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Test of the filter design effect on Evil Waveform monitoring in SBAS

for Galileo E1 and E5a signals

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BIOGRAPHY

Ikhlas Selmi is currently part of the Signal processing and NAVigation (SIGNAV) research axis of TELECOM team at ENAC. She graduated as engineer in Telecommunication and Signal Processing from ESIEE. She received her Ph.D. in 2013 from Telecom SudParis on mitigating GNSS interference between indoor and outdoor signals. She is currently working on GNSS signal distortion generated by the satellite payload.

Paul Thevenon graduated as electronic engineer from Ecole Centrale de Lille in 2004 and obtained in 2007 a research master at ISAE in space telecommunications. In 2010, he obtained a PhD degree in the signal processing laboratory of ENAC in Toulouse, France. From 2010 to 2013, he was employed by CNES, the French space agency, to supervise GNSS research activities and measurement campaigns. Since the July 2013, he is employed by ENAC as Assistant Professor. His current activities are GNSS signal processing, GNSS integrity monitoring and hybridization of GNSS with other sensors.

Christophe Macabiau graduated as electronics engineer in 1992 from the ENAC in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D in 1997 and has been in charge of the signal processing lab of ENAC from 2000 to 2012. He is currently the head of the TELECOM team of ENAC.

Olivier Julien is a Senior Principal Engineer in u-blox AG, Switzerland since December 2018. He was the head of the Signal Processing and Navigation (SIGNAV) research group of the TELECOM laboratory of ENAC, in Toulouse, France. He received his engineer degree in 2001 in digital communications from ENAC and his PhD in 2005 from the Department of Geomatics Engineering of the University of Calgary, Canada. His research interests are turned towards the use of satellite-based navigation systems for safe navigation.

Mikael Mabilieu is a standardisation engineer on SBAS in the EGNOS exploitation team of the European GNSS Agency (GSA). Since his graduation as engineer from the French civil aviation school (ENAC) in 2006, he has been involved in GNSS standardization activity carried by the main civil aviation standardisation bodies such as the EUROCAE WG 62 on Galileo, RTCA Special Committee 159 on GPS and the International Civil Aviation Organisation (ICAO) Navigation System Panel in charge of ICAO standard. Mikael is involved in the evolution of GNSS concepts (ARAIM and SBAS L1L5) supporting the development of the associated standards (SARPs and MOPS) for use in aviation.

Jaron Samson has been working as a System Engineer at ESA's EGNOS Project Office in Toulouse (France) since 2012. Prior to 2012, he worked as a Navigation Engineer at ESA's Technical Centre (ESTEC), supporting Galileo, EGNOS and the GNSS Evolutions Program. Jaron holds an M.Sc-degree in Physical and Mathematical Geodesy from Delft University of Technology (The Netherlands).

ABSTRACT

Evil Waveforms (EWF) are non-nominal distortions that can be observed on satellite signals and cause additional bias on the estimated user position. A Threat Model (TM) has been proposed by ICAO for GPS L1 C/A to describe the possible distortions that can be observed on the GPS signals [1]. This Threat model is also adopted for Galileo E1-C and E5a-Q signals. A previous paper focused on the Signal Quality Monitoring (SQM) design and compliance test for Galileo signals. In the present paper, the effect of the pre-correlation filter design applied at the aircraft and reference station receivers on the EWF induced bias and SQM compliance test is assessed. Two aspects of the filter design are considered: the filter center frequency shift due to temperature variation or electronic component aging, and the filter gain roll-off out of the filter bandwidth. The obtained results of EWF differential biases and SQM test in [2] are

considered as the baseline results used to evaluate the effect on the tested filter parameters. This paper concludes on the tolerable center frequency offset and gain roll-off based on the comparison of the obtained EWF results for Galileo E1 and E5a to the baseline one.

INTRODUCTION

The so-called Evil Waveform (EWF) [3] are signal distortions that occur at the satellite level due to payload failure. The first important GNSS EWF was observed in 1993 and other cases [4] occurred recently confirming the potential integrity and continuity risk of this type of signal anomaly. To characterize those distortions and protect civil aviation users from their effect, three threat characterizations, also known as Threat Models (TM), were adopted in 2001 by ICAO for GPS L1 C/A [5]. They are classified in three categories: TM-A, TM-B and TM-C. TM-A is associated with a failure in the Navigation Data Unit. It appears on the C/A code as a leading or lagging falling edge on all the positive chips with respect to their expected end-time. TM-B models degradation in the analog section of the satellites by an amplitude modulation applied to the correct signal. It can be also seen as the output of a second order system taking the nominal C/A code as an input. TM-C is a combination of both digital and analog failures. The ICAO Threat Space (TS) standardized for GPS L1 C/A is given in Table 1. The proposed TM for GPS L1 C/A signal is here assumed to be also valid for new GNSS signals as the Galileo E1 and E5a ones.

The ICAO TM for Galileo E1 and E5a is given in the last update of Galileo SARPS (June 2020). To assess the effect of the filter design on the EWF cases located at the borders of the standardized TS and for the sake of more conservative assumptions, a larger TS (that goes beyond the standardized one) is used to test the EWF biases for Galileo signals as given in Table 2.

Table 1. Standardized Threat Space for GPS L1 C/A

	Δ (μ s)	σ (Mnepers/s)	f_d (MHz)
TM-A	[-0.12; 0.12] chip or [-117.3; 117.3] ns	-	-
TM-B	-	[0.8; 8.8]	[4; 17]
TM-C	[-0.12; 0.12] chip or [-117.3; 117.3] ns	[0.8; 8.8]	[7.3; 13]

Table 2. Tested Threat Space for Galileo E1 and E5a

ICAO parameters		Δ (μ s)	σ (Mnepers/s)	f_d (MHz)
TM-A	Galileo E1	[-0.16; 0.16]	-	-
	Galileo E5a	[-0.16; 0.16]		
TM-B	Galileo E1	-	[0.1; 700]	[0.1; 55]
	Galileo E5a	-	[0.1; 370]	[0.1; 30]
TM-C	Galileo E1	[-0.16; 0.16]	[0.1; 700]	[0.1; 55]
	Galileo E5a	[-0.16; 0.16]	[0.1; 370]	[0.1; 30]

The second step after defining the three TMs is to design a Signal Quality Monitoring (SQM) algorithm [2] [6] able to detect EWF threat. The presented work here is conducted in the frame of Dual Frequency Multi-Constellation (DFMC) SBAS systems. So, the designed SQM has to cover all Hazardous EWF for SBAS users while respecting the SBAS integrity and continuity requirement. Hazardous TM-A, TM-B and TM-C correspond to the interval of TM parameter giving distortions with differential bias larger than the Maximum Error Range (MERR) that can be tolerated by the SBAS user. The SQM compliance test is conducted within both satellite scenarios risen and rising:

- The so-called risen scenario appears when the signal is undergoing an EWF when being visible to several SBAS monitor stations. So, for each SBAS user, the EWF bias is the maximum transient differential bias since the considered reference stations observe the evolution of the bias measurement before and after the EWF occurs.
- In the rising scenario, the EWF event occurs when the affected satellite is not visible from the SBAS network. The affected satellite only becomes visible from the SBAS network later. In this case only the steady state differential bias is considered to characterize each EWF.

The SQM detection process is mainly performed by SQM metrics which are computed using multi-correlator outputs [5]. An additional monitor called the Code-Carrier-Incoherence (CCI) [2] is also applied on the reference bias measurement and can be used to detect jumps on the pseudorange measurement. However, this CCI monitor is available only during the risen satellite phase since it requires that the time variation of the code to carrier measurements is observed when the EWF occurs.

In this paper, the impact of the design of the airborne receiver filter and reference station filters on the EWF differential bias and SBAS monitoring performance for Dual-Frequency Multi-Constellation (DFMC) system is to assess. The presented user space and Signal Quality Monitoring (SQM) performance in [2] are referenced in this study as the baseline for the assessment of the impact of the tested aspects of the filter design. To evaluate the impact of the considered filter design parameters, the following elements are assessed and the observed changes when comparing them with baseline results of [2] are analyzed:

- The differential tracking biases
- The area delimited by the Maximum tolerable Error Range (MERR) set to 1 m for Galileo E1 signal and 2 m for Galileo E5a. The used approach to compute the MERR is presented in [2].
- The compliance of the baseline SQM proposed in [2] on the tested TM-A, B and C TS

The four baseline filters used in [2] are two Butterworth and two resonator filters, which are implemented to cover the worst case of filters with highest differential bias that can be experienced by SBAS user. The detailed description of these four filters is given in first section.

