Subcarrier Ambiguity Resolution Techniques for HOBOC signals under Harsh Realistic Scenarios

Pedro Fernandes, *GMV, Portugal*
Pedro Boto, *GMV, Portugal*
Elena Simona Lohan, *TUT, Finland*
Gonzalo Seco-Granados, *UAB, Spain*
J. A. Garcia-Molina, *ESA and HE Space, The Netherlands*

BIOGRAPHIES

Pedro Fernandes holds a B.Sc. in Electronics and Telecommunications and Computers Engineering from Instituto Superior de Engenharia de Lisboa, Portugal and a Post Graduate in Open Source Software from ISCTE, Instituto Universitário de Lisboa, Portugal. He joined GMV in 2007 being involved in operational projects under GALILEO and EGNOS programmes and several projects related with GNSS receivers technologies and signal processing techniques.

Pedro Boto holds a M.Sc. in Aerospace Engineering from Instituto Superior Técnico of Lisbon, Portugal. He joined GMV in 2014 being involved in several projects related with signal processing techniques.

Elena Simona Lohan received her M.Sc. degree from Polytechnics University of Bucharest in 1997, a DEA degree from Ecole Polytechnique, Paris, France, in 1998, and a Ph.D. degree from Tampere University of Technology (TUT), Finland, in 2003. She is now an associate professor at TUT and a visiting professor at Universitat Autonoma de Barcelona, Spain. She is a coeditor of Galileo Positioning Technology (Springer) and a coeditor of a recently published Springer book Multi-Technology Positioning. She has coauthored more than 160 international publications. Her current research interests include wireless location techniques, location-based services, and privacy-aware positioning solutions. She is a Senior Member of the IEEE.

Gonzalo Seco Granados holds a PhD degree from Univ. Politecnica de Catalunya (UPC) and an MBA from IESE, Universidad de Navarra. Since 2006, he is associate prof. at the Dept of Telecom. Eng. of UAB and head of the Signal Processing for Communications and Navigation (SPCOMNAV) group.

J. A. Garcia-Molina is a Radio Navigation engineer at ESA/ESTEC in Noordwijk, The Netherlands, where he leads several R&D projects and internal research activities on GNSS receiver technology and signal processing techniques for ground and space applications in the context of different ESA programs (including Galileo). His main research interests include signal processing and estimation theory, GNSS/Galileo receivers and signals, hybrid and cooperative/collaborative positioning, array signal processing, identification and localization of jammers/spoofers, SDR receivers, and cloud positioning techniques and applications.

ABSTRACT

Currently, a main challenge in HOBOC (High Order Binary Offset Carrier) modulations is the presence of ambiguities caused by multi-peaked autocorrelation functions. In harsh environments, such as urban and suburban, distinguishing multipath and BOC (Binary Offset Carrier) side peaks is key to acquisition and tracking stages. This problem originates in the notches of the multi-peaked autocorrelation function, resulting in increased difficulties in acquisition process and locking on the wrong peak for tracking. To overcome this issue at acquisition level, it is required to use a finer time step with full BOC processing which in turn slows down the process, whilst for tracking, the use of complex techniques (with respect to the standard PLL/DLL) will ultimately bring a trade-off between complexity, robustness, accuracy and convergence time.

This work addresses the lack of a thorough comparison of techniques specifically applied to the use with high order BOC modulations such as $BOC_{cos}(15,2.5)$ and $BOC_{cos}(10,5)$. This study presents an assessment of this specific problem from two different perspectives based on different classes of techniques: open and closed loop. The state of the art for both types of techniques is investigated through experimentation in a bit true simulator, representative of real receivers and capable of processing SW simulated signals, in a thorough test campaign to create a solid baseline of test data to be used in the analysis of

the techniques performance in order to highlight its features and provide a comprehensive insight aiming its application in real-world receivers.

INTRODUCTION

Due to the effect of the subcarrier, BOC signals split the main energy component of the signal spectrum shifting it away from the band center, so that they have a higher degree of separation from the BPSK (Binary Phase Shift Keying) modulated signals on the same frequency. Moreover, BOC signals have a greater RMS (Root-Mean-Square) bandwidth compared with the BPSK signals with the same spreading code frequency to take advantage of the fact that the greater the RMS bandwidth is, the better the inherent ability to mitigate white Gaussian noise and narrowband interference during tracking. Also when it comes to tracking, due to ACF narrow peak, BOC signals provide a higher accuracy when compared with the BPSK modulations of the same chip rate.

On the other hand, the BOC modulations add side peaks to the auto-correlation of the signal, which causes an ambiguity that needs to be solved at the receiver. In fact, the tracking loops need to make sure that they are tracking the main peak, and not one of the side peaks.

While the ACF of BPSK modulated signals is a triangle Λ, BOC signals present a saw tooth-like ACF. The notches in the BOC ACF are called ambiguities.

The normalized BOC(m,n) ACF without filter can be expressed as described in [Eq.1].

$$R_{BOC}(\tau)=\begin{cases}\sum_{i=0}^{N_B-1}\sum_{l=0}^{N_B-1}(-1)^{i+l}\Lambda\left(\tau-i\frac{T_c}{N_B}+l\frac{T_c}{N_B}\right) & \text{for BOCsin}\\ \sum_{k=0}^{1}\sum_{j=0}^{1}\sum_{i=0}^{N_B-1}\sum_{l=0}^{N_B-1}(-1)^{i+l}\Lambda\left(\tau-i\frac{T_c}{N_B}+l\frac{T_c}{N_B}-k\frac{T_c}{2N_B}+j\frac{T_c}{2N_B}\right) & \text{for BOCcos}\end{cases} \qquad \text{[Eq.1]}$$

Where N_B is the BOC modulation order or twice the ratio between sub-carrier rate and chip rate, T_C is the chip interval, and Λ is the triangular function of support $2T_C$ and unit maximum [1].

Summarizing, higher order BOC signals are spread in the frequency domain hence increasing the signal potential performance and multipath robustness, supporting compatibility while guaranteeing interoperability but with inherent problems related with the multi peak ACF.

AMBIGUITY CHARACTERIZATION

Ambiguity can be simplistically described as the inability of a given technique to have its operating point centered on the main peak of a given ACF. And this phenomena can occur in both acquisition and tracking stages as consequence of a poor acquisition, a loss of lock derived from poor signal conditions or from a combination of both.

Ambiguity in Acquisition

The existence of side peaks on the HOBOC modulations has a great impact on the acquisition process. When comparing ACF for BPSK and BOC signals it is very clear that the width of the main lobe is much smaller in the later which is reflected on a smaller step on the time bins to be able to detect the main peak of the ACF though with a significate computationally impact on the search process of this acquisition stage. For the BPSK modulation, for a 3 dB loss, the step is about 0.5 chips, while for the same characteristics, BOC needs 0.2 chips (with 4092 chips instead of the 1023 for the BPSK). The consequence of failing to have a short time bin step is missing the peak. Basically, the acquisition process can fail completely if the step is higher than about one quarter of the correlation function main lobe width.

Ambiguity in Tracking

The ambiguity issue also has a strong impact on the tracking performance of the incoming signal. As stated earlier, if a side peak is locked instead of the main peak, the consequence is the potential occurrence of a LoL (Loss-Of-Lock). .

When a technique is locked on the side peak, the first consequence is the loss of power hence making the tracking stage more susceptible to noise and multipath which in turn facilitates the loss of lock. Furthermore, even if lock is not lost and the technique is able to keep tracking a secondary peak – not recognizing such condition – accuracy is significantly affected and consequently the positioning solution, providing inadequate information to the user.

TECHNIQUES

A literature review of the work already done was made for which the techniques considered as most promising are following described divided by processing stage (acquisition/tracking) and technique category (open/closed loop).

Open Loop

Open loop techniques refer to techniques conceptually suitable for either acquisition or tracking stages or both, having a snapshot (or open-loop) approach when studied in the tracking stage. This work follows two different approaches from the correlation point of view: preservation of main correlation lobe sharpness and main lobe widening (BPSK like) aiming the application of these techniques to tracking and acquisition respectively. Several techniques were studied with the purpose of performing an extensive comparison between the unambiguous acquisition and tracking methods in terms of advantages and disadvantages since there is still missing a common understanding regarding if, and under which conditions the wide-main-peak-class of algorithms outperforms the narrow main peak ones. The studied algorithms fall mainly in three different points which are unambiguous acquisition, unambiguous tracking and joint methods for both unambiguous acquisition and unambiguous tracking.

The ambiguous BOC or Full BOC (FB) refers to the situation when the incoming signal is correlated with a reference BOC-modulated PRN code, at different frequency trials and it can be used in acquisition and/or tracking. When used in acquisition, a sufficiently small time-bin step (i.e., smaller or equal to a quarter of the main lobe width of the ACF) should be employed in order to be able to capture the main peak. When used in tracking, there is the probability of a false lock to side lobes of the ACF that is not addressed inherently by the Full BOC. On the other hand, one of the advantages of FB is its robustness to bandwidth limitations showing just a very small performance deterioration compared to the infinite BW case.

