below the tracking threshold, the receiver loses lock. The main sources of unreliability in tracking loops are multipath and tracking of cross-correlation peaks. In the case of MBOC signals, the probability of false peak tracking is higher since the autocorrelation function contains false peaks on both sides of the main one.

Tracking accuracy – it is the accuracy of the measurements from the tracking loop, considering the different error sources, such as thermal noise, multipath and interference. Multipath is the main source of error in tracking, and advanced algorithms should be developed in order to mitigate it. The discriminator choice is very important, since it provides the first estimate of the code tracking error. Two widely used types of discriminators are: early-minus-late (EML) and dot-product (DP). The DP discriminator requires three correlators, as compared to only two in the EML structure. The choice of the correlator spacing (i.e., the time offset between code replicas) – front end bandwidth can bring a minimal tracking error for EML and DP discriminators and provide unbiased code delay estimation, as discussed in [4].

MBOC TRACKING ALGORITHMS

There are only a few tracking algorithms that have been specifically proposed for tracking the MBOC signals, and some of them are based on old tracking schemes (BPSK and BOC(1,1)), [2,7,9,12]. BOC(1,1) tracking is mainly limited by the biased the autocorrelation side-peaks. The tracking of tracking, and there are techniques for elimination of the side-peaks of autocorrelation function. CBOC has different design requirements for the GNSS receiver as compared to TMBOC, since in the CBOC case the local replica is a weighed sum of two squared-wave sub-carriers, and has four different levels, more than one bit being required for the encoding, as discussed in [2]. Below an overview of the MBOC tracking techniques proposed up to now is presented, including other techniques that could also possibly be used for that purpose. Also, we mainly discuss receiver architectures that use pilot channels for tracking only but also architectures that use pilot and data channels in collaborative tracking.

TRADITIONAL TRACKING

Traditional tracking exploits the autocorrelation function between the local code replica and the incoming signal. A traditional tracking architecture for CBOC is shown on Figure 3. It assumes replication of the same CBOC replica and usage of **E** (**early**), **P** (**prompt**), and **L** (**late**) correlation in order to lock on the right correlation peak (correlation peak with the most signal power).

It was shown that the tracking of CBOC and TMBOC improves multipath rejection capability, and gain between 2.4 and 3 dB in terms of C/No as compared to traditional BOC(1,1) tracking, at the expense of implementing wider front-end bandwidth [2]. Demodulation of MBOC using just BOC(1,1) replica is not a good solution for MBOC tracking, since multipath error envelopes are higher than in the case of the pure BOC(1,1) tracking. Therefore, a pure BOC(1,1) receiver cannot benefit from the new modulation schemes, as explained in [12].

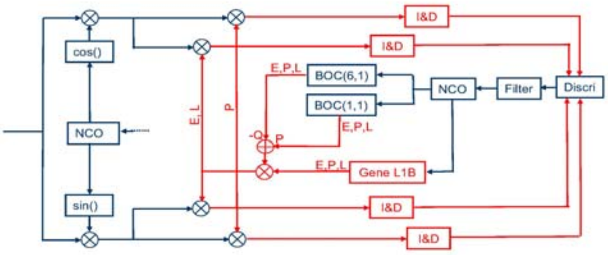

Figure 3 – Traditional CBOC tracking architecture, [11]

TM61

TM61 tracking technique was proposed for the CBOC and TMBOC tracking in [2,12]. TM61 tracking differs from the traditional CBOC tracking as early and late replicas correlate with the incoming signal in BOC(6,1) mode, and the prompt replica correlates in BOC(1,1) mode. Thus, most of the energy stays at the prompt replica, and there is no loss due to high BOC(6,1)/MBOC correlation losses [2]. BOC(6,1) on the early and late correlator improves synchronization using steep BOC(6,1) autocorrelation slope. The TM61 tracking architecture is shown on Figure 4.

This technique brings a degradation of 2.5 dB in code tracking noise as compared to the traditional CBOC tracking, but it is still 0.6 dB better than traditional BOC(1,1) tracking, as shown in [2].

