EXECUTIVE SUMMARY REPORT

OLTBOC

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1.0	2022/11/11	19	First Issue for FR.
1.1	2023/02/09	20	Update of the documentation taking into account the following Actions from FR: - [AI-FR-18]: New section added, 6.2, with the recommendations for the way forward to the analysed techniques; - [AI-FR-19]: Update of the results from figure to tabular form in section 5.2. - [AI-FR-027]: Added in the conclusions, section 6. , the better robustness of the E5 Full AltBOC over the Meta E5aQ+E5bQ;

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. PURPOSE

The purpose of this document is to present a final report on the tasks carried out during the OLTBOC project, providing the reader with a complete, broad view of the full scope of activity.

1.2. SCOPE

Current version of this document is issued within the scope of Task4 of the OLTBOC project, posing as the Final Report (FR) for the activity.

1.3. DEFINITIONS AND ACRONYMS

1.3.1.DEFINITIONS

Concepts and terms used in this document and needing a definition are included in the following table:

Table 1-1 Definitions

Concept / Term	Definition

1.3.2.ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 Acronyms

Acronym	Definition
AC	Astrium Correlator
ACF	Autocorrelation Function
AltBOC	Alternative BOC
BGD	Broadcast Group Delay
BOC	Binary Offset Carrier
BPSK	Binary Phase Shift Keying
CmP	Code minus Phase
C/No	Carrier-to-Noise density ratio
CRLB	Crámer-Rao Lower Bound
CTE	Code Tracking Error
DCB	Differential Code Bias
DE	Double Estimator
DFT	Discrete Fourier Transform
DLL	Delay Lock Loop
DMS	Direct Meta-Signal
DOME	Double Optimization Multi-correlator-based Estimation
DOP	Dilution of Precision
DPDI	Differential Post-Detection Integration
DSB	Double Side-Band
EmL	Early minus Late
FDMA	Frequency Division Multiple Access

Acronym	Definition
FLL	Frequency Lock Loop
FPLL	Frequency assisted Phase Lock Loop
GNSS	Global Navigation Satellite System
GPDIT	Generalized Post-Detection Integration Truncated
GPS	Global Positioning System
HS	High Sensitivity
IF	Intermediate Frequency
ISC	Inter-Signal Corrections
KF	Kalman Filter
LS	Least Squares
MDR	Multipath to direct signal amplitude ratio
MEE	Multipath Error Envelope
ML	Maximum Likelihood
NCO	Numerically Controlled Oscillator
NPDI	Non-coherent Post-Detection Integration
NWPR	Narrowband-Wideband Power Ratio
PDI	Post-Detection Integration
PLL	Phase Lock Loop
PNT	Position, Navigation and Time
PPP	Precise Point Positioning
PRN	Pseudo-Random Noise
PSD	Power Spectral Density
PVT	Position, Velocity and Time
RF	Radio Frequency
RMS	Root Mean Square
RTK	Real-time kinematic
SA	Selective Availability
SBT	Side-band Translation
SD	Squaring Detector
SISRE	Signals in Space Ranging Error
SNR	Signal to Noise Ratio
SSB	Single Side Band
SSP	Standard/Single Point Positioning
STD	Standard Deviation
SW	Software
TOA	Time of Arrival
UEE	User Equipment Error
URE	User Equivalent Range Error
VCO	Voltage Controlled Oscillator
WP	Work Package

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	Statement of Work (SoW)	ESA-TRP-TEC-SOW-009648	1.0	31/07/2018
[AD.2]	Proposal entitled "Open Loop Techniques for High Sensitivity GNSS Receivers applied to BOC Signals"	GMV 13019/18 V1/18	1.0	09/10/2018
[AD.3]				
[AD.4]				
[AD.5]	OLTBOC – D3 – Design Definition and Justification File	TBD	1.4	15/06/2021
[AD.6]	OLTBOC – D4 – SW Receiver Test Plan	TBD	1.5	16/03/2022
[AD.7]				
[AD.8]				

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.1]	J. L. Issler, M. Paonni, and B. Eissfeller, "Toward centimetric positioning thanks to L- and S-band GNSS and to meta-GNSS signals", Proc. ESA NAVITEC, pp. 1–8, Dec. 2010.			2010
[RD.2]	GSA, "World's First Dual-Frequency GNSS Smartphone Hits the Market, June 4, 2018, URL: https://www.gsa.europa.eu/newsroom/news/world-s-first-dual-frequency-gnss-smartphone-hits-market (accessed on May 2019).			2018
[RD.3]	M. Paonni, J. T. Curran, M. Bavaro, J. Fortuny-Guasch "GNSS Meta-signals: Coherently Composite Processing of Multiple GNSS Signals", Proc. ION GNSS+, pp. 2592-2601, 2014.			2014
[RD.4]	J. W. Betz, *Engineering Satellite-Based Navigation and Timing*, Wiley IEEE Press, 2016.			2016
[RD.5]	W. de Wilde, J.-M. Sleewaegen, K. Van Wassenhove, F. Wilms, "A First-of-a-kind Galileo Receiver Breadboard to Demonstrate Galileo Tracking Algorithms and Performances", Proc. ION GNSS, pp. 2645-2654, Sept. 2004.			2004
[RD.6]	M. Navarro Gallardo, G. López-Risueño, M. Crisci, G. Seco-Granados, "Code-Subcarrier Smoothing for Code Ambiguity Mitigation", *Proc. AIAA International Communication Satellite Systems Conference (ICSSC)*, October.			2013

3. META SIGNALS CONCEPT DEFINITION

The term "meta-signal" was originally coined in [RD.1] as a bundle of signals lying at different carrier that are considered as a whole ensemble. This concept appeared in the context of GNSS carrier phase ambiguity resolution, where the use of signals at different frequencies is of the utmost importance. This approach has been widely adopted by many professional receivers by combining GPS L1 and L2 signals to resolve carrier phase ambiguity. Recently, the trend has been pushed down to the mass-market arena due to the emergence of dual-frequency GNSS chipsets for smartphones, capable of providing GNSS measurements at L1/E1 and L5/E5 [RD.2]. The idea originally proposed in [RD.1] was to exploit GNSS signals whose carrier frequencies were an integer multiple one of the other, since this greatly simplifies the carrier phase ambiguity resolution.