Two variants of the FB were analyzed specifically for tracking, the nominal one, based on the Narrow Correlator (NCORR) discriminator and a second one based on a Modified Bump Jumping (MBJ).
This Modified Bump Jumping was implemented to deal better with false locks and the main idea for its operation is to look at zero crossings not only around the previous estimate, but also around previous estimate $\pm 1/N_B$ to tackle the nearest false lobes and take the one that is contained in the largest S-curve linear zone. It is not expected to achieve the same accuracy as FB but at least to be more robust.

Closed Loop

Closed loop techniques rely on an acceptable alignment of the local replica with the received signal for which it continually tracks the error that is fed-back in order to force the desired alignment by means of controlling the correlation peak. Traditional methods of tracking, such as the typical PLL/DLL [4] present a limitation in the context of HOBOC signals which is intrinsically connected to its design in which a multi peak correlation is obtained hence creating the conditions for the occurrence of the so called ambiguity and false peak lock. Several techniques were studied covering BPSK-like techniques, Bump and Jumping (BJ) and three-loop techniques but for the purpose of this paper, the following techniques are described: Bump and Jumping (BJ), Double Estimator (DET), Code Subcarrier Smoothing (CS).

BJ method is currently considered as the reference technique to address ambiguity. It was proposed by P. Fine and W. Wilson in [5]. It allows to solve ambiguous code tracking for signals with multiple peaks in their ACF by judging whether the tracking locked point belongs to the main ACF peak or not. From the point of the resources needed, it requires two extra correlators besides E (Early), L (Late) and P (Prompt) which are VE (Very Early) and VL (Very Late) that are positioned to track the adjacent secondary ACF peaks with a distance $d_{VE\text{-}VL}$ of one sub chip period, i.e. $\pm T_S/2$ from the prompt correlator being $T_S = 2.T_C/N_B$.

Depending on the signal type, even more correlators can be used to avoid the lock on the secondary peaks of the autocorrelation function, but the objective is to track the adjacent secondary ACF peaks since the probability of getting locked on these is higher.

BJ is thus used for jumping to the peak with the highest signal power. First, the algorithm determines whether or not the correct correlation peak is being tracked by comparing the amplitude of the ACF peak currently being tracked (i.e. P correlator output) to the amplitude of the adjacent peaks (i.e. VE and VL correlator outputs).

The DET [6][7] exploits the fact that a BOC modulated signal can be represented as the product of a spreading code and the periodic repetition of the subcarrier: the DET tracks their delays independently using two separate tracking loops, the DLL for the code and the Subcarrier Code Lock Loop (SLL). When tracked separately, no ambiguity is present and lock on secondary peak is avoided.
With the tracking of the subcarrier code delay, the usual ACF for the BOC modulation is not seen anymore, instead, a 2D correlation is obtained.

CS [8] presents a combination between the time delay estimated by the DSB (Dual Side Band) and the time delay estimated using the FB by means of a Hatch filter. The idea of this combination is the same as the carrier smoothing but instead of using the carrier measurement, two code measurements are combined. The idea behind the Hatch filter is to smooth an unbiased but noisy measurement using a biased but noise free measurement. In this case the measurements used are the BPSK and the FB delay.

TEST ENVIRONMENT

To be able to test the techniques under study, a specific platform was developed, reliable and flexible enough to cope with any required change. Following is a description of the platform and its key components.

Signal Generator

The signal generator used in this study (Figure 1) is able to create signal samples for $BOC_{cos}(15,2.5)$ and $BOC_{cos}(10,5)$ while being able to incorporate multipath models and for that purpose LMS [9] channel was the one selected.
To configure the inclusion of a propagation channel, several parameters are required to be setup. These parameters have a direct impact on multipath and dynamics characteristics of which the following are of key importance:

- Sampling frequency;
- Environment (urban);
- Maximum speed [km/h];
- Satellite elevation;
- Number of echoes;

Processing

The high level design of the platform is shown in Figure 2. As can be seen, there are two possible ways to process the signals: open loop and closed loop. Receiver module is designed in a way that it's capable of processing signal samples systematically and deterministically using different receiver techniques and approaches, ensuring input repeatability and consistency in the results comparison by controlling the random process seed.

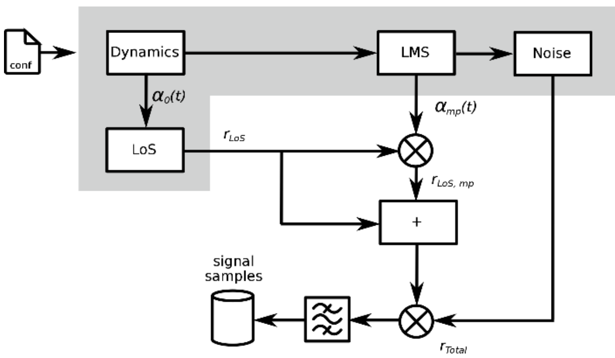


Figure 1. Signal Generator

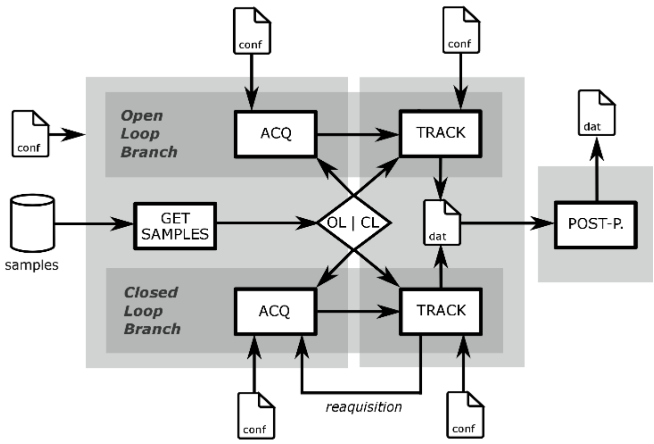


Figure 2. Platform high level design

Post Processing

The last block in the processing chain of the platform enables the generation of metrics and results to be used for the analysis and complete understanding of each technique specificities in the exercised test conditions.
It receives the outputs of the Processing module which are stored in intermediate files for modularity reasons.

Test Scenarios

For the purpose of demonstrating in this paper the ability of the techniques in avoiding or reverting a false lock condition, two test scenarios are presented capable of providing good evidence of the techniques performance while also being representative of real application scenarios in which the signal conditions pose significant challenges. These are configured to drive the simulator into false locks and reacquisition process, aiming the evaluation of the performance of the techniques regarding false lock recovery and in the event of a reacquisition.

The scenarios underlying configurations are based on LMS channel model for urban multipath and car dynamics for satellites with low elevation angles with details presented in Table 1. The single difference between the two scenarios is the occurrence of controlled false lock injections to add a degree of flexibility in manipulating the environment.

Table 1. Test scenarios baseline configuration

Parameter	Value
Surrounding	Urban
Simulation Time	600 [s]
Max. Speed	50 [km/h] (car)
Satellite Elevation*	27º
Echoes minimum power	-40 dB
Number of Echoes	10

CHARACTERIZATION

For the purpose of clarity, following is presented the characterization of acquisition and tracking stages for the baseline technique (FB). This characterization is key for the correct configuration of the software receiver simulator, namely for acquisition integration times and also for establishing the tracking threshold that allows the correct triggering of reacquisition.

Acquisition

To select the most adequate integration times for acquisition, a set of tests were designed to characterize the FB acquisition for a P_{fa} of 1e-3 under different conditions. Following is depicted the trend of P_d against C/No for both $BOC_{cos}(10,5)$ and $BOC_{cos}(15,2.5)$ for a fixed integration time of 20ms for a P_{fa} of $1e^{-3}$ and a frequency step bin of 250Hz.

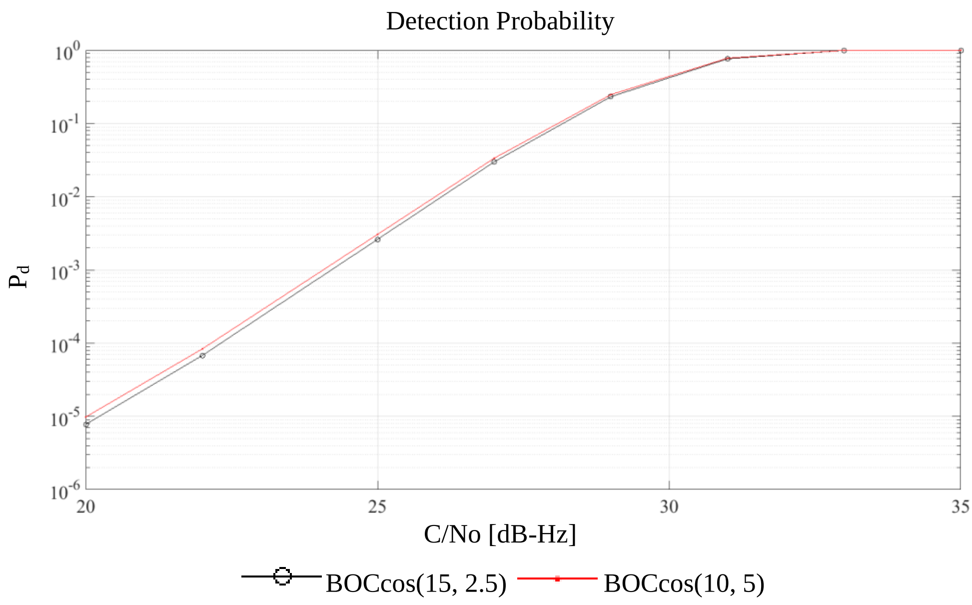


Figure 3. Pd for the acquisition stage for BOCcos(15,2.5) and BOCcos(10,5)

From the presented results it can be seen that the P_d is equivalent between modulations for the same settings.