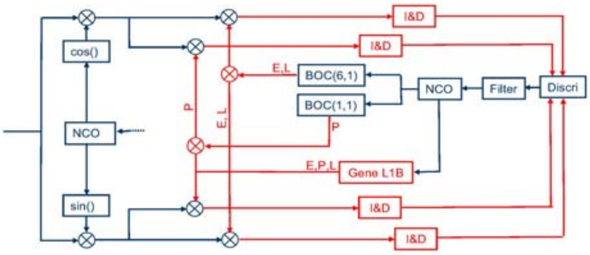

Figure 4 – TM61 tracking architecture [11]

MODIFIED TM61

Variation of this tracking technique, that we simply named as modified TM61, is based on the tracking architecture assuming replication of BOC(1,1) and BOC(6,1) subcarrier, in an alternating way such that the percentage of time when one of them is used varies. Depending on the power ratio of each component in the CBOC signal, which is controllable by α, where α is the time ratio of the BOC(6,1) component in the replica, we obtain different shapes of the autocorrelation function and values for the tracking error, as stated in [2].

The discriminator based on the principle of using different replicas for early, late and prompt can be defined with the following discriminator function:

$$D_{dp} = (I_E^{\alpha} - I_L^{\alpha}) I_P^{\alpha'} + (Q_E^{\alpha} - Q_L^{\alpha}) Q_P^{\alpha'} \quad \textbf{(2)}$$

where α corresponds to the local replica used for early and late correlators, and $\alpha' = 1 - \alpha$ for the prompt correlator. In the special case of $\alpha = 0$ for the prompt, and $\alpha = 1$ for the early and late correlator (TM61) the squaring losses are only dependent upon the prompt replica and the asymptotical variance depends upon the early and late replicas only.

It was shown in [2] that for the correlation losses to be minimal, the optimal solution is to use a plain BOC(1,1) for the prompt correlator replica, and a plain BOC(6,1) for the early and late replicas, which corresponds to the TM61 tracking solution.

DUAL CORRELATOR

In order to compare the tracking performance of MBOC modulation, the dual correlation technique described in [12] is also analyzed, based on the investigation of two parallel correlations: one between the incoming MBOC and a BOC(1,1) replica and one between the incoming MBOC and a BOC(6,1) replica. Each correlation is weighed adding linearly two outputs, such that changing the values of the weights dedicated to two correlations, ρ and β, respectively, CBOC(6,1,1/11) will be tracked using local replica CBOC(6,1, $\beta^2/(\beta^2+\rho^2)$).

This means we cam investigate ***different tracking strategies depending*** on weather we want to put more or less attention to the BOC(6,1) component, which is controllable by the ratio ρ / β. Optimal value for this ratio is shown to be in the range [1.6, 3.2], as shown in [2], as a good compromise between the multipath error envelopes and code tracking error caused by the noise.

This scheme allows some flexibility to obtain different tracking strategies that can be adjusted ‘on the fly’, according to the user requirements and the application.

ASPeCT

This tracking technique proposed for BOC(1,1) tracking [7] can also be used for MBOC tracking. It assumes separate tracking of the side-peaks of the autocorrelation function. As previously shown on Figure 1, MBOC has two side-peaks that can be independently tracked. Elimination of side-peaks in the autocorrelation function is the core of ASPeCT’s algorithm. It combines two correlations, one with traditional replica (same as the expected incoming signal) and the other one with plain PRN code, and the incoming satellite signal. The linear combination of weighed correlations can eliminate side-peaks of the autocorrelation function, as shown in [7].

COMPOSITE TRACKING

Composite tracking assumes collaborative loop tracking between data and pilot channels [6]. The tracking algorithms are based on a modification of the correlation function, in order to include both data and pilot channels. Traditional discriminators are modified in order to combine different strategies. The pilot channel is used for the bit synchronization, and the data channel for improving the system performance. The novelty of this approach consists in combining non-coherent and coherent tracking with different discriminators, and collaborative code tracking versus single channel code tracking.

S-CURVE SHAPING

The S-curve shaping method is based on finding the optimum correlator configuration capable to form the ideal discriminator curve by using a large number of correlators, each with specific weight and correlator spacing, and fitting these parameters with respect to the ideal S-curve [8]. This method can be used for MBOC tracking, since it provides good performance and low multipath error. It uses a large number of correlators.

SIDE-PEAK MITIGATION

Methods used for BOC(1,1) side peak mitigation, like the bump and jump technique, that increases the number of correlators by two additional ones, can also be used for MBOC tracking, [7]. The additional correlators serve in performing tests to verify if the receiver is well locked on a strongest correlation peak. If not, the tracking module ‘jumps’ and locks on the peak with the highest power.