Based on the analysis of the existing filter designs carried out by some manufacturers, two aspects of the filter design are assessed:

- the shift of the filter's center frequency due to temperature variation or filter aging
- the gain roll-off out of the filter bandwidth

Filter analysis conducted by receiver manufacturer confirms the center frequency instability phenomena that shifts the filter center frequency with a certain percentage of its bandwidth. In this study, several values of frequency shift are tested with the four filters to assess its effect on the EWF differential bias with TM-A and TM-B. An increase of the observed TM-A and TM-B biases means an extension of the area to be covered by the SQM and so a potential increase of its complexity. The tolerable center frequency shift is defined as the limit value that does not induce larger TM-A and TM-B biases with respect to the baseline one.

The effect of different values of gain roll-off suggested by the receiver manufacturer are also tested. In the baseline filters, two values of filter gain roll-off are considered: 36 dB per octave for Butterworth filters, and 30 dB for resonators. Those filter roll-off values were considered too demanding by receiver manufacturers. In order to test the effect of using less selective filters, resonator filter roll-offs are replaced with values lower than 30 dB/octave, such as 24 dB/octave for airborne receiver filter.

Based on the analysis of the induced EWF bias variation for TM-A and TM-B, the impact of the tested filter design on the area to be covered by the SQM is assessed. When the results show an increase of the EWF bias (due to the change in the filters design), an additional test of the SQM compliance is added to verify the impact on the SQM complexity. Based on this analysis, the conclusion on the tolerable gain roll-off is derived.

Since the TM-C area to be covered by the SQM is a combination of TM-A and TM-B areas, the conclusion on the effect on the TM-C differential bias is derived by the TM-A and TM-B results. However, when testing the SQM compliance, all TM-A, B and C are considered to check its performance on all hazardous cases.

In the next paragraphs, the details of this methodology are described and the obtained results are shown. Then, the used filter and filtering procedure to evaluate the baseline of the EWF bias and SQM are given. First, the used procedure to test the frequency shift and compare the result to the EWF baseline is presented. Then, the used procedure to test the filter roll-off and compare the result to the EWF baseline is presented.

EWF BASELINE SIMULATION

In this section, the EWF simulation algorithm including the signal generation and acquisition steps are described. It is mainly focused on the signal generation step at the payload and signal or correlation function filtering at the receiver.

Baseline EWF generation steps

The first step is the generation of the nominal signal and the nominal correlation function. Then, the TM-A, TM-B and TM-C distortions are applied. The second step consists in filtering the signal to simulate the effect of the antenna

and RF/IF filter. In this study, a single filtering stage is used to model both the antenna and RF/IF filters. The effect of this filtering step on the distorted signal is here simulated following one of these two different procedures:

1. When only digital signals at baseband (around a carrier frequency of 0 Hz) are considered, the filtering step is applied to the correlation function of the distorted signal. This filtered correlation function is then used to evaluate the absolute tracking delay associated to the considered EWF case.
2. When the tested filters are implemented as pass-band around an intermediate frequency (IF), the baseband digital signal is translated to the IF before going through the filtering step. The filtered signal is translated again to baseband and correlated to the local replica to generate the distorted correlation function. In this study an IF of 150 MHz is chosen when testing filters at IF. This procedure is only applied when testing the effect of a non-zero frequency shift.

For the baseline of the EWF characterization and SQM presented in [2], signal generation and filtering step are applied following the first methodology using only baseband signals. In the next paragraph, the design of the baseline filters is detailed.

Design of the baseline filters

To simulate the precorrelation filtering impact (including the RF/IF filter and the antenna filter) at the airborne and the reference station receiver, four filters are considered:

- Filter 1: 6th-order Butterworth.
- Filter 2: resonator filter type with a constant group delay equal to zero. The design of this filter is based on the full definition of the transfer function:
 - The amplitude response is 1 within the desired filter bandwidth. The filter roll-off outside of the filter bandwidth is set to 30 dB/octave.
 - The phase response is such that the group delay is constant and equal to 0.
- Filter 3: resonator filter type with a concave group delay and a 150 ns maximum differential group delay. The design of this filter is based on the full definition of the transfer function:
 - The amplitude response is 1 within the desired filter bandwidth. The filter roll-off outside of the filter bandwidth is set to 30 dB/octave.
 - The phase response is such that the differential group delay reaches 150 ns at the edge of the filter bandwidth following a 3rd order function and then goes back down following a 9th order function.
- Filter 4: the amplitude response is that of a 6th-order Butterworth filter. The phase response is that of smallest order Butterworth filter leading to a differential group delay greater than 150 ns.

Figure 1 shows the transfer functions of the four filters in term of amplitude (in dB), phase (in degree) and group delay (ns). In Figure 1, the filters are generated in the baseband with a double-sided bandwidth of 24 MHz. These filters are used to characterize the baseline EWF bias. The parameters used to define the user and reference station receiver are given in Table 3

Table 3. Assumptions used to compute the Galileo E1 and E5a EWF Threat Space

	Galileo E1 signal (<i>CBOC</i> (6.1))		Galileo E5a and GPS L5 signal <i>BPSK</i> (10))	
	reference	User	reference	User
Tracking technique	EML ((1.1) local replica)	EML ((1.1) local replica)	EML (<i>BPSK</i> (10) local replica)	EML (<i>BPSK</i> (10) local replica)
Correlator spacing	0.08, 0.1 and 0.12 chip		0.9, 1 and 1.1 chip	
Pre-correlation bandwidth (double-sided)	24 MHz	12,14,16,18,20, 22,24 MHz	24 MHz	12,14,16,18,20, 22,24 MHz
Equivalent reception filter	Filter 1	Filter 1 To 4	Filter 1	Filter 1 To 4
	Differential tracking error is estimated as the maximum on all combinations of user and reference configurations.			