For the purpose of the testing campaign, a parallel code phase search acquisition is performed for a window of ±5kHz in steps of 25Hz. Different configurations (integration time) are used in such way to keep a P_d of 99.9% to guarantee the acquisition stage success. As such, adequate acquisition integration times are set for each of the test cases.

The time series presented are limited to the first iteration for readability purposes with the figures of merit presented in the metrics table computed as the average of all the iterations hence enabling a quantitative study.

The analysis is split by modulation starting with the more demanding $BOC_{cos}(15,2.5)$, and finishing with $BOC_{cos}(10,5)$. For each, three different noise levels (20, 25 and 35dB-Hz) are exercised. Although aiming the analysis of acquisition step, tracking is also performed (FB Closed Loop) in order to make a quick assessment of the possibility of tracking after the acquisition stage is finished hence validating it.

These results demonstrate the integration time impact, adapted for the C/No of interest, reflecting, as expected, increased acquisition times for longer integration times along with a degradation in the C/No estimate. This finding is true for both modulations and reveals the time performance impact of a successful acquisition for low C/No levels.

Table 2. Acquisition Results Summary

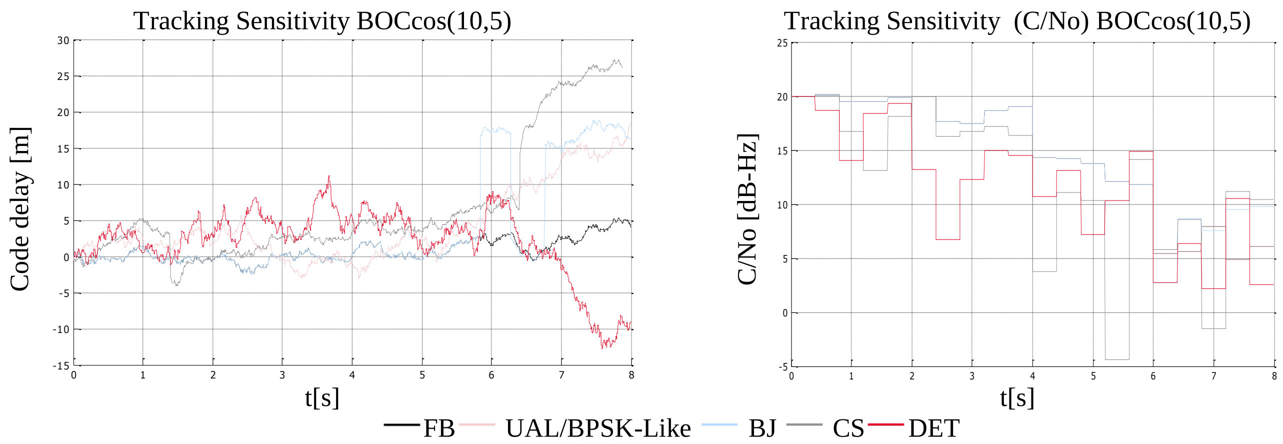
Mod.	Scenario	C/No Ref. [dB-Hz]	C/No Est. [dB-Hz]	Int. Time [ms]	Pd	Acq. Time [s]	Code Delay STD [m]
$BOC_{cos}(15,2.5)$	Static	20.00	29.62	400	0.9881	218.38	0.39
		25.00	34.33	160	0.9996	111.08	0.32
		35.00	38.88	20	1	64.71	0.08
	Car Dynamics	20.00	28.23	400	0.9881	259.83	0.32
		25.00	34.78	160	0.9996	94.11	0.31
		35.00	39.49	20	1	36.21	0.08
	Urban MP + Car Dynamics	20.00	26.75	400	0.9881	293.81	0.32
		25.00	32.80	160	0.9996	134.32	0.33
		35.00	38.26	20	1	29.22	0.13
$BOC_{cos}(10,5)$	Static	20.00	32.00	400	0.9895	176.44	0.48
		25.00	30.58	160	0.9996	75.57	0.28
		35.00	35.49	20	1	24.12	0.12
	Car Dynamics	20.00	31.24	400	0.9895	167.72	0.42
		25.00	32.23	160	0.9996	83.42	0.30
		35.00	36.77	20	1	34.32	0.13
	Urban MP + Car Dynamics	20.00	31.11	400	0.9895	212.08	0.55
		25.00	32.03	160	0.9996	161.69	0.33
		35.00	37.26	20	1	88.78	0.24

As the entry point of a receiver processing acquisition impact cannot be neglected, and despite the tracking techniques performance is recommended to be analyzed separately from acquisition, the fact is that the quality of the raw estimates impact the techniques since in some cases it’s even the root cause for false lock. As such some considerations on this stage follow. Although it is relevant for a receiver to have the lowest possible TTFF, for the purpose of this study, this problematic is less relevant, along with the implementation of a single acquisition mechanism which prevents any comparison.

BOC modulation inherently takes benefit of the spectral separation to improve its ability to be more robust against multipath, but on the other hand, this increases the demand for resources, one relevant point is the fact that the parallel search pushes this demand in order to be efficient, hence, with impact on real receiver’s implementation which use, depending on the application, could be prevented. Although the consequences of such a resource demanding mechanism can’t be considered for some applications, the fact is that for the signals under analysis, bit sign transitions can occur at each spreading code period with significant effects on acquisition performance as pointed out in [10] hence validating the decision.

Tracking

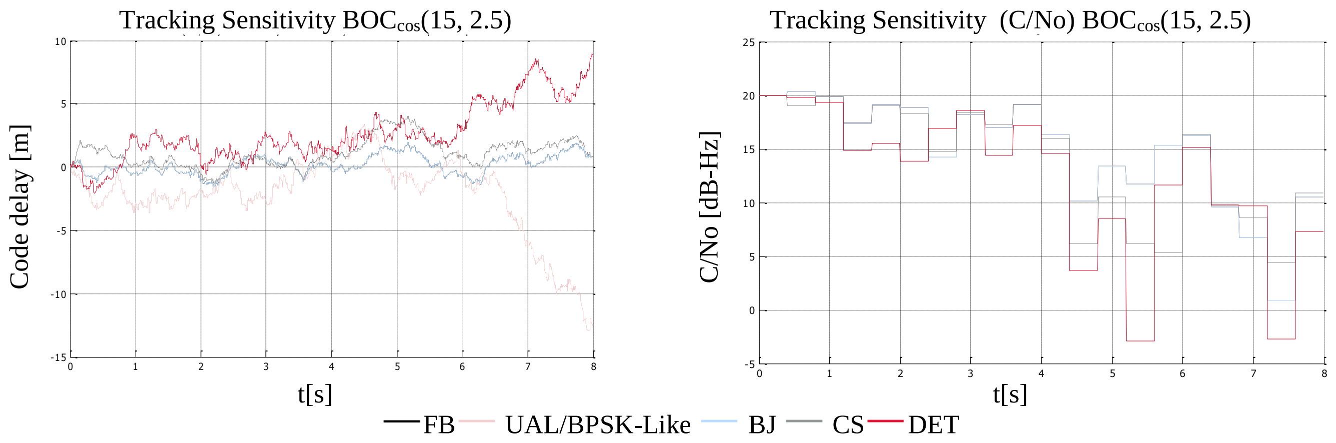
By creating a controlled C/No profile that goes from 20dB-Hz to 0 dB-Hz, the tracking threshold can be determined taking advantage of a non-tracking reference established in the time period in which C/No is ~0dB-Hz that enables a direct comparison with previous periods in determining the tracking sensitivity. The results from such tests are depicted below for both $BOC_{cos}(15, 2.5)$ and $BOC_{cos}(10, 5)$, and it can be seen that for $BOC_{cos}(10, 5)$ all techniques are able to properly track down to 18dB-Hz with accurate estimates of C/No.



a) **b)**

Figure 4. Code delay (a) and C/No estimates (b) for BOCcos(10, 5) for a reference C/No of 20dB-Hz

Regarding BOCcos(15,2.5) this lower limit is found to be lower for C/No values of approximately 16dB-Hz.



a) **b)**

Figure 5. Code delay (a) and C/No estimates (b) for BOC_{cos}(15, 2.5) for a reference C/No of 20dB-Hz