Thus, [RD.1] proposed the use of a future GNSS signal in S-band placed at 2485.89 MHz and a "composite" or "meta-signal" in L-band placed at the central frequency 1245.875 MHz. The latter is exactly half way between the Galileo E5b and the Galileo E6 signals, which thus would become the individual components a meta-signal with central frequency at 1245.875 MHz. Each of these components would be at +/- 38.805 MHz from the central frequency, which is actually 35 times a reference frequency of 1.023 MHz. This means that the meta-signal composed the Galileo E5b and Galileo E6 signals could be understood as an equivalent AltBOC signal with a subcarrier frequency ratio equal to 35 (wrt to the nominal 1.023 MHz). A similar approach could also be followed by considering the Galileo E5a and the Galileo E6 signals as a meta-signal with central frequency at 1227.60 MHz, thus requiring the use of a future GNSS signal in S-band placed at twice this frequency. In this case the individual Galileo E5a and Galileo E6 signals would be at +/- 51.15 MHz from the central frequency, which thus could be understood as an AltBOC signal with a subcarrier frequency ratio equal to 50. Both examples are illustrated in Figure 3-1 for the sake of clarity.

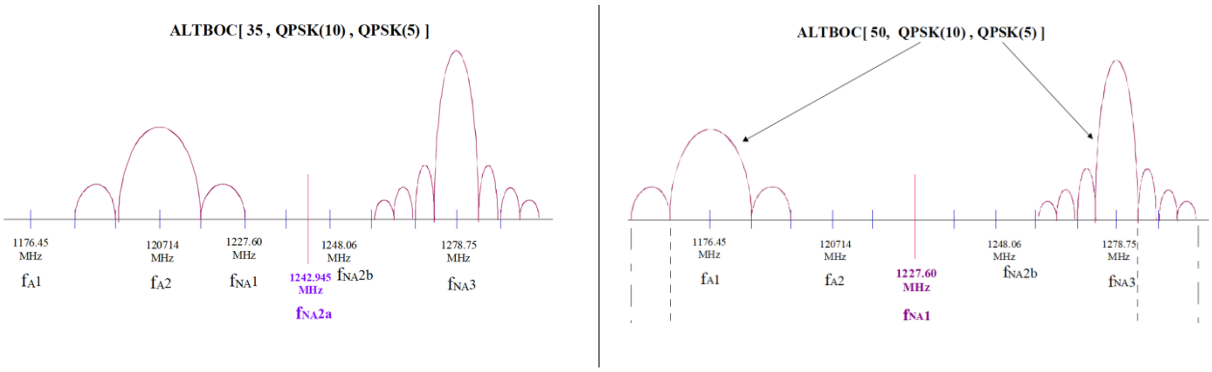

Figure 3-1. Example of two different meta-signals by considering either the ensemble of Galileo E5b with Galileo E6 signals (left) or Galileo E5a with Galileo E6 signals (right) [RD.1].

The fundamental concept of a GNSS meta-signal was later considered in [RD.3] as a way to obtain an equivalent signal with a much higher mean-square bandwidth than none of their individual signal components. This can be clearly seen in the previous Figure 3-1 where the spectral occupation of the illustrated meta-signals (and thus the mean-square bandwidth) is much higher than none of the individual signals. This approach would allow the use of new signals (i.e. meta-signals) providing a much higher accuracy than conventional signals, thus potentially becoming a competitive alternative to carrier phase positioning.

Apart from the actual achievable performance of meta-signals, another aspect that deserves further investigation is that regarding the processing of meta-signals. Because of the similarities between the latter and AltBOC signals, the same processing approaches already adopted for AltBOC processing seem to be applicable to meta-signals as well. In particular, the divide-and-conquer approach whereby individual signals are processed first and once being tracked, they are combined coherently to (ideally) achieve the same performance than the one that would be obtained in case they had been processed jointly, all at a time.

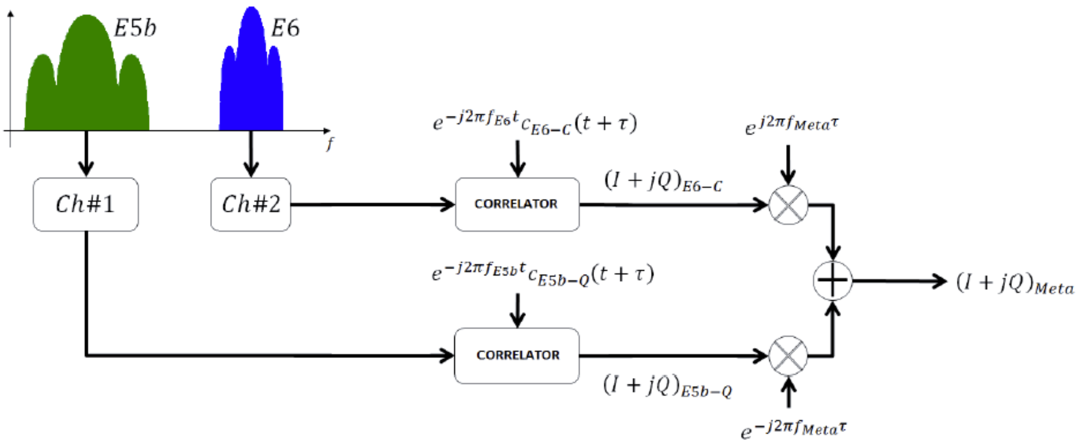

Figure 3-2: Divide-and-conquer approach for tracking a Galileo E5b+E6 meta-signal [RD.3].