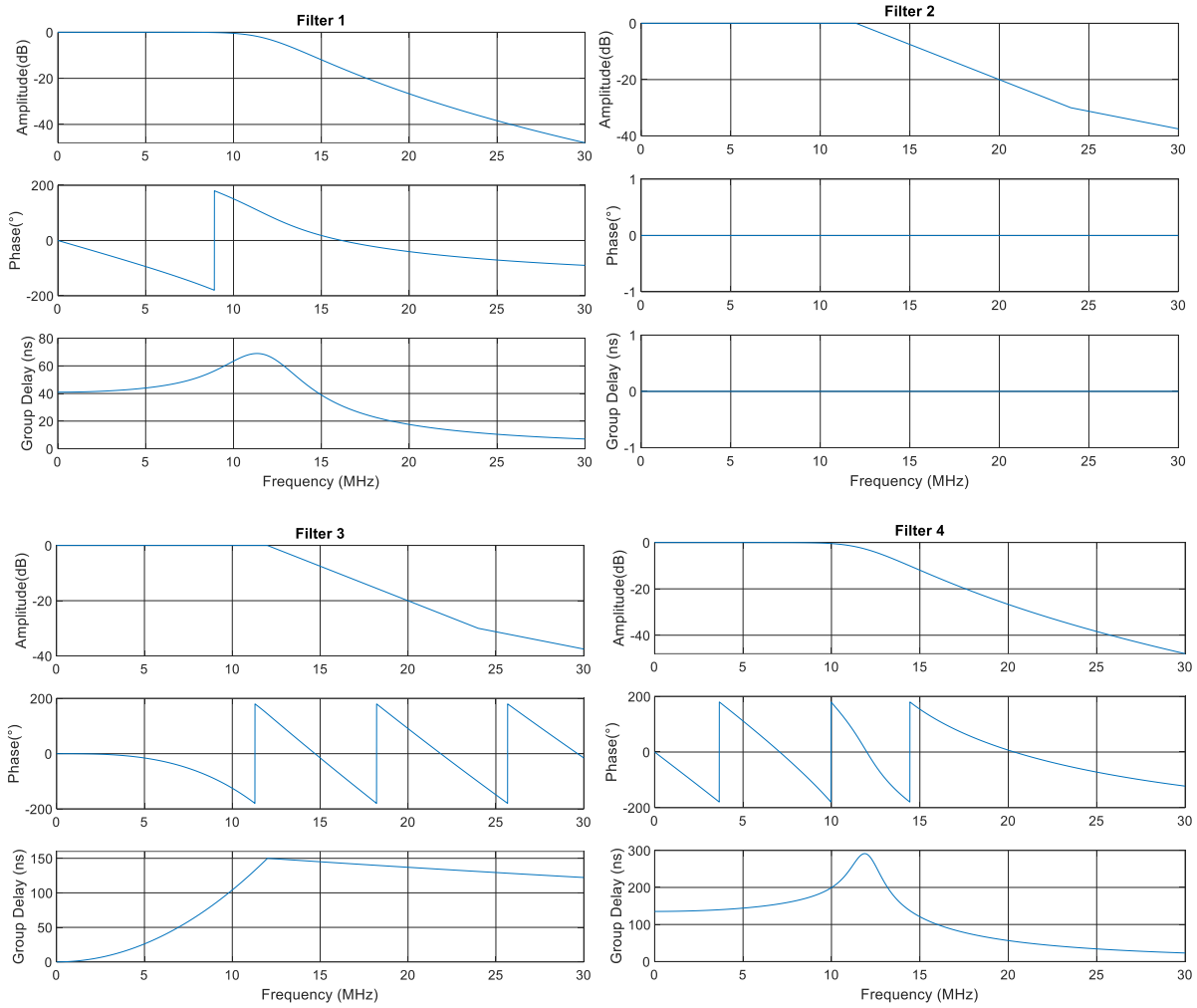


Figure 1. Gain (top), phase (middle) and group delay (bottom) variation of the four filters generated at baseband

EFFECT OF THE CENTER FREQUENCY SHIFT

The center frequency of the tested baseline filters is set to the signal carrier frequency (0 Hz when only baseband signals are considered). Receiver manufacturer indicated that on real filter, the center frequency is never aligned with the signal carrier (at IF/RF) because of the frequency instability due to temperature variation or filter parts aging [7]. A frequency offset that can go up to 25% of the filter bandwidth is usually observed on the filter center frequency. In this section, the frequency instability effect on the TM-A and TM-B differential bias is evaluated.

Tested frequency shifts

To test the center frequency shift effect, the baseband signals and filters are translated around an Intermediate Frequency (IF) of 150 MHz. In this study, only the results with a positive shift of the filter center frequency are given and analyzed. The effect of a negative frequency offset on the signal spectrum is symmetrical to the positive one and so induces the same bias variation. The following frequency offsets are added on the filter center frequency:

- for the reference station (filter 1 with a bandwidth of 24 MHz), the frequency offset is set to 1 or 1.5 MHz (~4% and 6% of the filter bandwidth) and the case without frequency shift is also tested. Intermediate values of frequency offset as 200 and 500 kHz have also been tested on the reference station giving similar results, but will not be presented in this article.
- for the aircraft filter, two values of positive frequency shift are tested with the four filters and all the tested bandwidths between 12 and 24 MHz:
 - 15 and 20% of the filter bandwidth for Galileo E5a.
 - 10 and 15% of the filter bandwidth for Galileo E1.

Different values of frequency offset are tested on the reference station and the user receiver since the temperature variation that can be experienced on these two filters is not of the same level. The aircraft receiver has to be tested for a higher level of temperature variation in the range of [-10.7; +88]°C. Here, it is assumed that the user filter is experiencing a temperature variation of 100°C ($\cong 88 + 10.7$). On the reference station, the temperature variation is assumed in the range of [-2; 30]°C. In this study, the reference station filter is tested for a temperature variation of 32°C. The theoretical frequency offset due to temperature variation can be computed as [8]:

$$\Delta f = \alpha \times \Delta T \times f_{center}$$

- α is the filter technology temperature coefficient in $ppm/^\circ C$
 - The standard value of α is $-30 ppm/^\circ C$
 - Lower α associated to SAW technology is $-10 ppm/^\circ C$
- ΔT is the temperature variation
- f_{center} is the signal carrier frequency of 1575.42 MHz on L1 and 1176.45 MHz on L5.

With the tested α of -10 and $-30 ppm/^\circ C$, the frequency shift on the aircraft receiver ranges between -1.6 and -4.7 MHz on for Galileo E1 and between -1.1 and -3.5 MHz for Galileo E5a. The tested ranges of frequency shift (15 and 20% of the bandwidth for Galileo E5a and 10 and 15% for Galileo E1) are inspired from these values obtained with the theoretical expression.

Results on the EWF bias

In this section, the obtained TM-A and TM-B differential bias when shifting the filter center frequency with the previously defined offset on the reference station and user receiver are compared to the baseline differential bias obtained with the baseline filters (perfectly centered around f_{center}). In this study, the results obtained for Galileo E5a and E1 signals are presented.

The EWF differential tracking bias considered here to characterize the EWF effect is the steady state differential bias computed as:

$$E^i = \max_{k,m} (|(User_bias_m^i - User_bias_m^{nominal}) - (Ref_bias_k^i - Ref_bias_k^{nominal})|)$$

where

- $User_bias$ and Ref_bias are respectively the user and Reference station pseudorange measurements at the steady state of the smoothing filters
- i denotes the i^{th} distortion of the threat space
- m represents the m^{th} type of user of the user design space
- k represents the k^{th} type of reference receiver of the reference receiver design space

Results for Galileo E5a

Results for TM-A

The obtained differential bias when adding the tested frequency shift of 15 and 20% of the filter bandwidth on the user filters, and 0 and 1 MHz on the reference station filter are given in the left of Figure 2. The black curve of Figure 2 corresponds the baseline differential bias where the baseline filters are used (without any frequency shift). The curves on the right of Figure 2 are the result of the difference between the differential bias obtained with the tested shifts and the baseline one. It appears that for all Δ lower than 0.14 μs , the baseline differential bias is larger than the one obtained when adding the tested values of frequency offset. It means that when shifting the filter center frequency, the effect of these TM-A on the differential bias is decreased. It may be due to the fact that part of the distortion is removed when the filter bandwidth is shifted (as shown in the example of Figure 4).

With a frequency shift of 15% of the filter bandwidth on the user filter (and both tested values on the reference station), the curves of the differential bias remain below the baseline one.

For Δ larger than 0.14 μs , the differential bias is higher than the baseline one only when 20% of the filter bandwidth is added to the user filter center frequency. However, the shown differential bias in these cases is caused by the chosen DLL design which is not enough efficient to track the heavily distorted signal as explained in the Appendix. In this study, the high differential biases obtained in these cases are due to the ENAC DLL design limitation and not the EWF effect.

Based on the presented results for the frequency shift of 15 or 20%, the baseline differential bias used to characterize the TM-A for Galileo E5a is not exceeded (except cases where the DLL design reaches its limitation). It is then

possible to tolerate a frequency shift of 15 or 20% of the filter bandwidth without modifying the baseline TM-A differential bias used to test the SQM compliance.