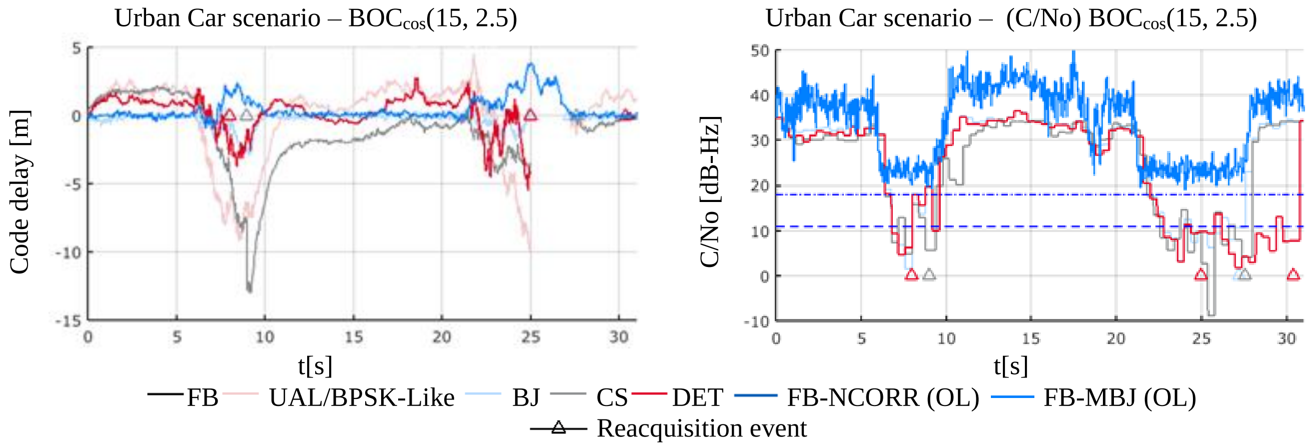
These results allow the correct configuration of the platform in terms of defining the correct reacquisition threshold which for $BOC_{cos}(10, 5)$ should occur around 18dB-Hz while for $BOC_{cos}(15, 2.5)$ should be around 16dB-Hz.

RESULTS

The analysis, quantitative and qualitative, is presented per modulation and per technique followed by a summary describing all the most important findings. Techniques are presented in sequence from the so called reference techniques (FB/FB-NCORR, UAL/"BPSK-like", BJ) to the unambiguous candidates (CS, DET and MBJ) thus covering all the open and closed loop techniques proposed to be assessed. It should also be noted that some of the plots have segments that are blanked whenever code delay is greater than 40 [m] in order to improve its readability.

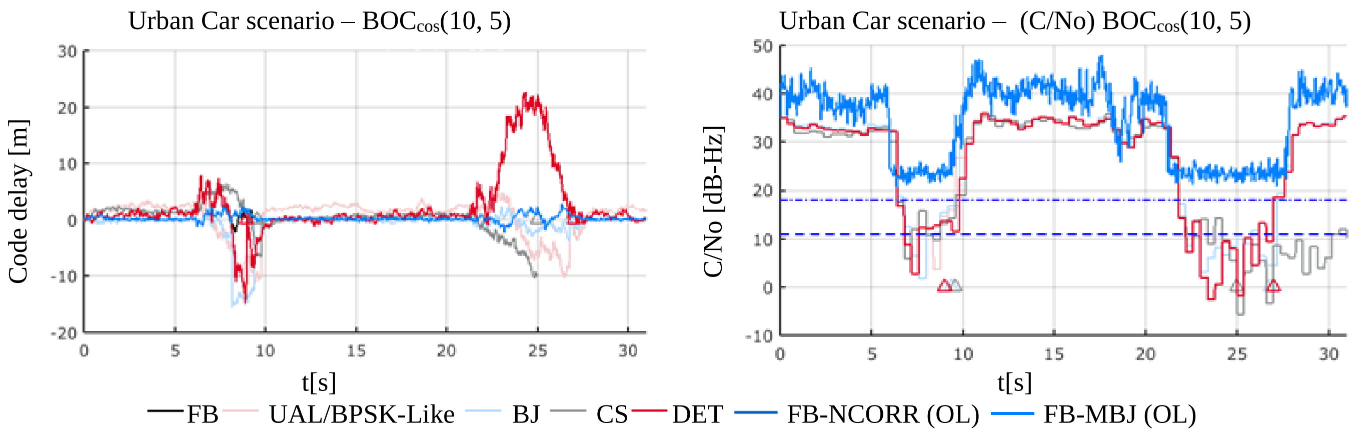
First scenario presented is a realistic urban scenario with car dynamics followed by a second scenario in which on top the first one a set of controlled false lock injections are performed to further exercise the techniques and highlight is capabilities.

Realistic Harsh Scenario



a) **b)**

Figure 5. Code delay (a) and C/No estimates (b) for BOC$_{cos}$(15, 2.5) for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [0, 32] [s])



a) **b)**

Figure 6. Code delay (a) and C/No estimates (b) for BOC$_{cos}$(10, 5) for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [0, 32] [s])

The following tables present the numerical results for this scenario. Values marked in bold highlight the best technique for each of the metrics and it's clear that these are scattered which is a good evidence of not having a clear winner.

The findings are similar between modulations and like for BOC$_{cos}$(15, 2.5), testing BOC$_{cos}$(10, 5) under the same scenario leads to the same conclusion, that no single technique excels the others in a significate number of metrics. Due to this similitude, the analysis details shall only be presented for BOC$_{cos}$(15, 2.5).

As expected, when tracking the main peak, FB is the most robust technique as can be seen around second 8 on Figure 5 where the technique does not enter in reacquisition unlike CS and DE, being able to keep tracking the main peak. Also, FB is the most accurate technique since it's the one that deviates less from the reference. Due to being unable of correcting the false lock, when the technique drifts to a secondary peak it stays there until the conditions deteriorate enough to enter reacquisition or a drift to the main peak occurs. This inability of correcting the false lock condition is thus the technique biggest handicap.

Table 3. BOC_{cos}(15, 2.5) quantitative metrics for urban car scenario.

Metric	FB	UAL/BPSK-like	BJ	CS	DET	FB-NCORR	FB-MBJ
C/No estimate (avg) [dB-Hz]	23.58	23.59	23.21	22.19	23.22	**32.15**	32.15
STD Code delay error [m]	**3.96**	4.63	3.98	5.57	4.72	5.79	11.06
Mean Code delay error [m]	-1.73	**-0.24**	-0.79	-2.24	-0.80	-5.46	-5.32
#Re-acquisitions	**40**	40	44	46	45	0	0
Tracking availability [%]	86.38	86.20	84.77	89.27	**90.24**	**100.00**	**100.00**
Time in false lock [%]	27.94	26.69	23.42	27.17	**18.84**	0.00	0.00
Mean Time to Lose Lock [s]	**30.06**	9.00	19.83	12.49	11.18	0.00	13.49
Mean Time To Recover False Lock [s]	14.02	7.37	6.14	5.97	**4.24**	103.51	8.52

Table 4. BOC_{cos}(10, 5) quantitative metrics for urban car scenario.

Metric	FB	UAL/BPSK-like	BJ	CS	DET	FB-NCORR	FB-MBJ
C/No estimate (avg) [dB-Hz]	24.34	24.35	24.50	23.16	23.42	**32.18**	32.18
STD Code delay error [m]	6.80	**6.37**	9.94	12.75	6.75	6.82	9.83
Mean Code delay error [m]	-1.50	**-1.00**	-1.27	-1.69	-1.29	-15.72	-0.67
#Re-acquisitions	**34**	34	36	48	41	0	0
Tracking availability [%]	85.59	84.94	90.75	87.93	89.93	**100.00**	**100.00**
Time in false lock [%]	27.46	26.81	**16.34**	24.03	20.44	0.00	0.00
Mean Time to Lose Lock [s]	**25.22**	14.99	17.42	16.55	17.35	0.00	10.81
Mean Time To Recover False Lock [s]	14.71	7.99	**4.15**	6.18	5.82	382.60	6.14

In low C/No conditions with dynamics, BJ frequently induces many false jumps that can lead to situations of loss of lock (LoL) or reacquisition as can be seen on Figure 7 around second 49 where the technique jumps to the 2nd peak triggering a reacquisition event 2 seconds later. With a false jump the technique goes to a secondary peak and as a consequence, the level of energy is not as high as the main peak and the technique is more susceptible to LoL. From a different perspective, the C/No estimates are lower, triggering more easily a reacquisition, impacting tracking availability.

On the other hand, this jumpiness, which affects both forms of BJ (open and closed loop), allow it to effectively correct some false locks like the one occurring on second 296.5 on Figure 8. While FB stays in false lock for approximately 80 seconds of the simulation, BJ is able to correct its tracking having more accurate estimates than FB for a long period of time. However, it is important to state that the scenario conditions at the time of the correction were favorable (attested by the C/No estimate of 30dB-Hz), had these been worse and BJ wouldn't have been able to properly correct the false lock.

CS behavior follows UAL but with a slight delay. On the other hand, this advantage can be a disadvantage as the technique is not able to react fast enough to correct its tracking and as consequence it can trigger a reacquisition while some of the other techniques are able to maintain track of the main peak (see second 9 on Figure 9). This happens due to the fact that CS is bound to UAL and its underlying high jitter that can go as far from the reference as 20 [m], driving the measurements away from the reference hence leading to lower C/No estimates.