4. PROCESSING OF META-SIGNALS – SLL APPROACH

The SLL approach to track a meta-signal is depicted in the next figure:

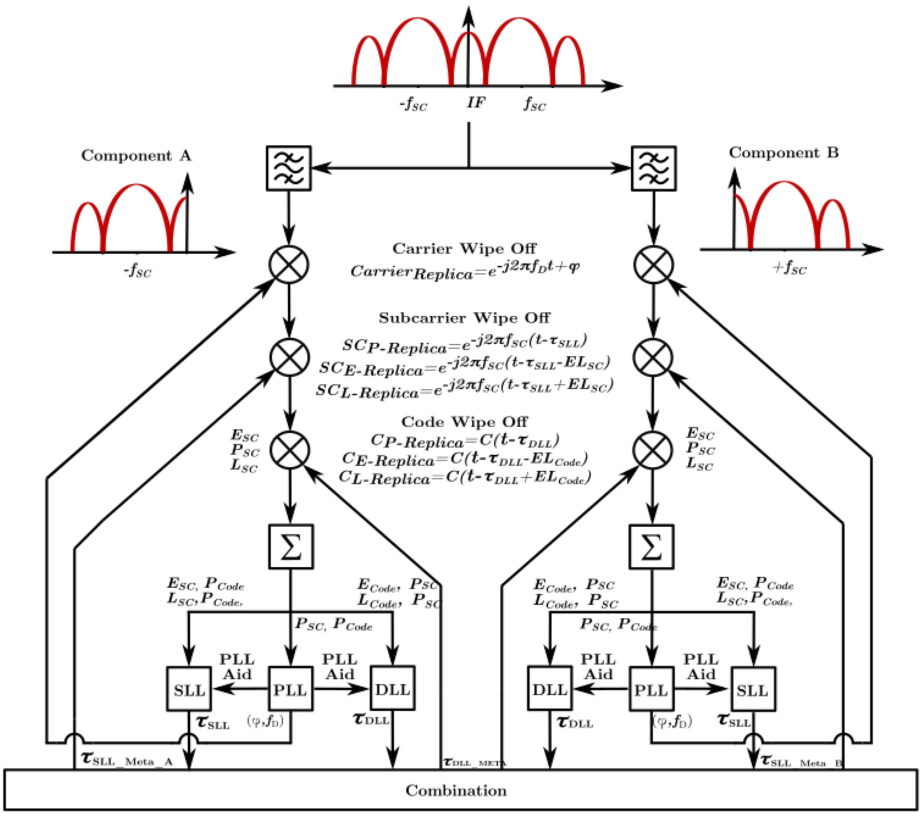

Figure 4-1 SLL Approach for Meta-Signal Tracking.

On the SLL approach, each component of the input signal will be tracked individually. On the previous figure these components are described as Side A, Side B and Meta Side. Side A and B will have its own PLL, DLL and SLL whereas the Meta Side will have only a DLL and SLL.

The individual estimates of each side DLL and SLL are then combined in order to have the most precise unambiguous estimate.

The meta estimate is done by taking Side A and Side B DLL and SLL discriminator outputs and then combine those estimates on the meta-DLL and SLL. These combinations are depicted in the next figures:

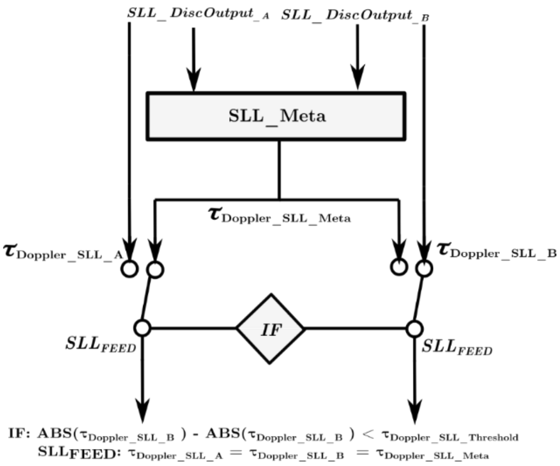

Figure 4-2 SLL Approach - SLL Meta-Signal Combination.

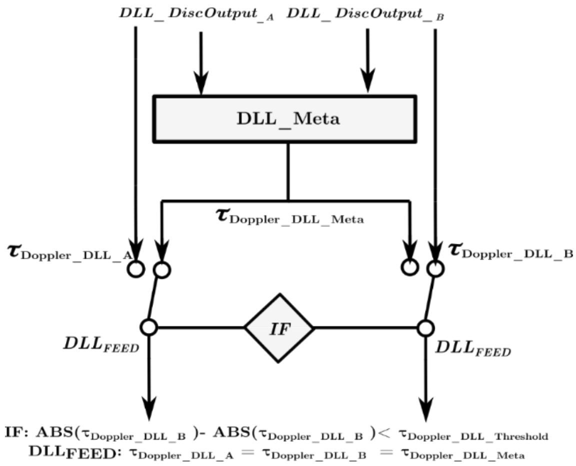

Figure 4-3 SLL Approach - DLL Meta-Signal Combination.