COMPARISON OF ALGORITHMS

Due to high complexity of traditional tracking MBOC schemes, new tracking schemes must be developed in order to optimize the receiver’s architecture. Simplifications proposed in the light of TM61 and Dual Correlator technique [2] degrade the navigation accuracy by up to 3 dB in terms of code tracking noise. If a higher accuracy is expected, new tracking schemes or modifications of existing techniques must be considered.

Current state-of-the-art solutions provide separate schemes for CBOC and TMBOC architectures. Each of them has its advantages and disadvantages, presented in Table 1Table 2. One disadvantage of the TM61 correlation technique is that the autocorrelation function is similar to the one of BOC(6,1), so special care should be taken for the mitigation of false tracking locks. The first false lock point for the CBOC, as can be observed from the Figure 2 would be at 0.6 chip period, causing pseudorange error of approximately 180m, making this easily detectable. Still, a false lock detector is needed in order to make sure that the receiver is tracking the signal based on the autocorrelation main peak [10].

While BOC(1,1) receivers are MBOC compatible, as they provide only a slight performance degradation in terms of the amplitude of the autocorrelation peak and code tracking noise, it is clear from Figure 1 that narrowband receivers (with a bandwidth << 12 MHz) do not have access to MBOC features. Correlation degradations of the autocorrelation function peaks for each modulation investigated and a 25 MHz bandwidth are shown in Table 1.

We can observe that the mixed configuration performance for TMBOC signal tracked by BOC(1,1) receiver presents the worst performance in comparison to advanced CBOC and TMBOC receivers trascking, providing superior performance, as shown in [4]. The CBOC signal demodulated with a BOC(1,1) receiver shows lower correlation losses of amplitude peak.

Receiver\Signal	CBOC (6,1,1/11)	TMBOC (6,1,4/33)
BOC(1,1)	0.05	0.15
BOC(6,1)	0.7	0.86
CBOC(6,1,1/11)	0	0.2
TMBOC(6,1,4/33)	0.22	0

Table 1 – Normalized correlation degradation of the autocorrelation function for different receiver types – BOC(1,1) and MBOC

Consequently, TM61 is a good candidate for CBOC tracking, but not for TMBOC tracking. TMBOC tracking produces high correlation losses when using TM61 or Dual Correlator scheme, [2]. This happens due to high BOC(6,1)/TBOC(6,1,4/33) correlation losses. Figure 5 shows different autocorrelation functions for CBOC and TMBOC for TM61 tracking. As we can observe from Figure 5, although there is no negligible correlation degradation when using TM61 tracking, this degradation is small for CBOC (~ 0.05 normalized), and the best results are achieved with CBOC signal in antiphase (CBOC(6,1,1/11,’-’)). Early and late replicas are in the BOC(6,1) mode correlating with MBOC signal, producing high correlation degradation (normalized amplitude of the correlation peak being almost 0.4). TMBOC tracking with TM61 has worse performance in terms of correlation losses. This problem can be solved by using time-multiplexed local replicas, composed of BOC(1,1), with zeros where BOC(6,1) is used, and BOC(6,1), with zeros at the BOC(1,1) places, respectively. This method greatly reduces correlation losses, as shown in [2] and puts TMBOC tracking at almost equal level with CBOC tracking with respect to code tracking error.

If we consider the modified TM61 technique, using local replica composed of different percentage of BOC(1,1) and BOC(6,1) for each correlator, we can notice that as the ratio of BOC(6,1) component is increased in the local replica, correlation losses increase, as illustrated in Figure 6. This figure shows the autocorrelation peak when the percentage of BOC(6,1) in the local replica increases from 0.1 to 1 in steps of 0.1. As discussed above, while TM61 provides the best solution with respect to code tracking noise (in terms of equivalent C/No), it was also shown in [2] that in terms of multipath performance the optimal ratio is 0.5.