Another interesting point of the CS simulation occurs on second 93 (Figure 9) where it reacquires tracking 3.5m away from the reference revealing an apparently worst behavior compared to DE (which also reacquires tracking at the same time) originating from the fact that the technique needs some time to stabilize the measurements on top of the poor reacquisition and the scenario conditions that make it even more difficulty for CS to stabilize its tracking leading to a drift situation and estimates approximately 13.7 [m] away from the reference before being able to track the locked peak some seconds after.

Despite the robustness shown by DET, similar to FB in some cases in keeping track of the main peak (seen for example from second 235 to 240 on Figure 10) it's possible to see that the track is not as accurate as the one presented by FB since it reveals more jitter on its measurements worsening DET accuracy with respect to FB being this, DET weak point. As can be seen between seconds 103 to 112 on Figure 9 where the conditions deteriorate and DET shows a high jitter not being able to maintain track of the main peak and entering in reacquisition seconds later, something that for instance BJ does not suffer in the same time period.

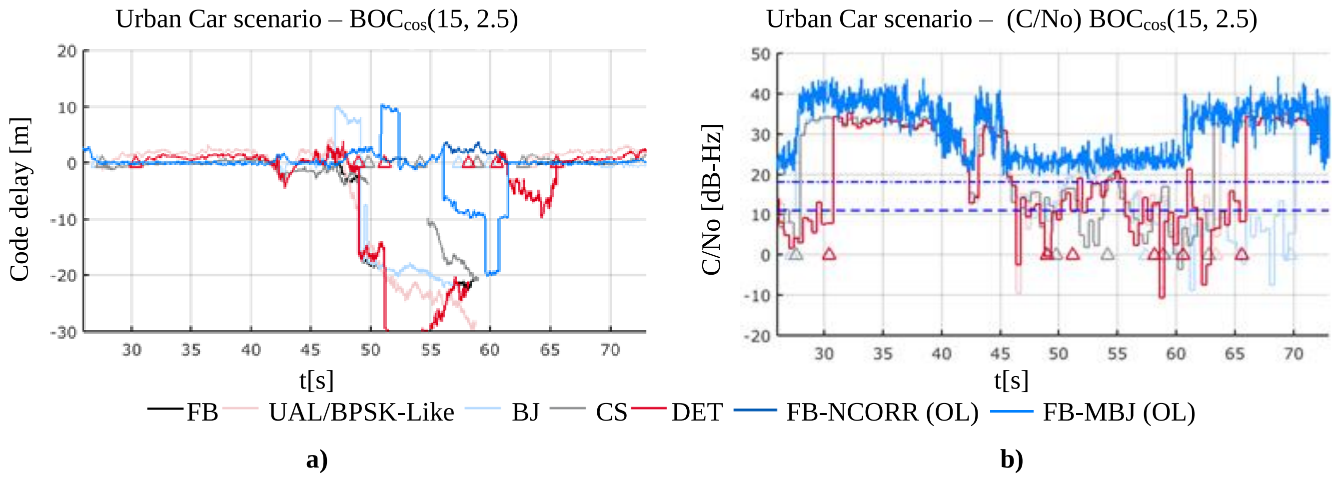


Figure 7. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [26, 74] [s])

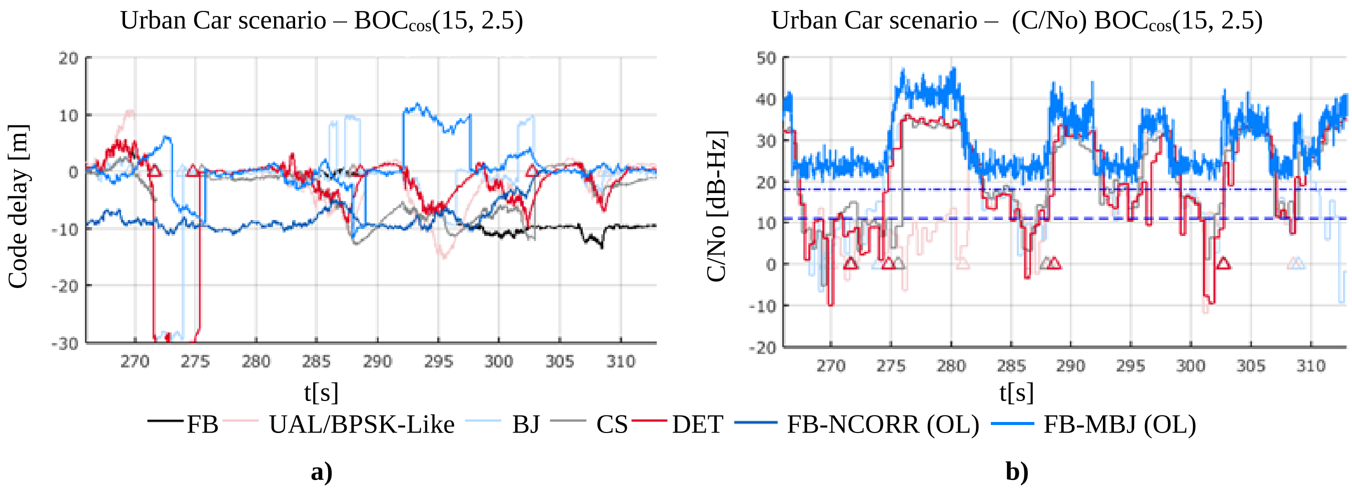


Figure 8. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [266, 314] [s])

The OL FB-NCORR performance is almost the same of FB, but because FB triggers reacquisitions when it locks on a side peak it stays longer than NCORR on the main peak as is the case in the period between second 225 and 240 on Figure 10. Because of this fact OL NCORR accuracy is considerably lower than the one presented by FB.
The main advantage when comparing with FB is the absence (by concept definition) of failed reacquisitions, so the technique may be far from the reference with a high error on the estimates but is never unavailable like FB can be.

The OL FB-MBJ has the same advantage as FB-NCORR. Since there are no failed reacquisitions, the technique may be far from the reference with a high error on the estimates but never unavailable like BJ after a failed reacquisition. However during track it has long periods far from the reference being unable to correct the side peak track like the case from the 215th second to the 240th on Figure 10. The CL BJ can have periods of unavailability but not as long. The FB-MBJ can be more robust than BJ but its accuracy is poorer due to the long periods far from the main peak.

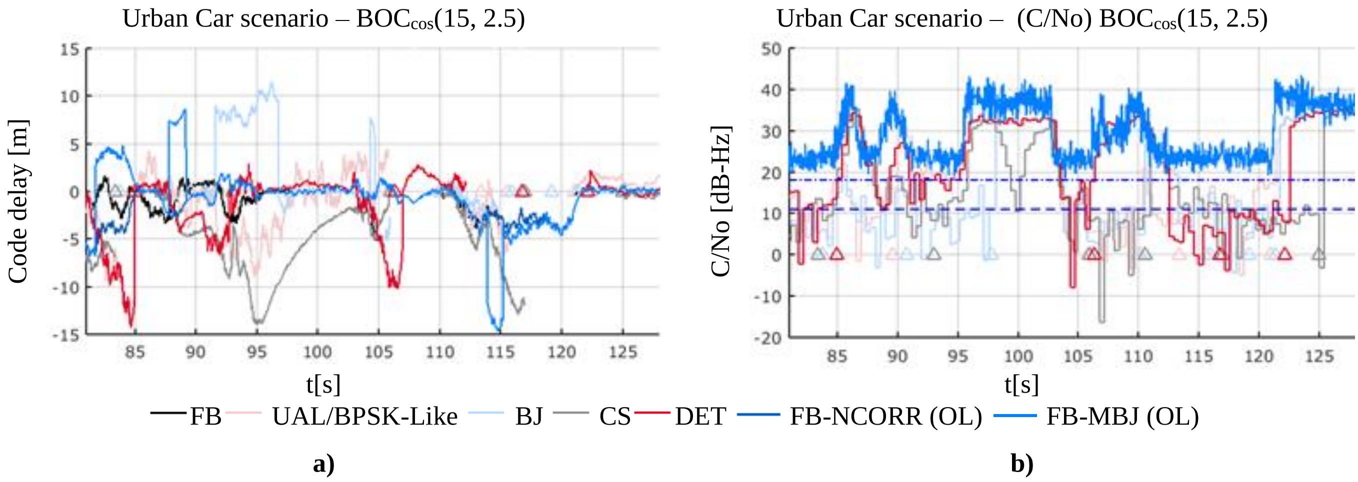


Figure 9. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [81, 129] [s])