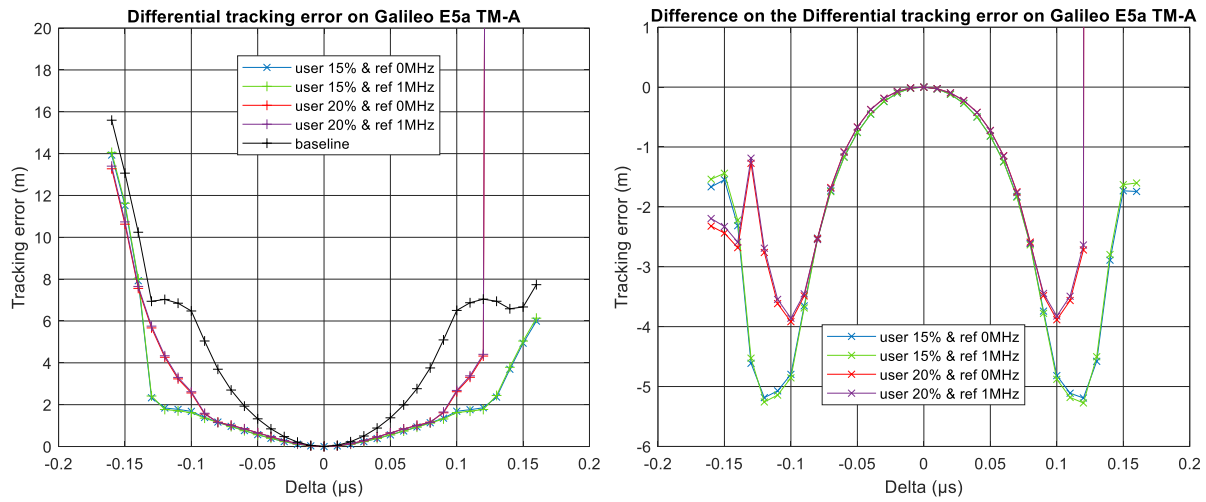


Figure 2. TM-A Differential bias obtained with the tested frequency shift on the user filter of 15 and 20% and on the reference station of 0 and 1 MHz (left figure) and difference on these differential biases with the baseline one (right figure) for Galileo E5a.

Results for TM-B

Figure 3 shows the TM-B differential bias iso-contour at the MERR (of 2 m) obtained with a frequency shift equal to 15% and 20% of the filter bandwidth applied to the used filter and with 0 and 1 MHz of frequency offset on the reference station filter.

With a frequency shift of 15% of the filter bandwidth applied to the user filter (curve blue and green), the area determined by the iso-contour at 2 m is included in the one defined with the baseline results (black curve) except a small area for f_d between 5 and 6.5 MHz. The area defined by this iso-contour results in differential biases that are below (lower than) the ones obtained in the baseline case with respect to the TM-B parameters. It means that in most parts of the TM-B TS the observed differential bias is decreasing compared to the baseline one. As it is mentioned for TM-A, this lower differential bias can be due to the fact that with a shifted bandwidth, part of the effect of the distortion on the signal is filtered as shown in the example of Figure 4.

However, when testing a frequency shift equal to 20% of the filter bandwidth (curve red and purple), the iso-contour of 2 m is moved to higher f_d values. It means that more TM-B cases are exceeding the MERR of 2 m and so need to be covered by the SQM.

Note that with a frequency shift lower than 15% such as 5% or 10% of the filter bandwidth have also been tested on user filters. The obtained differential bias in this case is in between the baseline one and the result with a frequency shift of 15%. Hence, it can be concluded that the highest frequency offset that can be tolerated without modifying the area of TM-B distortion to be covered by the SQM can be set to 15% of the user filter bandwidth.

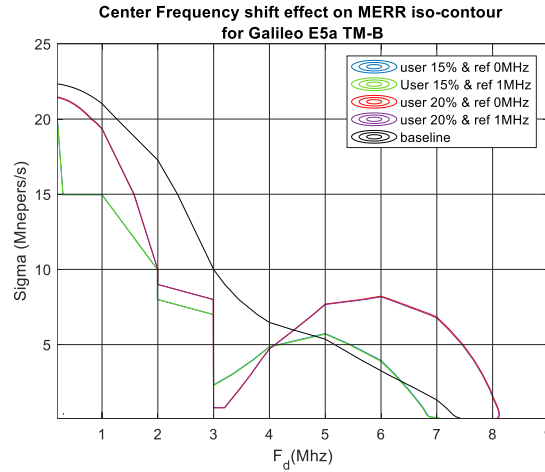


Figure 3. the MERR iso-contours with baseline filters and the tested frequency shift of 15 and 20% of the filter bandwidth on the user filter and 0 and 1 MHz on the reference filter for TM-B applied to Galileo E5a signal

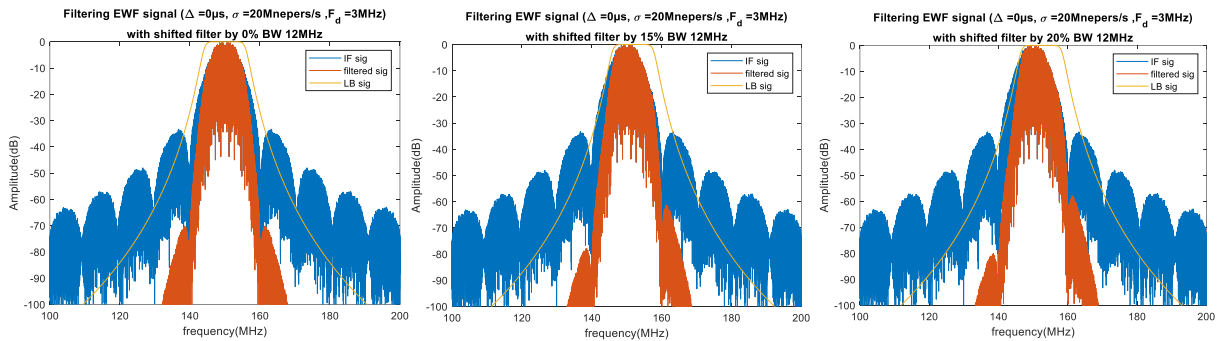


Figure 4. Example of the frequency shift effect on the spectrum of a distorted Galileo E5a signal by TM-B ($f_a = 3 \text{ MHz}$ & $\sigma = 20 \text{ Mnepers/s}$) using filter 1 with a bandwidth of 12MHz and a frequency offset of 0 (left), 15% (middle) and 20% (right).

Results for Galileo E1

Results for TM-A

The obtained differential bias with the baseline filters and when adding the tested frequency shift of 10 and 15% of the filter bandwidth on the user filters and 0 and 1.5 MHz on the reference station filter are given in the left of Figure 5. The right figure shows the difference between the differential bias affected by the frequency shift applied to the center frequency and the baseline one. It appears that with all the tested values of frequency shift, the differential bias remains lower than the baseline one.

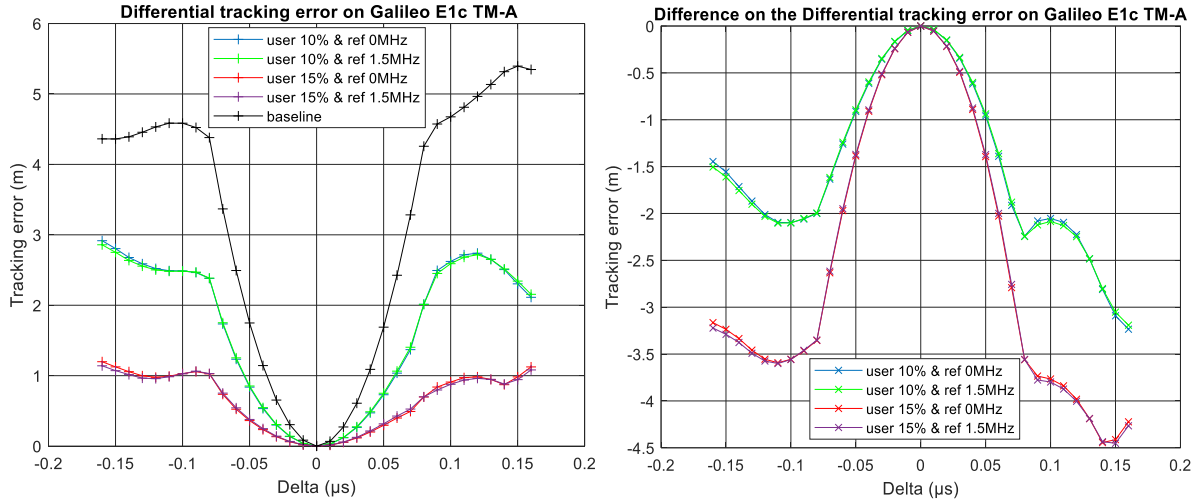


Figure 5. Differential bias obtained with the tested frequency shift on the user filter of 10 and 15% and on the reference station of 0 and 1 MHz (left figure) and difference on these differential biases with the baseline one (right figure) for TM-A GalileoE1

Results for TM-B

Figure 6 represents the TM-B differential bias iso-contour at the MERR of 1 m with baseline filters and with a frequency shift of 10% and 15% of the filter bandwidth on the user filter, and 0 and 1.5 MHz on the reference station filter.