The Meta tracking both on the SLL and DLL will be performed as an averaging of the output of the discriminators of both Side A and Side B as depicted on the previous figures.

The DLL and SLL estimates on all sides (A, B and Meta) are combined to form a more precise estimate, taking into account the unambiguity of the DLL and the precision of the SLL.

The combination of the measurements can be performed making use of a hatch filter depicted in the next figure:

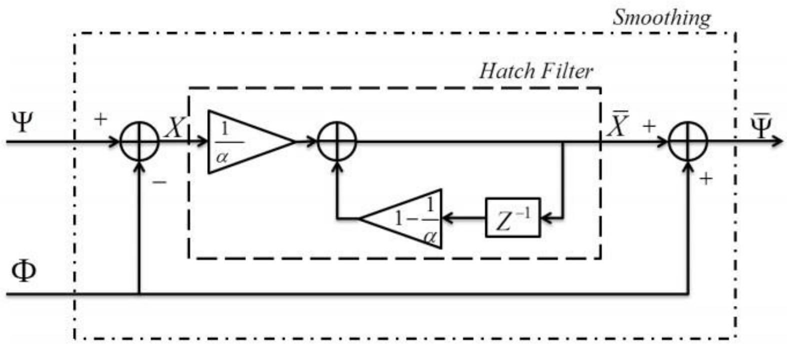

Figure 4-4: Block diagram of the smoothing with the hatch filter.

The Hatch filter will combine the SLL and DLL estimates taking into account the block diagram of Figure 4-4. The parameter alpha will be 0.5 at the beginning of the simulation (in order for the unambiguous estimation to have more weight and quickly lead the combination to the right peak). At second 4 the alpha will go to 3000 in order to have more stable measurements and make total use of the SLL precision.

The variables used to compute the PVT solution are the combined estimate and the DLL code estimate.

5. PERFORMANCE TEST RESULTS

In order to fully assess the added value of the proposed techniques, two main set of tests were defined. The first ones are related to controlled environments, in which, the signals are synthetic and the environments very controlled, with multipath, ionosphere and noise injection into the signals to assess the sensitivity and the limits of the techniques. The second set of tests are performance tests, in real conditions, processing real signals, providing a feel of how the techniques behave in both urban and open sky environments. The PVT results shown

Next are presented the tests performed and the main conclusions drawn from such analysis.

5.1. UNIT TEST

The unit tests aimed at carefully identify the working limits of the techniques under different circumstances. To this aim, synthetic signals were used, so the environment is fully controlled and the conclusions extracted can be pinpointed. Because of the use of synthetic signals, the Meta E5bQ+E6C will not be under analysis, nevertheless, all the other modulations/techniques will be evaluated under the following scenarios:

- **CRLB Analysis**

  The main purpose of this test is to assess the performance of the techniques in static conditions. For this matter, a single satellite with the CN0 profile presented in [AD.4] for a static receiver was simulated.

  The main findings from the CRLB analysis is the good agreement between the experimental and theoretical values as can be seen on the next figure.

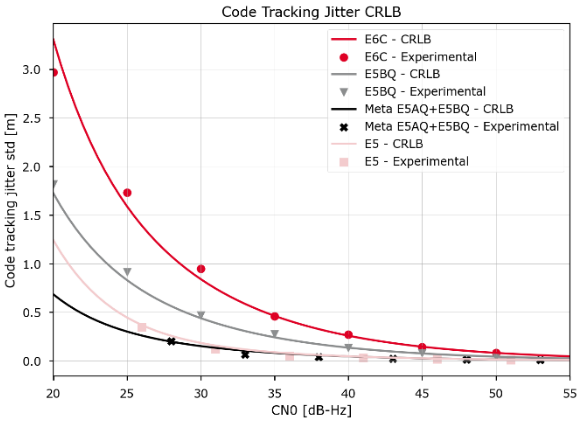

Figure 5-1: CRLB comparison for the stairs profile.

  Also from the CRLB analysis it was noticed that the first technique to lose lock was the Meta E5aQ+E5bQ, the Meta signal's SLL discriminator has to be a coherent discriminator. This means that it is greatly dependant on the PLL phase estimation. For very low CN0s, the phase estimation becomes really noisy which compromises the SLL's capability of maintaining lock.

- **Sensitivity Analysis**

  In this test, the sensitivity of the previous modulations will be studied. Namely, how far in terms of noise these techniques are able to track the incoming signal, in two different environments, the first is static and the second dynamic.

  The same conclusions shown in the CRLB analysis can be taken for the sensitivity, with the Meta E5aQ+E5bQ not being able to track at 20dB-Hz while all of the other techniques are able. Additionally, the proposed dynamics have a marginal impact on the loops performance since the estimates are similar between both scenarios.

- **Multipath Analysis**

This tests' purpose is to study the impact that the multipath has on the tracking loop estimations. Two scenarios were defined, one where a fixed user is considered and a second one with a vehicular user instead. All the scenarios include a single satellite with CN0=45dB-Hz.

From the multipath analysis, the pseudorange error will be shown next for the single satellite:

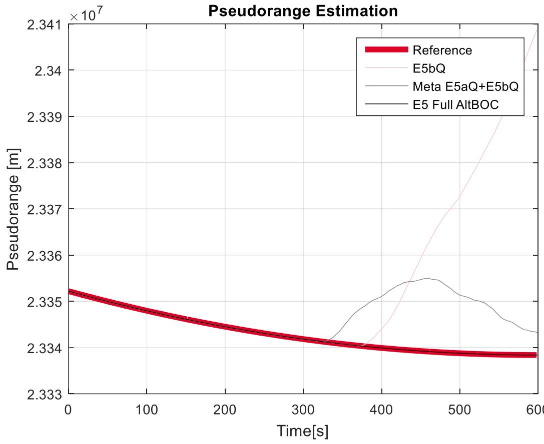

Figure 5-2: Pseudorange Estimation for Multipath Fixed User.