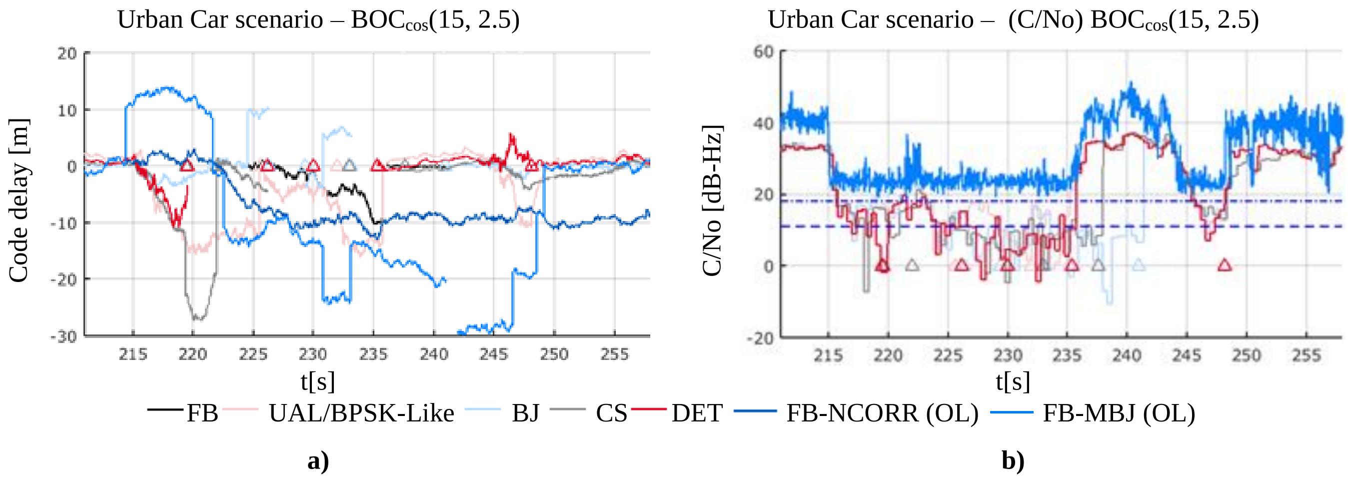


Figure 10. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle) with reference C/No of 35dB-Hz (Block [211, 259] [s])

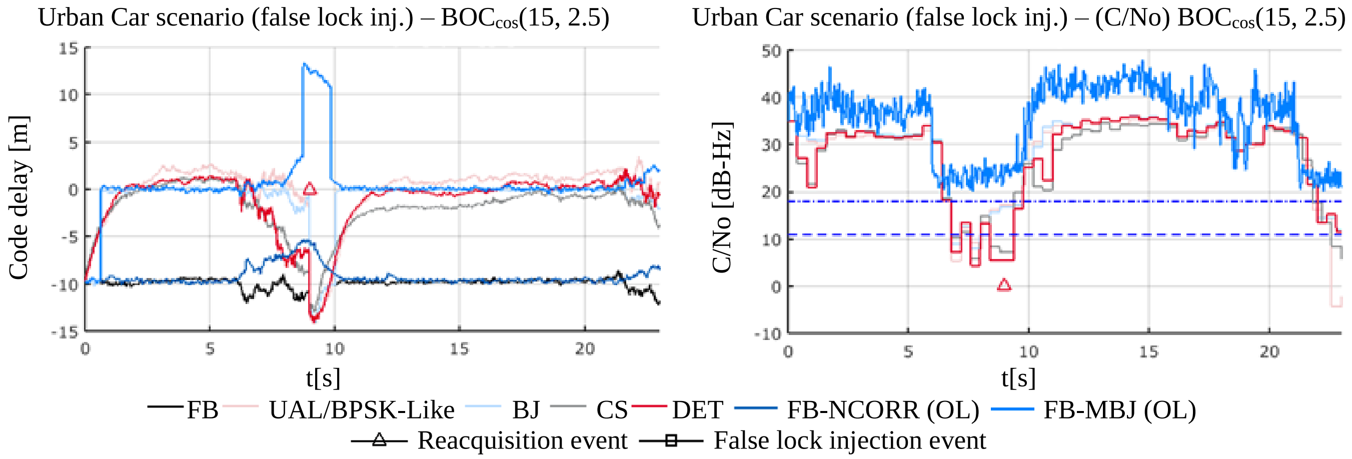
Realistic Harsh Scenario with False Lock Injections

The findings are similar between modulations and like for $BOC_{cos}(15, 2.5)$, testing $BOC_{cos}(10, 5)$ under the same scenario leads to the same conclusion, that no single technique excels the others in a significant number of metrics. Due to this similitude, the analysis details shall only be presented for $BOC_{cos}(15, 2.5)$.

FB techniques confirm that they are unable to correct the tracking from an initial false lock condition. This inability contributes to its lower robustness and of course the lower accuracy coming from the false lock that typically leads to reacquisition events that may even fail due to poor scenario conditions like is the case in second 9 (see Figure 11).

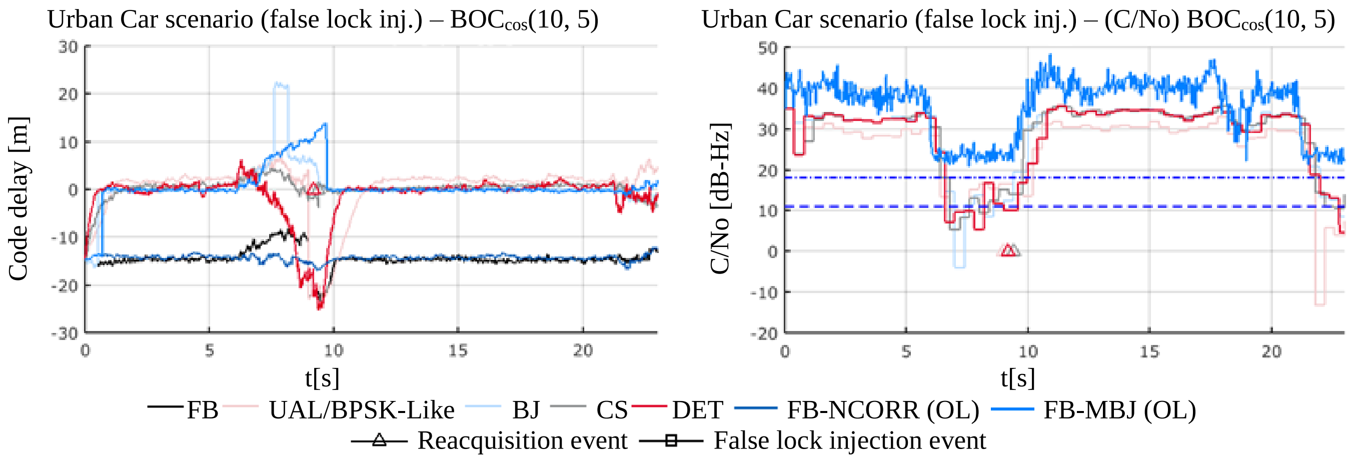
At second 200 on Figure 14, the first false lock injection can be seen. All the techniques are able to correct this except for FB that stays locked to the secondary peak entering in reacquisition 21.2 seconds later, earlier than BJ that due to its correction is able to keep tracking for 5.7 [s] longer.

On the other hand, at second 50 (see Figure 13), the robustness of FB (when tracking the main peak) can be attested. All the other techniques suffer with the degradation of the conditions, unlike the FB processing that stays very near to the reference, avoiding a reacquisition or losing lock. BJ has a false jump (but later it returns to the main peak), DET and CS enter in reacquisition 6 and 7 seconds before FB. Nevertheless not even FB is able to resist a reacquisition, as it happens on the 58th second.



a) **b)**

Figure 11. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle, with injected false locks) with reference C/No of 35dB-Hz (Block [0, 24] [s])



a) **b)**

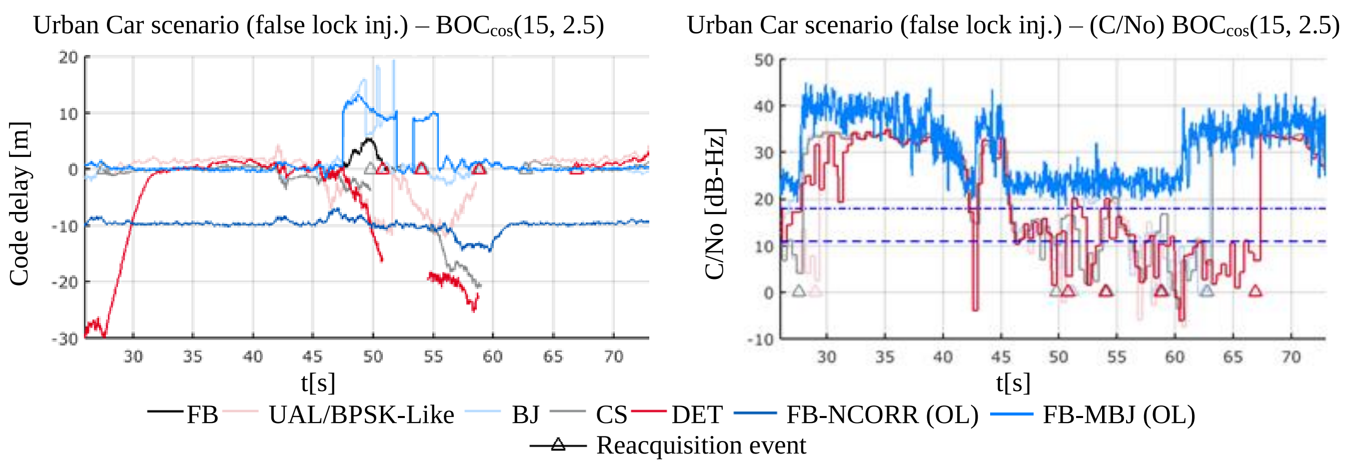
Figure 12. Code delay (a) and C/No estimates (b) for $BOC_{cos}(10, 5)$ for a realistic scenario (urban car, low satellite elevation angle, with injected false locks) with reference C/No of 35dB-Hz (Block [0, 24] [s])

Table 5. $BOC_{cos}(15, 2.5)$ quantitative metrics for urban car scenario (with false lock injections).