It appears that, when allowing center frequency shifts up to 15% of the user filter bandwidth (red and purple curves), the iso-contour at the MERR of 1 m slightly exceeds the f_d limit (around 20 MHz) defined in the baseline case (black curve).

However, with a frequency shift of 10% of the filter bandwidth applied to the user filter (blue and green curves), the area defined by the iso-contour at the MERR of 1 m is included in the same area shown with the baseline results (except a very tiny area for f_d around 18 MHz and σ lower than 0.3 Mnepers/s)

These results suggest that 10% of the filter bandwidth is the highest frequency shift that can be accepted on the user filter center frequency without modifying the TM-B TS area to be monitored by the SQM for Galileo E1 signal.

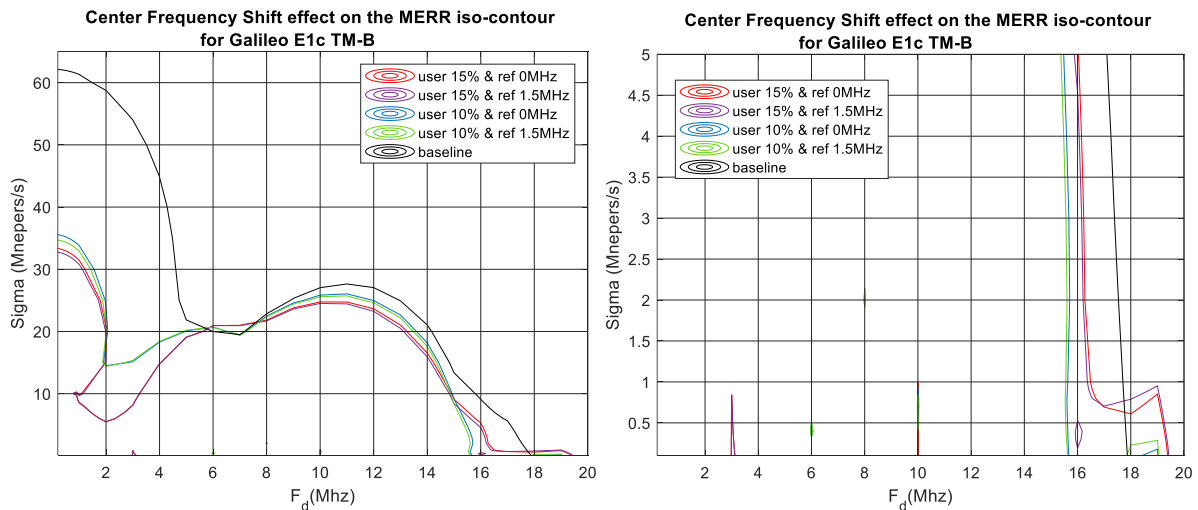


Figure 6. the MERR iso-contours (on the left and a zoom on low σ on the right) with baseline filters and the tested frequency shift of 10 and 15% of the filter bandwidth on the user filter and 0 and 1.5 MHz on the reference filter for TM-B applied to Galileo E1 signal

Conclusion on tolerable frequency shift

Different values of center frequency offsets are tested on the user and reference station filters. Those values are inspired from the results of the theoretical expression of the frequency instability due to temperature variation applied to the user and reference station receiver. For Galileo E5a, two values of frequency offset are tested on the reference station filter: 0 and 1 MHz. On the user filter, the results with a frequency shift equal to 15 and 20% of the filter bandwidth are presented for Galileo E5a signal. For Galileo E1, the tested values of frequency offset on the reference station filter are 0 and 1.5 MHz. On the user filter, the results with a frequency shift equal to 10 and 15% of the filter bandwidth are presented.

All the tested frequency offsets are only simulated as a positive shift of the filter center frequency since the negative shift gives the exact same result as with the positive one. The TM-A and TM-B differential bias variation caused by the center frequency shift applied to Galileo E5a signal suggests that the highest frequency offset that can be tolerated on the user filter is 15% of the filter bandwidth. The obtained results for Galileo E1 signal prove that the highest tolerable frequency shift can be set to 10% of the user filter bandwidth to avoid including TM-B distortions with larger f_d in the set of EWF to be monitored.

Based on the analysis of the TM-A and TM-B differential bias results, a 10% of the receiver filter bandwidth shift on the aircraft's filter center frequency is acceptable for Galileo E5a and E1 signal processing.

EFFECT OF THE FILTER GAIN ROLL-OFF

For GPS signals, the minimum acceptable gain roll-off to be used with double delta discriminator is set to 30 dB/octave in DO-229E [9]. However, there is no requirement on the filter gain roll off when using the Early-Late discriminator that is also allowed in [9]. These remarks raised a question about the possible need for a similar requirement in the DFMC SBAS MOPS [10] when using the Early-Late discriminator which is the only tracking technique allowed in [10]. In the present study, the need for such a requirement in the case of Galileo signals is assessed based on the analysis of its effect on the EWF induced tracking bias and SQM compliance.

In this section, a lower value filters gain roll-off is tested to evaluate the effect of the use of a less selective filter by the aircraft receiver on the EWF bias and SQM compliance. The obtained results are compared to those of the EWF baseline with the baseline filters which respect a gain roll-off requirement of 30 dB/octave.

Tested gain roll-off

Among the baseline filters, two of them have a gain roll-off of 36 dB/octave (filter 1 and 4) as per 6th order Butterworth filter definition. For these filters, the gain roll-off will not be modified to avoid changing the filter type. The transfer function of filter 2 and 3 is defined based on two inputs: the gain roll-off and group delay variation. In the baseline filters, the value of 30 dB/octave is chosen for filter 2 and 3. In order to test the effect of a less steep gain roll-off, this value is replaced by 24 dB/octave. Figure 7 shows the curve of the filter 2/3 attenuation with respect to the frequency with a gain roll-off of 30 and 24 dB/ octave for a bandwidth between 12 and 24 MHz. The black dotted line represents the requirement on the antenna frequency selectivity given in DO-229E [9] for L1 signals. It appears that with a gain roll-off of 24 dB/octave, filter 2 with the largest tested bandwidth of 24 MHz is slightly exceeding the requirement on the frequency selectivity. 24 dB/octave seems to be the lowest gain roll that can be accepted to respect L1 frequency selectivity requirement for all tested bandwidth. The dotted magenta line corresponds to the suggested frequency selectivity for L5 filters given in DO-292 [11]. This L5 frequency selectivity is not considered here since it will be updated in the future version of DO-292.

The new tested set of filters includes:

- Filter 1 and 4 as 6th order Butterworth filters with a gain roll-off of 36 dB/octave.
- Filter 2 and 3 with a gain roll-off of 24 dB/octave (instead of 30 dB/octave).

In this study, the EWF differential bias obtained when applying the new set of filters is compared to the one given by the baseline filters.