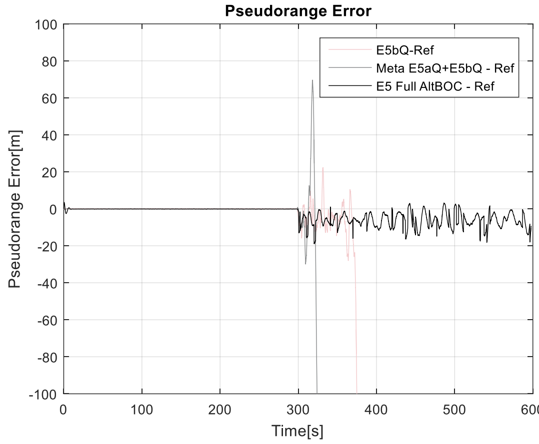

Figure 5-3: Pseudorange Estimation Error for Multipath Fixed User.

From the previous figure is seen that the Meta technique is the first technique to lose track, closely followed by the SSB that is able to sustain track for an extra 60 seconds. However, the full AltBOC modulation never loses track, maintaining good pseudoranges estimations. This behaviour corroborates the previous analysis and also demonstrates that the full AltBOC technique is the more robust modulation mainly due to the extra power gained.

The main difference from the static to the vehicular scenario is the fact that the E5BQ SSB loses track at the same time of the Meta Technique. So again, the dynamics do not present an important role in terms of performance degradation.

- **Ionospheric Analysis**

  This tests' purpose is to study the impact that the ionosphere has on the tracking loop estimations, mainly the impact on the Meta since two bandwidths are combined. Three scenarios were defined, one where the ionosphere is not present, a second one with a mild ionospheric delay and the last with a severe ionospheric delay.

  It was found that the ionospheric intensity does not have an impact in the loops performance which present the same absolute value of the correlation prompt for the different ionospheric values.

- **PVT Analysis**

  The purpose of this test is to assess the PVT performance of the different techniques. Two environments were defined. The first one with a static user while the second one has a vehicular user. Each signal was processed by the receiver, which generated a RINEX file with the outputs. The RINEX file, along with the navigation RINEX file provided by the signal generator, was then fed into the PVT Engine to produce the Solution.

  From the analysis, the E6C is the worst performing modulation due to its lower chipping rate. There is a slight improvement when using E5BQ, however, the biggest improvement is seen for the Meta E5AQ+E5BQ and E5 modulations due to their higher chipping rate as well as higher CN0. For this scenario, the difference between these two modulations appears to be residual and can be attributed to the higher CN0 of the latter. On the other hand, please remember that the E5 modulation is using a lower coherent integration time. Additionally, the dynamics, once again, have a marginal effect in terms of the tracking loops performance.

5.2. PERFORMANCE TESTS

- **Static Open Sky**

The main purpose of this test is to assess the performance of the different techniques in a static open sky scenario. It is the simplest scenario a real receiver can be put through.

For this purpose, a signal was recorded on the rooftop of GMV Madrid in Tres Cantos. The signal was recorded approximately at 2022-05-26 11:46:07 UTC.

On the next figure can be seen the code jitter present at the output of the tracking loops, by computing the third order difference:

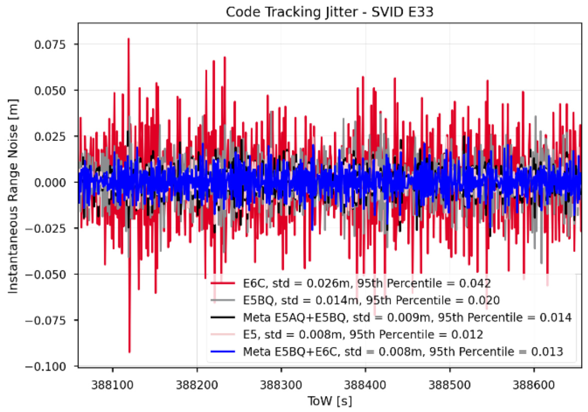

Figure 5-4: Code tracking Jitter for E33 in the OS scenario.

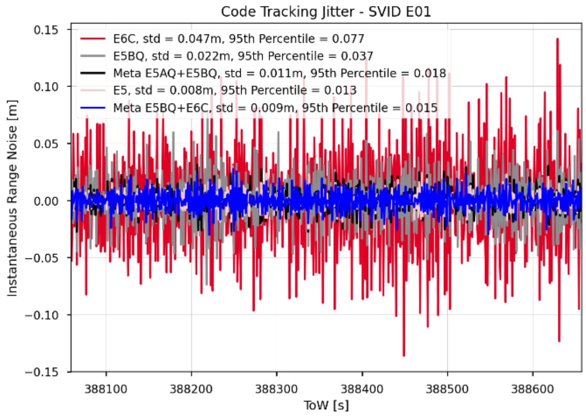

Figure 5-5: Code tracking Jitter for E01 in the OS scenario.