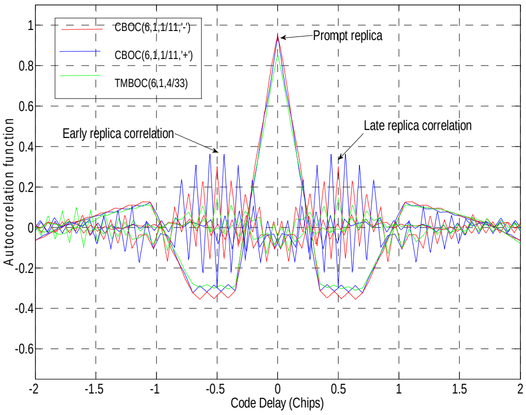

Figure 5 – TM61 technique : Autocorrelation function of *E*,*L* (BOC(6,1)) and *P*(BOC(1,1)) replica

In Figure 7 we assumed the usage of the modified DP discriminator that has a discriminator function as given in (2). The chip spacing was chosen to be 1/6 chips and an infinite front-end bandwidth was assumed. The linear tracking region of the discriminator was placed between [-0.07,0.07] chips for all three modulation types. We can observe that although all three observed cases have the same slope in the linear region, out of this region TMBOC has the lowest output error.

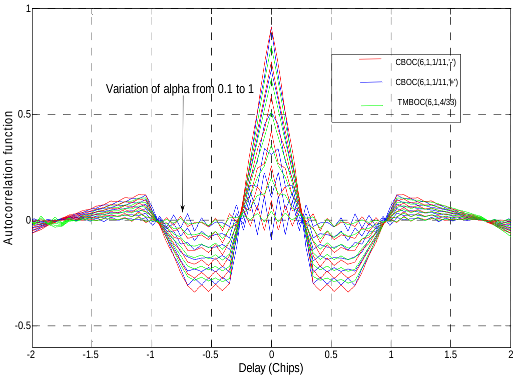

Figure 6 – MBOC autocorrelation function when varying α (percentage of BOC(6,1)) from 0.1 to 1

TM61 is a good tracking technique, if we target applications that rely on receivers with low complexity and average accuracy. The other proposed technique, Dual Correlator, uses more correlators since it assumes two independent correlations between the incoming signal and the pure replica. The autocorrelation peak for the Dual Correlator algorithm is shown on Figure 8. The higher the percentage of BOC(1,1) in the replica, the lower are the losses. The shape of the autocorrelation function is different than for TM61. The ratio between β and ρ on the Figure 8 varies from 1 to 5. Figure presents just several curves for different correlation ratio, in order to be seen well. A good point is that this technique is adjustable in software, and we can obtain different tracking techniques by changing this ratio, depending on the user requirements. Dual correlator technique provides better results for CBOC than TMBOC modulations. For both, there is an optimal ratio of ρ / β that provides minimal code tracking error and multipath performance, as shown in [12].

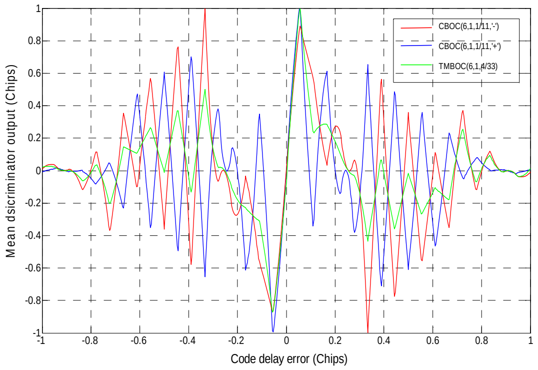

Figure 7 – Modified discriminator curve (DP) for new MBOC modulation schemes

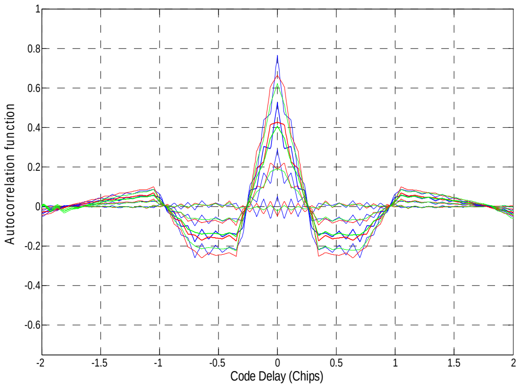

Figure 8 – Dual Correlator autocorrelation performance in the case ratio $\frac{\rho}{\beta}$ changes

ASPeCT algorithm can be applied on CBOC tracking, as shown in [7], at the price of reducing BOC(6,1) in the local replica on half, and decreasing the multipath performance. It introduces some additional degradation in tracking, increasing the code tracking noise of [0.6-1] dB, as some previous works showed [7]. It solves the problem of false locking points but there is still a probability of false locks due to BOC(6,1) ripples on DP discriminator. It can be used for CBOC tracking in synergy with other algorithms. Future ASPeCT tracking algorithms should consider improvements in terms of multipath, and also extension for TMBOC tracking.