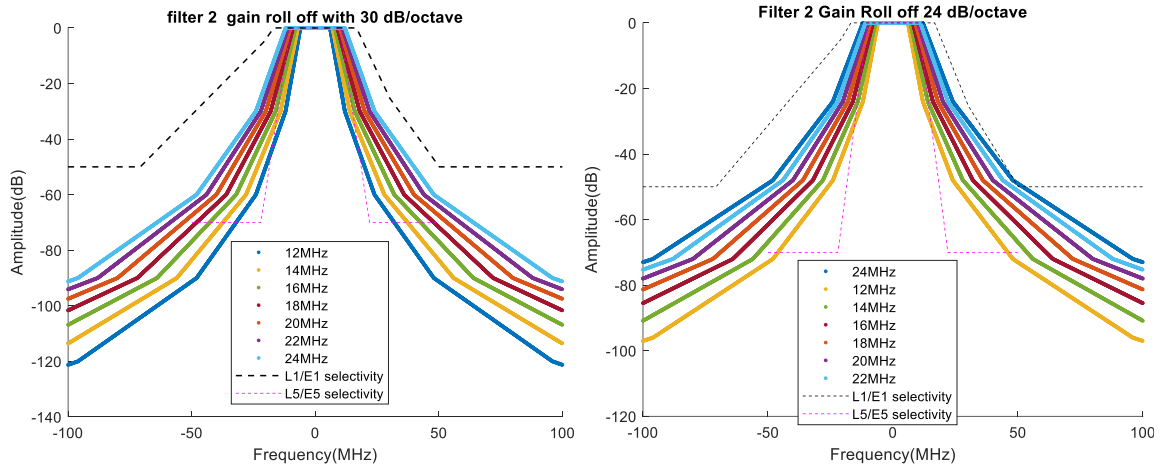


Figure 7. Filter 2 and 3 amplitude with a gain roll-off of 30 (left) and 24 (right) dB/octave

Gain roll-off results for Galileo E5a and E1
Galileo E5a signal

Results on the TM-A

Figure 8 shows the differential bias obtained with the baseline filters and the ones modified with a gain filter roll-off of 24 dB/octave on the figure on left. The figure on the right shows the difference between the two biases that goes up to 22 cm.

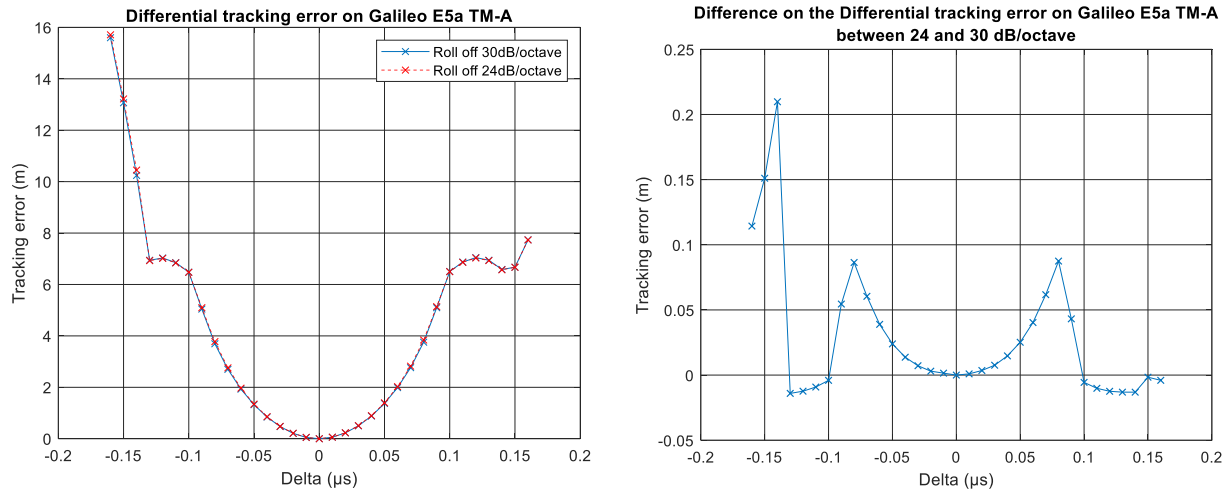


Figure 8. the Steady state differential biases with baseline filters and modified filters with 24 dB/octave filter roll-off (left) and the difference between them (right) for TM-A on Galileo E5a

Results on the TM-B

The differential bias obtained for Galileo E5a signal affected by TM-B is given in Figure 9. The iso-contours on the left figure represent the result obtained with the baseline filters (gain roll-off set to 30 dB/octave on filter 2 and 3) and those on the right figure are obtained with the second set of filters using 24 dB/filter roll-off. An additional part of the iso-contour at 2 m, which corresponds to the MERR for Galileo E5a, appears around an f_d of 14 MHz on the contour figure on the right. It means that using a gain roll of 24 dB/octave instead of 30 dB/octave adds more TM-B distortions exceeding the MERR level. And so more EWF cases need to be covered by the SQM to protect the SBAS user. In the next paragraph, the compliance of the baseline SQM proposed in [2] is tested with the set of distortions induced when using the modified set of filters (with 24 dB/octave gain roll-off requirement).

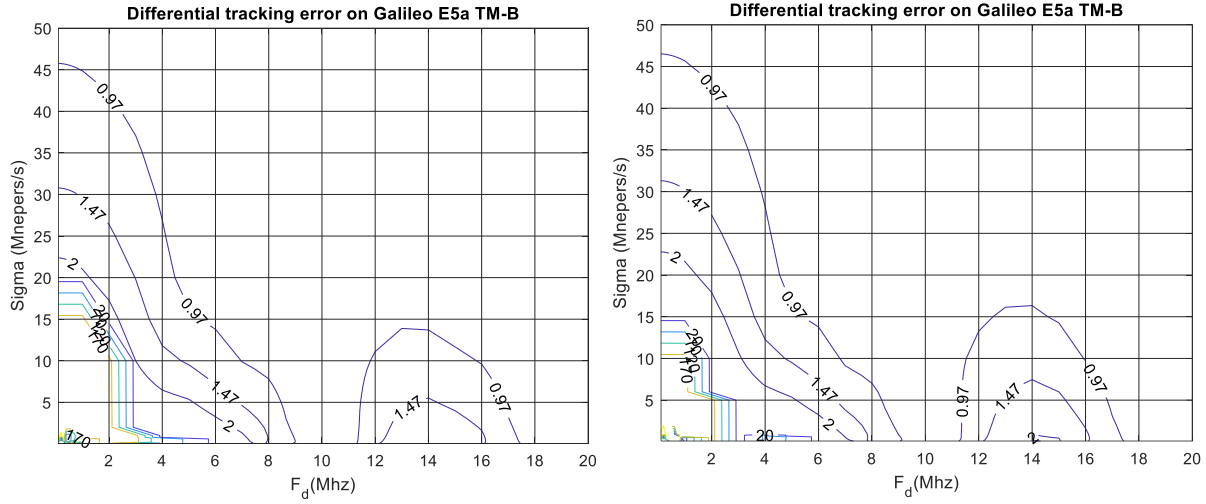


Figure 9. Steady state differential bias with baseline filters (left) and modified filters with 24 dB/octave (right) for TM-B on Galileo E5a

SQM compliance test applied to TM-A, B and C

The result of the SQM compliance test is evaluated in this section to check if using 24 dB/octave requirement on the filter gain roll-off changes the baseline SQM performance. The SQM compliance test is assessed for both risen and rising satellite scenarios defined in [2]. The tested TM-A, B and C TS are given in

Table 2. It corresponds to the same large TS tested in [2] to validate the compliance of the baseline SQM which uses two types of metrics:

- The SQM metrics based on a combination of the multi-correlator outputs. The expression of the used metrics in the baseline SQM are given as a function of I_0 the prompt correlator output and I_x the correlator output located x chip away from I_0 :
 - The simple ratio metric $M_{sr} = \frac{I_x}{I_0}$
 - The difference ratio metric $M_{sdr} = \frac{I_x - I_{-x}}{I_0}$
 - The double difference ratio metric $M_{ddr} = \frac{(I_x - I_{-x}) - (I_y - I_{-y})}{I_0}$
- The CCI (Code-Carrier Incoherence) monitor which detects a jump on the pseudorange measurement of the reference station.

The compliance of each metric M is checked by computing the metric test as:

$$Test_M = \frac{M - M^{nominal}}{threshold_M}$$

Where $M^{nominal}$ is the nominal value of the metric and $threshold_M$ is the metric threshold defined by the standard deviation of the metric and the probability of false alarm and missed detection that need to be satisfied for SBAS user for both satellite scenarios: risen and rising. More details on the evaluation of the metric threshold is given in [2].

For each distortion of the tested TS, the SQM is considered compliant with the SBAS requirements if one of the tested metrics satisfy: $Test_M \geq 1$. Otherwise the considered distortion is not detected by the SQM. For the tested TS, the compliance of the SQM is validated when all EWF with a differential bias exceeding the MERR have at least one compliant metric (among the tested SQM metric and CCI monitor) for each satellite scenario: risen and rising.