It was found that The modulations with a higher CN0 and chipping rate present a lower jitter corroborating, once more, the results present in the unit tests. Analysing the innovative techniques, the results obtained with Meta E5BQ+E6C are similar to the ones obtained with E5 and Meta E5AQ+E5BQ. The explanation for this behaviour lies in the fact that we are in the presence of a static scenario with very good conditions (open sky). Therefore, the CN0 levels are already high enough such that increasing the chipping rate doesn't seem to provide any major improvement.

Regarding the PVT solutions, it is possible to acknowledge an increase in accuracy performance going from the GPS L1 C/A + Galileo E1C + E5BQ combination to the GPS L1 C/A + Galileo E1C + Meta E5AQ+E5BQ or GPS L1 C/A + Galileo E1C + Meta E5BQ+E6C. These results are much better than the ones obtained for Ublox F9P. However, it is important to keep in mind that the Ublox solution only employs the GPS L1CA and Galileo E1C measurements and is not as tuned for a static scenario as the GMV Receiver.

- **Urban Dynamic Scenario**

For this scenario, a signal recorded near GMV in Tres Cantos, Madrid at 2022-07-20 09:21:07 UTC was processed for 10 minutes. On the next figure is present the code jitter (obtained making use of the third order difference metric) 95th percentile along with the STD:

Table 5-1 Code Tracking Jitter in the urban dynamic scenario - STD

Receiver	Satellite	E1C [m]	E5a-Q [m]	E5b-Q [m]	E5aQ+E5bQ [m]
XRC	E02	0.555	0.118	0.119	0.057
	E07	0.373	0.117	0.111	0.035
	E08	0.531	0.098	0.091	0.053
	E12	0.696	0.097	0.118	0.068

Receiver	Satellite	E1C [m]	E5a-Q [m]	E5b-Q [m]	E5aQ+E5bQ [m]
	E25	1.187	0.2	0.191	0.114
	E26	1.034	0.163	0.174	0.115
	E30	0.712	0.14	0.136	0.075
	E33	0.801	0.155	0.153	0.1
Ublox	E02	1.193	N/A	0.585	N/A
	E03	0.825	N/A	0.321	N/A
	E05	1.307	N/A	0.608	N/A
	E09	1.643	N/A	0.645	N/A
	E13	1.154	N/A	0.465	N/A
	E15	0.35	N/A	0.137	N/A
	E21	1.187	N/A	0.575	N/A
	E27	0.422	N/A	0.204	N/A
	E30	0.355	N/A	0.183	N/A
	E34	0.268	N/A	0.123	N/A
	E36	1.502	N/A	0.649	N/A

Table 5-2 Code Tracking Jitter in the urban dynamic scenario – 95th Percentile

Receiver	Satellite	E1C [m]	E5a-Q [m]	E5b-Q [m]	E5aQ+E5bQ [m]
XRC	E02	0.889	0.199	0.194	0.09
	E07	0.586	0.181	0.168	0.057
	E08	0.806	0.163	0.152	0.089
	E12	0.96	0.088	0.092	0.051
	E25	1.937	0.285	0.275	0.175
	E26	1.637	0.283	0.291	0.194
	E30	1.008	0.215	0.208	0.114
	E33	1.342	0.26	0.246	0.166
Ublox	E02	2.02	N/A	0.846	N/A
	E03	1.215	N/A	0.334	N/A
	E05	1.984	N/A	0.86	N/A
	E09	2.781	N/A	1.006	N/A
	E13	1.785	N/A	0.503	N/A
	E15	0.383	N/A	0.166	N/A
	E21	2.133	N/A	0.909	N/A
	E27	0.581	N/A	0.185	N/A
	E30	0.367	N/A	0.194	N/A
	E34	0.221	N/A	0.153	N/A
	E36	2.615	N/A	0.97	N/A

Out of all modulations, the E1C is the worst performing for both satellites due to its lower chipping rate followed by E6C and then E5BQ. All the other modulations and techniques used improve the performance but their individual accuracy is very similar, with the 95th percentile of the Meta E5aQ+E5bQ of 0.1m and the full E5 very similar to the Meta E5bQ+E6C performance with a slight advantage when compared with the Meta E5aQ+E5bQ. The main conclusions from the previous results is that the E5 AltBOC, and the Meta's outperform the E5bQ, but the performance difference between them is very similar, as previously seen in the Static Open sky scenario

If the analysis is focused without the initial period, the performance of the XRC+MSP3 is very similar to that presented by Ublox+MSP3. If we consider the exact same modulations, the 95th percentile for Ublox_E1C_L1CA_E5bQ is very close to XRC_L1_E1C_E5bQ. It is important to notice that both Ublox and XRC pseudoranges were processed by MSP3 PVT Engine, this way the comparison is fair in terms of pseudoranges. This means that the tracking is being well performed (results in line with ublox).

- **Rural Scenario**

In the following scenario the performance regarding the ESA rural scenario is analysed. It consists of a vehicular user moving in Nieuw-Vennep (The Netherlands) from 08:58 –11:25 GPST on the 22/01/2021. However, for this test, only the first 30 minutes were considered.

On the next figure is present the code jitter (obtained making use of the third order difference metric) 95th percentile along with the STD:

Table 5-3: Code Tracking Jitter in the Rural scenario - 95th Percentile.

	Code Tracking Jitter 95th Percentile			
Receiver	Satellite ID	E5b-Q [m]	E5a+b-Q [m]	E5a+b-I + E5a+b-Q [m]
XRC	E02	0.089	0.073	0.064
	E07	0.055	0.038	0.036
	E08	0.079	0.067	0.065
	E25	0.132	0.121	0.095
	E26	0.133	0.113	0.092
	E30	0.1	0.088	0.081
	E33	0.125	0.108	0.095
Ublox	E02	0.103	N/A	N/A
	E03	0.326	N/A	N/A
	E07	0.081	N/A	N/A
	E08	0.08	N/A	N/A
	E12	0.029	N/A	N/A
	E13	0.114	N/A	N/A
	E25	0.112	N/A	N/A
	E26	0.11	N/A	N/A
	E30	0.092	N/A	N/A
	E33	0.101	N/A	N/A

Table 5-4: Code Tracking Jitter in the Rural scenario - STD.