Metric	FB	UAL/BPSK-like	BJ	CS	DET	FB-NCORR	FB-MBJ
C/No estimate (avg) [dB-Hz]	24.34	24.35	24.50	23.16	23.42	**32.18**	32.18
STD Code delay error [m]	6.80	**6.37**	9.94	12.75	6.75	6.82	9.83
Mean Code delay error [m]	-1.50	-1.00	-1.27	-1.69	-1.29	-15.72	**-0.67**
#Re-acquisitions	**34**	34	36	48	41	0	0
Tracking availability [%]	85.59	84.94	**90.75**	87.93	89.93	100.00	100.00
Time in false lock [%]	27.46	26.81	**16.34**	24.03	20.44	0.00	0.00
Mean Time to Lose Lock [s]	**25.22**	14.99	17.42	16.55	17.35	0.00	10.81
Mean Time To Recover from False Lock [s]	14.71	7.99	**4.15**	6.18	5.82	382.60	6.14

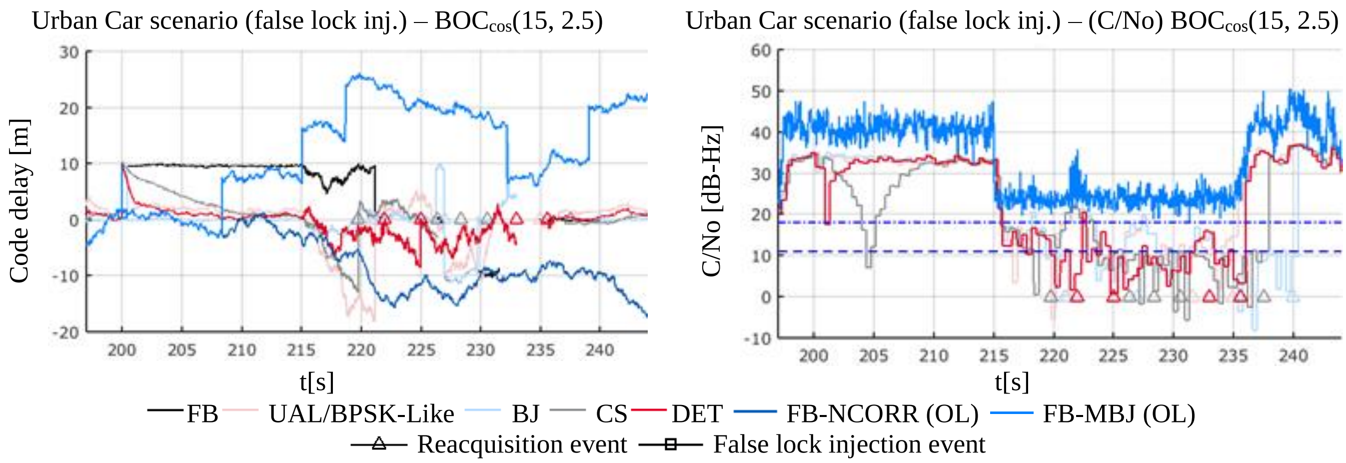
Table 6. BOC$_{cos}$(15, 2.5) quantitative metrics for urban car scenario (with false lock injections).

Metric	FB	UAL/BPSK-like	BJ	CS	DET	FB-NCORR	FB-MBJ
C/No estimate (avg) [dB-Hz]	23.38	-24.51	24.70	22.87	24.34	**32.65**	32.65
STD Code delay error [m]	7.87	**4.11**	7.19	6.02	5.70	32.71	5.10
Mean Code delay error [m]	-1.54	**0.12**	-1.00	-1.21	-1.08	23.66	0.84
#Re-acquisitions	**33**	33	35	43	43	0	0
Tracking availability [%]	90.68	90.57	93.10	89.45	**94.84**	100.00	100.00
Time in false lock [%]	23.46	16.77	12.33	21.16	**14.71**	0.00	0.00
Mean Time to Lose Lock [s]	**38.29**	11.47	25.41	14.82	9.71	5.61	13.61
Mean Time To Recover from False Lock [s]	13.68	5.30	3.11	6.33	**3.44**	95.68	3.58
Execution time [hours]	**25.35**	25.35	27.98	28.80	34.15	50.31	55.73



a) b)

Figure 13. Code delay (a) and C/No estimates (b) for BOC$_{cos}$(15, 2.5) for a realistic scenario (urban car, low satellite elevation angle, with injected false locks) with reference C/No of 35dB-Hz (Block [26, 74] [s])



a) b)

Figure 14. Code delay (a) and C/No estimates (b) for BOC$_{cos}$(15, 2.5) for a realistic scenario (urban car, low satellite elevation angle, with injected false locks) with reference C/No of 35dB-Hz (Block [197, 245] [s])

At second 0, BJ, when the conditions are favourable, attested by the C/No estimates, is the fastest technique to correct the false lock situation. In this case it corrects earlier than DET or CS by approximately 1 second. Once again after the failed reacquisition for the secondary peak at second 8, BJ is the first technique that starts tracking the main peak, this time 1.5 seconds earlier than the others which again demonstrates that when C/No estimates are higher than 25 dB-Hz and the dynamics or multipath is not strong, BJ is the fastest technique to correct the false lock.

BJ weakest point becomes evident in second 50. When the scenario degrades (C/No ~ 15dB-Hz) BJ has many difficulties in determining which peak it is tracking, resulting in many false jumps which often end up triggering reacquisition (57,8 seconds). Nevertheless, FB maintains it's tracking because it does not leave the peak it is in (entering in reacquisition 8 seconds later).
At second 0, CS is very fast to correct the false lock (2.25 seconds), slightly behind DET in terms of speed. Even after the failed reacquisition at second 9, CS is able to go to the main peak, maintaining the tracking ability but this time considerably slower than DET or BJ, taking 10 seconds to correct the reacquisition to the side peak (more 6 seconds than DET and 8 than BJ). This higher time in correcting the false lock can be a downside of the technique (in terms of robustness and even accuracy), due to the time it is between peaks and the impact on C/No estimates that are lower and that ultimately may lead to reacquisition events.

At second 180 (see Figure 15), CS is far from the reference when compared with DET, BJ or FB and as stated previously, because of the UAL estimates feeding the filter, CS presents a considerable jitter when the scenario conditions deteriorate. Due to the delay it has with the UAL estimates, CS is not as responsive as UAL and when correcting the estimates the technique lacks the ability to quickly track the main peak and entering in reacquisition along the way (seen at second 220 on Figure 14.).

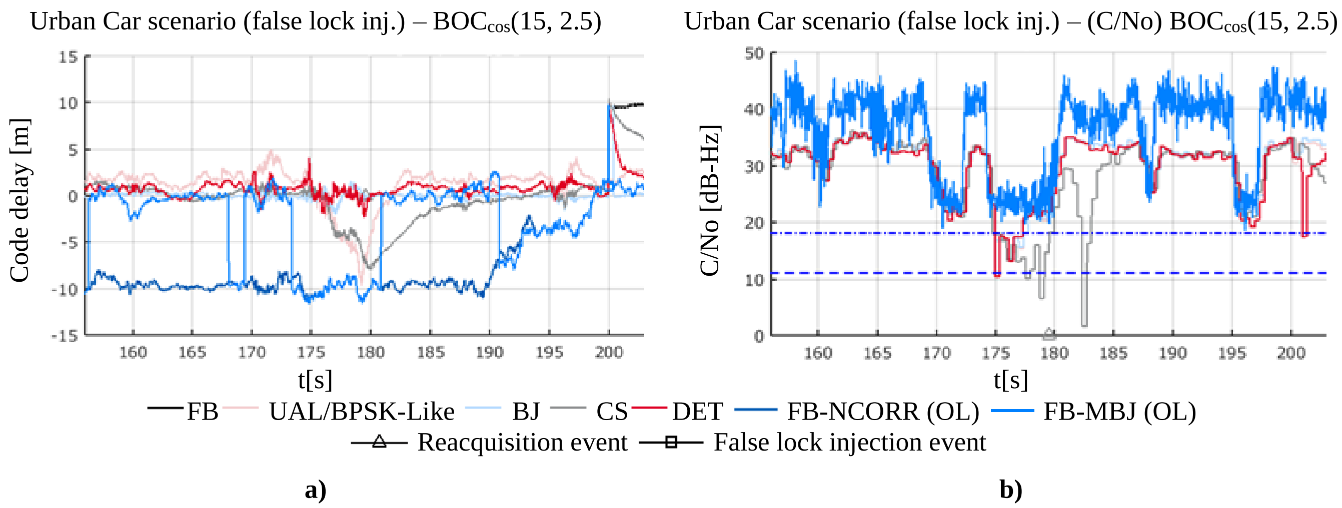


Figure 15. Code delay (a) and C/No estimates (b) for $BOC_{cos}(15, 2.5)$ for a realistic scenario (urban car, low satellite elevation angle, with injected false locks) with reference C/No of 35dB-Hz (Block [156, 204] [s])

In the event of the false lock injected in second 200 CS takes 6 seconds more than DET to correct the false lock and is seen that the technique is heavily impacted by UAL jitter, as is attested on second 220 where all the other techniques can sustain tracking unlike CS.