Figure 10 shows the result of the maximum differential bias (y axis) as a function of the highest metric test (x axis) in both risen and rising satellite scenarios. In the left figure, the results are shown for high differential bias (until 200 m) and the figure on the right corresponds to a zoom on the low values of bias. All the distortions located above the MERR level (represented by the red dotted line at 2 m) correspond to a positioning failure situation for SBAS user and need to be covered by the SQM. The distortion located at the right side of the black vertical line (at $Test_M = 1$) are detected by the tested SQM while satisfying the false alarm and missed detection SBAS requirement. EWF cases with a differential bias above the MERR line and non-compliant SQM performance (located at the left side of the

vertical black vertical line) are sources of integrity risk events for SBAS user. Figure 10 shows that almost all hazardous cases are detected by the baseline SQM except few cases with a high differential bias around 180 m. These undetected EWF are further investigated by looking at the power loss due to these distortions.

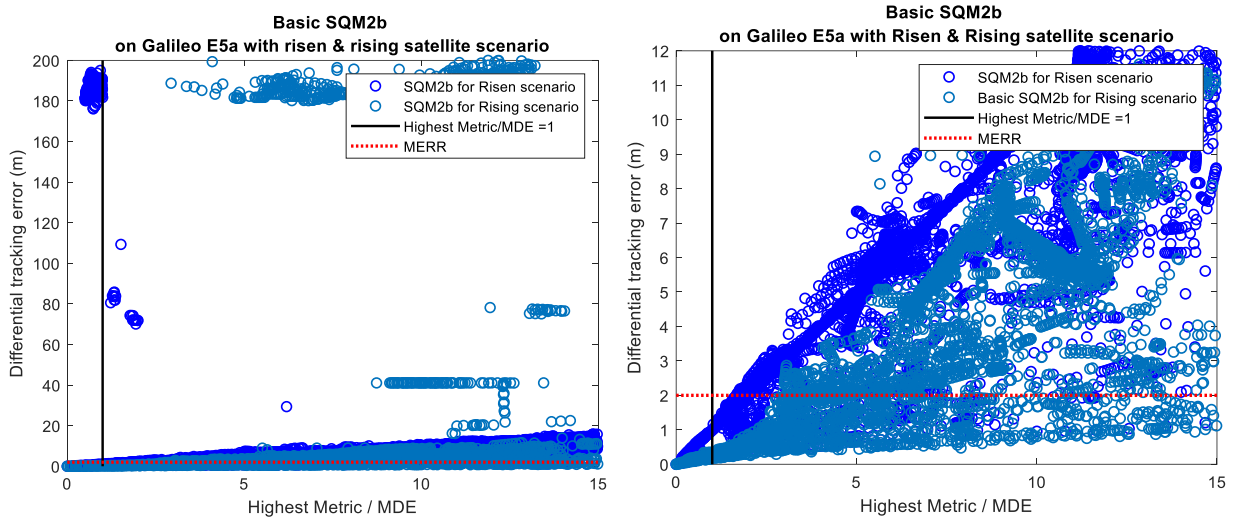


Figure 10. EWF differential bias as a function of the highest metric test (left) and a zoom on low bias (right)

Figure 11 represents the EWF differential bias as a function of the power loss (in dB) induced by the presence of the EWF on the correlation function. This power loss can be expressed as:

$$P_{loss}(EWF) = 10 \log \left(\frac{I_{0,EWF}}{I_{0,nominal}} \right)$$

Where $I_{0,EWF}$ and $I_{0,nominal}$ are the prompt correlator outputs on the distorted and nominal correlation function respectively.

The red circles in Figure 11 that represent the undetected cases (located at the left side of the black line in Figure 10) induce a high level of power loss that exceeds 35 dB, represented by the green vertical line. It means that when these undetected distortions occur, the acquisition or tracking loop of the aircraft receiver will lose the satellite signal because of its low C/N_0 . Hence, these distortions will not have an impact on the integrity of the SBAS user and so can be ignored by the SQM¹.

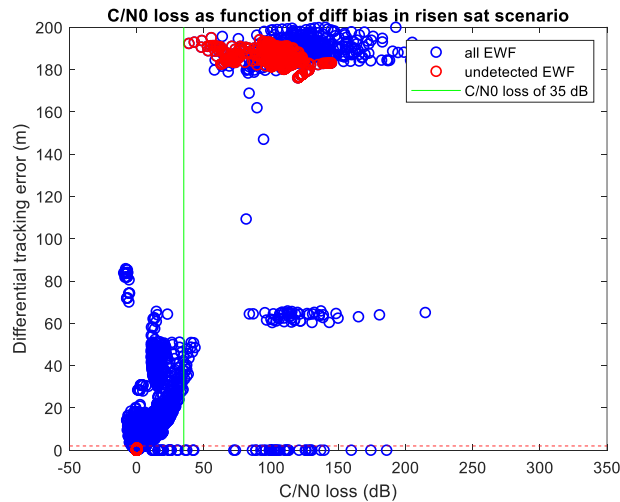


Figure 11. EWF differential bias as a function of the correlation loss

¹ The red circle in the bottom left corner is at (0, 0) so below the MERR.

Based on the presented results, the proposed SQM in [2] protect the SBAS users against the EWF TS resulting from the set of modified filters with the use of a 24 dB/octave gain roll-off requirement.

Galileo E1 signal

Results on the TM-A

Figure 12 shows the steady state differential bias observed when applying the requirement of 30 and 24 dB/octave on the user filters on the left, and the difference between them on the right with respect to the TM-A parameter Δ . It appears that only a difference of few centimeters (lower than 8 cm) is computed on the differential bias when going from a requirement of 30 to 24 dB/octave on the filter gain roll-off.

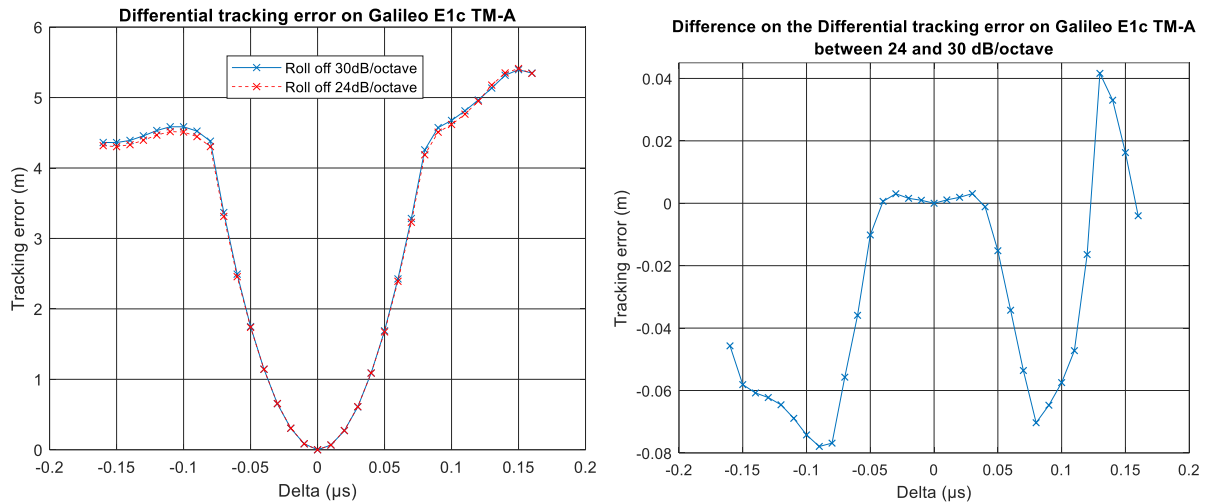


Figure 12. the Steady state differential biases with baseline filters and modified filters with 24 dB/octave filter roll-off (left) and the difference between them (right) for TM-A on Galileo E1

Results on the TM-B

The observed differential biases when applying a gain roll-off requirement of 30 and 24 dB/octave on the Galileo E1 TM-B TS are given in Figure 13. The difference between the two contour figures is given in Figure 14. It appears that a difference of less than 10 cm is observed on the most part of the TM-B TS. A larger difference that goes to 40 cm is observed on a small area around f_d of 19 MHz and σ lower than 2 Mnepers/s. But this difference does not induce a significant change in the shape of the MERR iso-contour at 1 m.