Code Tracking Jitter STD				
Receiver	Satellite ID	E5b-Q [m]	E5a+b-Q [m]	E5a+b-I + E5a+b-Q [m]
XRC	E02	0.056	0.046	0.042
	E07	0.033	0.023	0.022
	E08	0.048	0.042	0.039
	E25	0.084	0.077	0.062
	E26	0.28	0.27	0.058
	E30	0.064	0.056	0.051

Code Tracking Jitter STD				
	E33	0.145	0.177	0.057
Ublox	E02	0.103	N/A	N/A
	E03	0.326	N/A	N/A
	E07	0.081	N/A	N/A
	E08	0.08	N/A	N/A
	E12	0.029	N/A	N/A
	E13	0.114	N/A	N/A
	E25	0.112	N/A	N/A
	E26	0.11	N/A	N/A
	E30	0.092	N/A	N/A
	E33	0.101	N/A	N/A

The single band E5BQ remains the worst performing modulation throughout all the simulation. The E5 modulation performs slightly better than the Meta E5AQ+E5BQ due to its higher CN0, as seen on the previous tests. When comparing the XRC pseudorange performance with the one provided by Ublox, once again, the code tracking outputs of the XRC modulations are more precise with a lower 95th percentile, but much in line with the ones provided by Ublox. **T**

Regarding the PVT solution, the added value from the SSB E5bQ to the Meta techniques is marginal, however there is an improvement in terms of the 95th percentile. On top of that the mean value also increases from the E5bQ SSB to the meta techniques, which leads to a higher 95th percentile and meaning that the PVT Engine to fully process meta signal needs a very high fine tune in order to fully explot the modualtiosn. For the overall results, the ublox solution provides more accurate results than all of the processed solutions.

- **Urban Scenario**

  For this scenario a signal recorded near GMV in Tres Cantos, Madrid at 2022-08-04 09:32:57 UTC was processed for 10 minutes. On the next figure is present the code jitter (obtained making use of the third order difference metric) 95th percentile along with the STD:

Table 5-5 – XRC Code Tracking Jitter - STD

Receiver	Satellite	E1C	E6C	E5b-Q	E5a+b-Q	E5a+b-I + E5a+b-Q	E5bQ+E6c
XRC	E10	1.572	0.575	0.469	0.733	0.627	0.386
	E11	1.545	0.827	0.495	0.445	0.481	0.653
	E12	0.985	0.349	0.207	0.224	0.198	0.214
	E24	1.814	1.051	0.618	0.702	0.666	0.716
	E25	1.846	0.855	0.422	0.56	0.377	0.507
	E31	1.1	0.356	0.354	0.229	0.139	0.267
	E33	1.626	0.723	0.519	0.459	0.491	0.641
Ublox	E10	1.288	NA	0.812	NA	NA	NA
	E11	1.385	NA	0.165	NA	NA	NA
	E12	0.317	NA	0.286	NA	NA	NA
	E19	1.284	NA	0.047	NA	NA	NA
	E24	1.613	NA	0.989	NA	NA	NA
	E25	1.508	NA	1.039	NA	NA	NA
	E31	0.498	NA	0.417	NA	NA	NA
	E33	1.078	NA	0.623	NA	NA	NA

Table 5-6 - XRC Code Tracking Jitter - PERCENTILE95

Receiver	Satellite	E1C	E6C	E5b-Q	E5a+b-Q	E5a+b-I + E5a+b-Q	E5bQ+E6c
XRC	E10	2.89	0.71	0.365	0.786	0.387	0.106
	E11	3.106	0.97	0.351	0.374	0.133	0.176
	E12	1.602	0.406	0.25	0.116	0.082	0.067
	E24	3.569	1.669	0.38	0.701	0.216	0.646
	E25	3.514	1.074	0.409	0.398	0.124	0.101
	E31	1.974	0.488	0.328	0.242	0.125	0.122
	E33	3.524	0.746	0.221	0.198	0.099	0.124
Ublox	E10	2.275	NA	1.225	NA	NA	NA
	E11	2.485	NA	0.11	NA	NA	NA
	E12	0.228	NA	0.152	NA	NA	NA
	E19	2.046	NA	NA	NA	NA	NA
	E24	2.88	NA	1.388	NA	NA	NA
	E25	2.708	NA	1.638	NA	NA	NA
	E31	0.484	NA	0.201	NA	NA	NA
	E33	1.383	NA	0.625	NA	NA	NA

Taking into account the previous tables, it is possible to attest the added value in terms of code jitter when going from the E5bQ modulation to the Meta techniques and the full AltBOC. Once again, as seen in all previous test cases, the performance of the Meta techniques and full AltBOC is very similar, without any major difference between them. Nevertheless there is a small gain of performance when comparing the E5AQ+E5bQ Meta with the E5BQ+E6C Meta and Full AltBOC.

When comparing the XRC performance with Ublox, for the E5bQ modulation the code tracking jitter is in line, attesting a good tracking of the modulation. This means that the added value of the Meta techniques and full AltBOC is seen, providing a lower code tracking jitter than the one seen in Ublox.