S-curve shaping method is shown to outperform the previous multipath mitigation methods in [8]. Optimal weights are obtained for the discriminator by fitting the ideal discriminator curve in order to minimize code tracking and multipath error. This method can be used for MBOC tracking, finding the parameters of the discriminator for different correlator types. It may be that the use of more complex correlators, like narrow, double delta or Strobe would improve the receiver performance, and this should be investigated further. Also, composite tracking is still in its infancy, and should be further investigated, combining pilot channel/pilot+data channel tracking using common discriminator function and collaborative loop. It might be a good solution for MBOC tracking.

MULTIPATH PERFORMANCE

Multipath is the main source of error in the tracking of GNSS signal. It can be described using Multipath Error Envelopes (MEE), describing the distance between the theoretical and the real zero-crossing point of the discriminator function, when the received function is influenced by a single ray, as explained in [5]. To characterize the multipath effects, we have to consider strength (signal to multipath ratio SMR), phase Doppler and delay. TM61 tracking technique provides better results in terms of multipath error envelopes than traditional CBOC tracking, as shown in [5] if a DP discriminator is used. For High Resolution Correlator, for example, results are worse than using BOC(1,1) receiver. In this case S-curve shaping can provide better results. It is shown in the work of [8] that the multipath performance is the best when S-curve shaping is performed. It requires a great number of correlators though, each with a specific weight, being the main disadvantage of the scheme, if a low receiver complexity is the target.

Multipath performance of Dual Correlator algorithm is adjustable, depending on the BOC(6,1) ratio in the local replica, since BOC(6,1) have excellent multipath performance. This increase of BOC(6,1) component is limited by a code tracking error, and the trade-off between the two should be achieved depending on the application.

New signal modulations require ad-hoc multipath mitigation strategies. Since tracking techniques can be adjusted ‘on the fly‘, depending on the ratio of the replica of different subcarriers, multipath performance also changes rapidly. Also, implementing new discriminator functions and using more advanced correlator types can improve the multipath error. In our future work, we will investigate new correlator types and advanced algorithms that can suppress multipath error and provide more robust tracking.

CONCLUSION

In order to take advantage of the the new CBOC and TMBOC modulations, the design of new, more sophisticated techniques, based on the usage of additional correlators with a better discriminator curve shaping, and advanced performance with respect to tracking jitter and complexity is required. A general conclusion is that if a pure BOC(1,1) receiver is used for the tracking of CBOC and TMBOC, the degradation of signal tracking is high compared to pure BOC(1,1) signal tracking. Therefore, new tracking algorithms have been proposed, such as TM61 and Dual Correlator, that use a simplification in the tracking architecture comparing to traditional tracking, and still outperform traditional BOC(1,1) tracking. These algorithms are specific for each modulation type, and not optimal in the sense of a common, mass-market receiver that is able to track both signals.

Although TM61 and Dual Correlator provide good performance and is a good solution when the simplified architecture is a demand, if we need better accuracy and usage of full MBOC capabilities, new design of a tracking algorithm is needed, that combines the good features of each algorithm. Robust scheme that shows better multipath performance by implementing advanced multipath mitigation techniques able to suppress multipath error and improve the tracking performance.

Tracking schemes should be flexible and adaptable during the tracking depending on the user requirements. *Optimality* with respect to code tracking error for both CBOC and TMBOC is important and the *receiver architecture* should be also improved. Since TMBOC and CBOC have completely different structures, a real challenge would be to design a receiver architecture able to receive both signals with a simple as possible architecture.

Our future work will be based on these new tracking algorithms that use advanced discriminator functions and multipath mitigation techniques. Also, collaborative loop tracking principle can be used for tracking, as given in [6]. Composite tracking is a good idea that has to be further investigated since there is no previous work discussing much on this front.

REFERENCES

[1] Galileo Signal in Space Interface Control Document, ***OS SIS ICD, Draft , ESA,*** February, 2008.

[2] O. Julien and C. Macabiau, ***Two for One - Tracking Galileo CBOC Signal with TMBOC*** , Inside GNSS, Spring 2007.