At second 0, DET is very fast to correct the false lock (1.5 seconds), accompanied by CS (2.25 seconds) in terms of speed. However it isn't faster than BJ's that takes only 0.6 seconds to correct the tracking. Like all the other techniques it enters in reacquisition at second 9 being, once again, one of the quickest in reaching the main peak (in 2.5 seconds), only surpassed by the BJ's.

As for DET behavior in the false lock injection event it is indeed faster than CS in reaching the pull in range of the modulation (<0.17 chips) taking 1 second instead of the 5 seconds presented by CS. Then, due to the poor conditions of the scenario, DET reaches the main peak on second 208.3 while CS takes 7 second more. Due to the responsiveness of DET, the technique is able to avoid a reacquisition at second 219.8 unlike CS that is too far from the reference.

The FB-NCORR performance when compared with FB can be considered as worst since, as stated before, FB takes advantage of reacquisitions. On the other hand, the main advantage when comparing with FB is the fact that there are no failed reacquisitions, so the technique may be far from the reference with a high error on the estimates but is never unavailable like FB after a failed reacquisition.

The FB-MBJ has the same advantage as NCORR, since there are no failed reacquisitions, the technique may be far from the reference with a high error on the estimates but is never unavailable like BJ after a failed reacquisition. The downside is the false jumps due to the bump jumping nature.

ANALYSIS

From all the techniques, two of them cannot correct the false lock, OL FB NCORR and CL FB. CL FB, despite not being able to correct the false locks, due to the close loop conception, with the triggering of a reacquisition, provided that is successful, is able to lock on the right peak, so this is an advantage against the OL form of FB NCORR that stays in false lock throughout most of the simulation. Despite not being able to correct the false lock on its own, when both the techniques are tracking the main peak, these are the most robust and accurate ones. Performances are very similar (only when tracking the main peak), with a marginal advantage for the OL when dynamics are included and the noise levels are low.

When analyzing the unambiguous techniques, BJ ones (CL-BJ and OL-MBJ) seem a good alternative because they share the FB/FB-NCORR tracking while capable of correcting the false lock (by jumping to the right peak, comparing the VE and VL correlators). However, the jumps are not always performed when they should and the techniques present false jumps under severe scenario conditions. And under the influence of dynamics, multipath or extreme noise conditions, the number of false jumps is significant and the techniques are not always tracking the main peak or are moving back and forth between peaks, in prejudice of its accuracy and robustness (when the techniques are not locked on the main peak they lose energy and become even more susceptible to keep this state or trigger a reacquisition event). Between the OL MBJ and CL BJ the performance differences are marginal. For the studied scenarios, the MBJ presented more false jumps, but that confirmed that the implementation and configuration of the jump mechanism is crucial for the technique performance.

CS, DET and UAL are unambiguous like the BJ’s but their correction of the false lock is not by jumps. These three are constantly correcting the tracking, driven by its own conception. UAL is relatively fast correcting the false lock (but slower than DET and the BJ’s) presenting a very high jitter for low C/No values. When the noise conditions increase, despite not being as good, it is considerably close to all the other techniques while being also very robust (rarely losing track of the main peak) and its performance does not suffer as much as all the techniques with the increase of noise or the introduction of dynamics or multipath. Since the technique does not excel in any aspect, the gap in performance is higher for all the other techniques when compared with the performance downgrade evidenced by UAL.

CS and DET are very similar in their performance. DET, like the BJ’s, is very fast in correcting the false lock, which demonstrates a high responsiveness. After FB-NCORR and FB, DET is the most robust technique to the user dynamics. When the conditions improve, the technique goes straight away to main peak whereas others are still on the path to correction, as is the case of CS. This lack of speed weakens CS that spends more time between peaks (during the correction) becoming more susceptible to LoL situations or reacquisitions. On the other hand this low responsiveness makes it robust and capable of avoiding such situations, because if the scenario suddenly worsens DET reacts much faster, deviating faster from the main peak and entering in a bad situation faster. Nevertheless, from the simulations done, it seems that DET benefits more from its responsive behavior than CS from its somewhat more stable behavior. Also, CS has two sensitive points, the UAL component brings a high jitter making the technique less accurate and robust and the second, related to the hatch filter, that requires some time to stabilize its measurements, and if a bad reacquisition occurs on severe scenario conditions the technique has some difficulties locking to the peak and stabilize its track.

CONCLUSIONS

Despite not standing out as the single best technique in any of the criteria, DET really performs very well in all. It isn’t as robust to MP and dynamics as FB/NCORR but better than CS and the BJ’s. In terms of sensitivity, all the techniques have very similar performances. And regarding accuracy, DET is not better than FB/NCORR when tracking the main peak, nor the BJ’s on good scenarios, but taking into account the more demanding (realistic) ones, its accuracy is one of the best since the false jumps hurt BJ’s accuracy and the long time to correct the lock makes DET accuracy as good as CS.

The extensive simulation campaign showed that none of the techniques considered stands out over all the others for all criteria in the scenario conditions under analysis, which means that work on this topic should continue, including techniques presented during the study timespan like DOME [11] and Subcarrier Aided Code Tracking [12], developing variants or completely new ones.

ACKNOWLEDGEMENTS

The work presented herein is based on the outcome of a project funded by the European Space Agency on 'Techniques for Subcarrier Ambiguity Resolution in High-Order BOC Signals and Performance Analysis in Realistic Environment'. The content of the present article reflects solely the author's view and by no means represents the official ESA or GALILEO views.

REFERENCES

[1] E. S. Lohan, A. Lakhzouri, M. Renfors, "Binary-offset-carrier modulation techniques with applications in satellite navigation systems", Wiley *Wireless Communications and Mobile Computing*, Volume 7, Issue 6 (p 767-779), 2006.

[2] A. Burian, E. S. Lohan, and M. Renfors, "BPSK-like Methods for Hybrid-Search Acquisition of Galileo Signals", in CDROM *Proceedings of ICC 2006*, Turkey, Jun 2006.

[3] E. S. Lohan, "Statistical analysis of BPSK-like techniques for the acquisition of Galileo signals", in *AIAA Journal of Aerospace Computing, Information, and Communication*, vol3, May 2006, pp.234—243.

[4] E. Kaplan and C. Hegarty, Eds. "Understanding GPS – Principles and applications", Artech House, Boston, Second Edition, 2006.

[5] P. Fine, W. Wilson, "Tracking Algorithm for GPS Offset Carrier Signals", in *Proceedings of the 1999 National Technical Meeting of The Institute of Navigation*, San Diego, CA, pp. 671-676, January 1999.

[6] M. Hodgart, P. Blunt, M. Unwin, "The optimal dual estimate solution for robust tracking of Binary Offset Carrier (BOC) modulation", in *Proc. of ION GNSS*, 2007, pp. 1017–1027.

[7] P. Blunt, R. Weiler, M. Hodgart, "Demonstration of BOC(15, 2.5) acquisition and tracking with a prototype hardware receiver", in *Proc. of ENC GNSS*, May 2007.

[8] M. Navarro-Gallardo, G. Seco-Granados, G. López-Risueño, M. Crisci, "Code Smoothing for BOC Ambiguity Mitigation", in *Proc. International Conference on Localization and GNSS (ICL-GNSS)*, 2013.

[9] F. Schubert, R. Prieto-Cerdeira, A. Steingass, "GNSS Software Simulation System for Realistic High-Multipath Environments", *4th ESA Workshop on Satellite Navigation User Equipment Technologies (NAVITEC 2008)*, Noordwijk, The Netherlands

[10] M. Foucras, O. Julien, C. Macabiau, B. Ekambi, F. Bacard, et al.. Assessing the Performance of GNSS Signal Acquisition: New Signals and GPS L1 C/A Code. *Inside GNSS*, 2014, pp.68-79.

[11] J.A. Garcia-Molina, M. Navarro-Gallardo, G. Lopez-Risueño, M. Crisci, "Robust Unambiguous Estimation of High-Order BOC Signals: the DOME Approach", *NAVIGATION, Journal of the Institute of Navigation*, vol. 63, iss. 4, pp. 511-520, Dec. 2016.

[12] C. O'Driscoll, J.A. Ávila-Rodríguez, R. Ioannides, "Subcarrier Aided Code Tracking of High Order BOC Signals", in *Proc. of ION GNSS+ 2016*, (Portland, Oregon), Sept. 2016, pp.444-458.