Regarding the added value of the Meta techniques in the PVT domain, when compared with the E1C+E5bQ case, the added value is marginal (with a gain of approximately 10% for E5 Full AltBOC and Meta E5aQ+E5bQ). It seems that the main driver for the high accuracy PVT values is more related with the robustness of the tracking loops and the number of satellites, since the pseudoranges are similar between XRC and Ublox but this last is able to provide a more robust tracking as seen previously. On top of that, also for the Ublox case, the added value of double frequency is marginal when compared with single E1C frequency tracking which can be mostly related with the PVT engine, more than the code tracking loops itself, since this result is the same for both XRC and Ublox pseudorange values.

6. MAIN CONCLUSIONS AND NEXT STEPS

6.1. CONCLUSIONS

In the following section are described the main conclusions taken from the unit and performance testing:

- **The Meta techniques with the current implementation (SLL Approach) do not provide an added robustness despite the higher CN0 estimated when compared with the single side band tracking of the E5bQ;**

  Throughout the many simulations performed, both in very controlled environments (unit test) making use of synthetic signals and in real conditions, the robustness provided by the Meta techniques is at the same level of the E5bQ processing. The main factor for this is the use of a coherent discriminator for the SLL, meaning that the SLL is greatly dependant of the PLL phase estimations. For low CN0's the phase estimate becomes really noisy (and most of the times is the first component to enter in Loss of Lock) compromising the SLL's ability of maintaining lock.

- **The Meta techniques are more accurate in terms of code jitter than the E5bQ SSB and have a very similar performance to that of the E5 Full AltBOC;**

  Taking into account the unit testing and the performance tests, if the code tracking performance is taken into account, the jitter is lower for the Meta techniques when compared with the single side band of the E5bQ. This was to be expected taking into account the CRLB analysis, and is seen both in the unit testing and also in the performance testing with real signals. Additionally, if the E5 Full AltBOC is taken as the reference for the most accurate technique, the Meta techniques provide very similar estimates with marginal differences in terms of code tracking accuracy.

- **Under multipath conditions the Meta techniques do not bring any advantage in terms of robustness;**

  As previously seen, under multipath conditions the same conclusions regarding the robustness of the Meta techniques still applies. The Meta techniques are the first to lose lock, not providing any added benefit over the single side band processing of E5bQ.

- **Dynamics have a marginal impact on the performance of the code tracking loops of the Meta techniques;**

  The performance of the Meta techniques is the same either with or without user dynamics. This fact was seen throughout the unit tests, with marginal performance differences (for all the tested modulations) between a static and dynamic user.

- **Ionosphere does not have an impact in the performance of the tracking loops for the Meta techniques;**

  As seen in the ionosphere analysis, the tracking loops performance is the same for the different tested ionosphere configurations (low, mild and severe). This way the ionospheric effects do not degrade the Meta techniques processing with the SLL approach.

- **Accuracy of the E5bQ+E6C Meta is the same as E5aQ+E5bQ and full AltBOC processing;**

  Despite the expected accuracy of the Meta E5bQ+E6C being higher than the other Meta technique or even the full AltBOC, in the performance tests this is not visible, both in the code tracking performance and in the PVT final solution.

- **In static Open Sky Conditions the performance of the Meta techniques in terms of accuracy is better than E5bQ SSB**

  For a static open sky scenario, the performance of the Meta techniques is in line with the full AltBOC processing, this taking into account the PVT estimations. Meaning that for these semi perfect conditions the performance seen at tracking level translates to PVT.

- **In Urban environments the accuracy performance in terms of PVT of the Meta signals is marginally better than E5bQ SSB**

When urban environments are considered, the added value in terms of precision of the meta techniques is marginal when compared with the E5bQ SSB tracking. In this very demanding scenarios it is very important to have a high robustness in order to fully extract the value of the techniques (as seen in the OS scenario). Since the meta techniques are not more robust than the E5bQ SSB, the improved performance in terms of PVT solution is not seen, because the PVT estimation relies heavily on the E1 band (since pseudoranges from the Meta techniques are not available).

- **E5 Full AltBOC is the most robust technique**

  Throughout the performed tests, the E5 Full AltBOC proved to be the most robust technique. When analysing the accuracy performance, the Meta E5aQ+E5bQ is very close to the full E5 AltBOC technique, but the same is not true when analysing the robustness. In the unit testing, under very controlled environments, the E5 Full AltBOC managed to sustain its tracking whereas all of the other techniques were unable to do so. Also in the performance tests, the E5 Full AltBOC proved to be the most robust technique with a higher availability than all of the other modulations which was expected taking into account the results coming from the unit testing.

6.2. NEXT STEPS

The way forward for the increase of the techniques performance should focus on the following points:

- **Provide Robustness to the Meta Techniques**

  As seen throughout the different scenarios, one of major points to be addressed is the lack of robustness of the meta techniques when compared with the state of the art ones. In order to increase this robustness it is proposed a hybrid solution between the SLL use and the DLL. When environmental conditions are deteriorated the use of the SLL can be dropped relying only on the DLL. Despite the less accurate estimation of this solution, the robustness is guaranteed and tracking can be sustained for longer.

- **Add a Virtual Correlator**

  Due to the high frequency spacing between the different components of the meta signal, for the sampling frequency to be enough in order to guarantee a perfect placement of the EmL correlators it needs to be extraordinary high, not suitable, for example, for mass market receivers. In order to circumvent this, it is proposed the implementation of a virtual correlator allowing "sub sample" placement of the correlators, providing the perfect spacing for tracking.

With the previous suggestions, the techniques are expected to improve its behaviour in terms of performance, both in accuracy and robustness, reaching even closer to the E5 Full AltBOC performance levels.