[3] N. Hoult, L. Aguado, R. Crescimbeni, ***Performance comparison of TMBOC and CBOC signals Galileo Advanced Concepts,*** Thales research&Technology,2006.

[4] E.D. Kaplan, ***Understanding GPS - Principles and Applications***, Artech House, 2006.

[5] M. Fantino, P. Mulassano, F. Dovis, ***Performance of the proposed Galileo CBOC Modulation in Heavy Multipath Environment***, Wireless Personal Communication, Springer 2007.

[6] D. Borio, C. Mongredien, G. Lachapelle, ***Collaborative Code Tracking of Composite GNSS Signals***, IEEE Journal on Selected Topics in Signal Processing - special issue on advanced signal processing and robust navigation, 2008.

[7] O. Julien**, *Design of Galileo L1F Receiver Tracking Loops,*** Thesis, 2005, University of Calgary.

[8] M. Paonni, J-A. Rodriguez, ***Looking for an Optimum S-curve shaping of the Differnet MBOC Implemenations*** , ION GNSS ITM, 2007.

[9] A. de Latour, T. Grelier, ***Subcarrier Tracking Performances of BOC, ALTBOC and MBOC signals***, ION GNSS ITM, 2007.

[10] A. Simsky, J-M. Sleewaegen, ***Performance Assesment of Galileo Ranging Signals Transmitted by GSTB-V2 Satelites***, ION GNSS ITM, 2006.

[11] J. Avila-Rodriguez, E. Rebeyrol, L. Ries, ***CBOC – An implementation of MBOC***, CNES Workshop, Toulouse, 2006.

[12] O. Julien and C. Macabiau, ***On potential CBOC/MBOC Common Receiver Arcitectures***, ENAC, ION GNSS ITM, 2007.

[13] F. Nunes, F. Sousa, J. Leitao, ***BOC/MBOC Multicorrelator Receiver with Least-Squares Multipath Mitigation Technique***, ION GNSS, 2008.

[14] F. Nunes, F. Sousa, J. Leitao**, *Code Correlation Reference Waveforms for Multipath Mitigation in MBOC GNSS Receiver***, ION GNSS, 2008.

[15] J. Avila-Rodriguez, G. Hein, J. Betz, ***MBOC: The new optimized spreading modulation recommended for Galileo OS and GPS L1C***, CNES, DSTL, MITRE, 2006.

Tracking scheme	**TM61**	**Dual Correlator**	**S-curve shaping**	**Aspect**	**Composite tracking**
Tracking concept	- Simplified architecture BOC(1,1) for prompt BOC(6,1) for E,L -***minimal*** Number of correlators	-Two parallel correlations BOC(1,1) and BOC(6,1) -***Adjustable*** tracking	-Ideal correlator shaping technique -Fitting the curve -Find optimal (d,α) (spacing, weights)	-ACF Side peaks elimination -Controllable by β -Dot Product discriminator used	-Pilot and data channels combined -*same discriminator* -Non-coherent +coherent tracking
Tracking robustness	-Binary replica -Low complexity -Stable tracking region -Easy implementation	-Medium complexity -Number of correlators doubled -TMBOC tracking has high errors	-***High*** complexity -***Same*** S-curve for all architectures -Fitting process - slow	-More correlators needed 4 (5) for DP(EML) -Reduce BOC(6,1) on half	-Modest complexity -Complicated receiver architecture -Collaborative tracking loop
Tracking accuracy	-~3 dB improved vs. BOC(1,1) -Excellent multipath mitigation -Low tracking error	-Easily configurable in software BOC(1,1)/BOC(6,1) =[1.6,3.2] ***ideally*** -For TMBOC – high correlation losses	-Small tracking jitter -Good multipath Error < +/- 0.01 chip -Low code tracking error	-Degradation of 0.6-1 dB in noise -Multipath performance reduced 10%	-SER sign error rate -Tracking jitter 1.41 times smaller -Comparing to one channel tracking
Recommendation for CBOC tracking	-Simple receiver architecture vs. Performance -Only applicable to CBOC	-Good for CBOC TMBOC - ***modify*** -Receiver architecture more complex	-Modest complexity -implemented in software -Good solution	-Multipath degraded -Can be used For CBOC	-Possible good solution -should be investigated further

Table 2 – Comparison analysis of the tracking algorithms