Hence, relaxing the gain roll-off requirement from 30 to 24 dB/octave can be accepted for Galileo E1 without any change in the area to be monitored by SQM for TM-B TS.

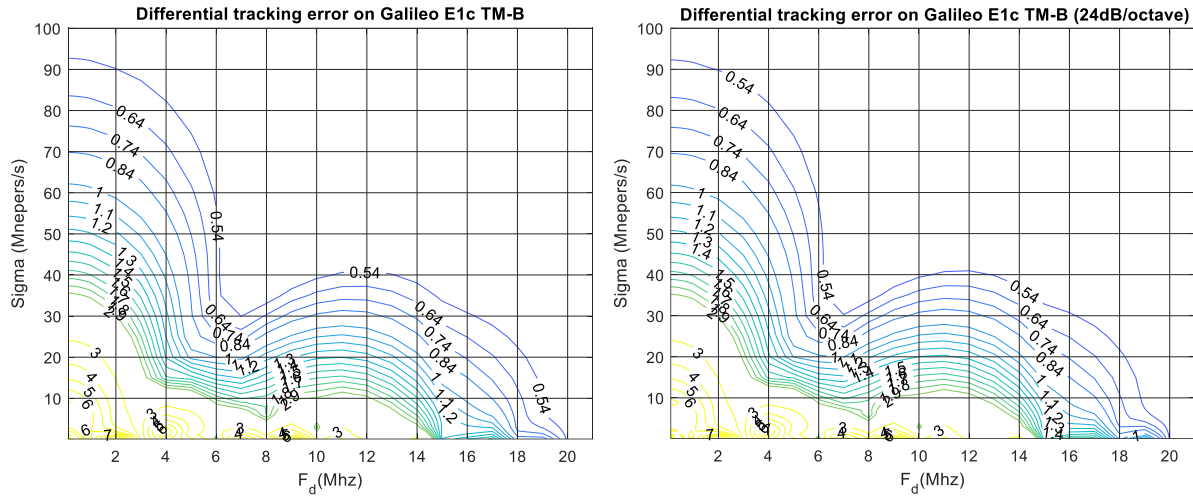


Figure 13. Steady state differential bias with baseline filters (left) and modified filters with 24 dB/octave (right) for TM-B on Galileo E1

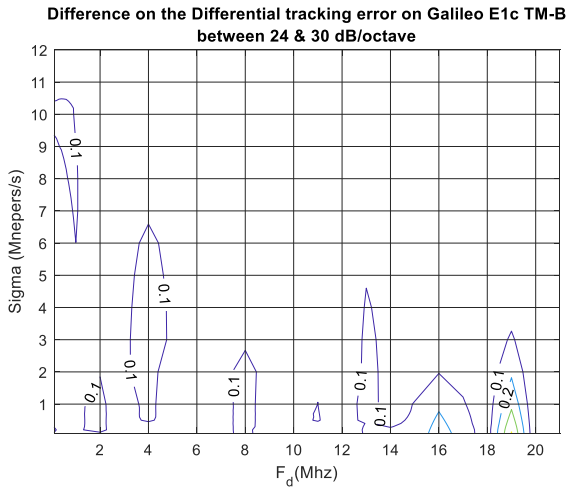


Figure 14. Difference on the steady state differential bias obtained with baseline filters and the modified set of filters with 24 dB/octave for all the Galileo E1 TM-B TS

Conclusion on tolerable gain roll off

Even if a gain roll-off requirement of 30 dB/octave will be more suitable from a SBAS SQM perspective, the presented results confirm that a 24 dB/octave requirement on the filter gain roll-off can be accepted based on the EWF results for Galileo E5a. The proposed SBAS SQM in [2] is able to cover the Galileo E5a TS induced by the modified set of user filter with the gain roll-off set to 24 dB/octave.

Similar results are also obtained with Galileo E1 with a very low change in the differential bias curve. The observed changes do not have an impact on the area of hazardous distortion exceeding the MERR. So, no additional SQM analysis is needed to confirm that the gain roll-off requirement could be relaxed to 24 dB/octave without a significant impact on the EWF characterization. The final definition for gain roll-off requirements (possibly more stringent) will then be driven by spectrum management and resistance to interference constrains at user level.

CONCLUSIONS

In this paper, filter design tests are carried out to evaluate its effect on the EWF characterization in term of differential bias variation and SQM compliance test. Two aspects of the filter design are considered:

- Filter gain roll-off:

Two values of gain roll-off requirement are tested here: 30 dB/octave which is already used in the baseline filters and 24 dB/octave. The results of differential bias for Galileo E1 show a very low difference caused when relaxing the gain

roll-off requirement to 24 dB/octave. However, with Galileo E5a signal, a more significant change in the differential bias curves is observed. To check if such a change will have an impact on SBAS user protection against EWF events, the SQM compliance test is rerun with the TM-A, B and C results obtained when applying a gain roll-off of 24 dB/octave. The SQM test confirms that all hazardous distortions remain covered when going from 30 to 24 dB/octave gain roll-off requirement.

In order to keep a safe margin with respect to the tested values, it is preferable to keep the requirement on the filter gain roll-off set to 30 dB/octave.

- Filter center frequency shift due to frequency instability caused by temperature variation.

Different values of center frequency offset are tested on the user and reference station filter. Those values are inspired from the results of the theoretical expression of the frequency instability due to temperature variation applied to the user and reference station. For Galileo E5a, two values of frequency offset are tested on the reference station filter: from 0 to 1.5 MHz. On the user filter, the results with a frequency shift from 10 to 20% of the filter bandwidth are presented. All the tested frequency offsets are only simulated as a positive shift of the filter center frequency since the negative shift gives the exact same result as with the positive one. The TM-A and TM-B differential bias variation caused by the center frequency shift applied to Galileo E1 and E5a signal suggests that the highest frequency offset that can be tolerated on the user filter is $\pm 10\%$ of the filter bandwidth.

FUTURE WORK

During the RTCA/EUROCAE meeting on January 2020, more aspects of the filtering step simulation were pointed:

- The antenna filtering effect and the RF/IF filtering step are simulated by a single filter stage using the four filters presented in this paper. To assess the effect of gain roll-off requirement on the RF/IF filter, the antenna filter needs to be simulated separately. To do so, an additional filter stage will be added based on the antenna frequency selectivity given in [12]
- When defining the transfer function of filter 2 and 3, the considered gain roll-off requirement is used to define the amplitude slope out of the filter bandwidth. However, the minimum tolerable value for this slope is not defined. Hence, the filter amplitude is assumed to continue decreasing for higher frequency. In order to make the behavior of the simulated filters closer to real ones, a minimum amplitude level needs to be considered. A minimum filter amplitude of -50 and -70 dB is suggested for Galileo E1 and E5a respectively.

These remarks will be taken into account to update the simulation and the presented results in this study.

In this paper, each of the two filter design aspects: gain roll off and center frequency offset are studied separately, and their effect is assessed independently from the other one. In order to conclude on the tolerable margin for each aspect, an additional test will be carried out, while taking into account the acceptable values for each filter design aspect (i.e. 24 dB/octave on the gain roll off and a center frequency shift of $\pm 10\%$ of the filter bandwidth).

As it is explained in the Appendix, the implemented DLL design at the user and the reference station receiver has some limitation that have an impact on the presented results. This DLL design (used in ENAC EWF tool) will be reviewed to improve its robustness to EWF cases with multiple zero crossing. Then the conclusion of this paper will be updated with the new results.

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APPENDIX

For Δ larger than $0.14 \mu\text{s}$, the shown TM-A differential bias, for Galileo E5a, is higher than the baseline one only when 20% of the filter bandwidth is added to the user filter center frequency. However, the shown differential bias in these cases corresponds only to the result of user filter 4 with a bandwidth of 12MHz (giving the maximum bias) where the DLL in ENAC EWF tool loses the tracking of the correlation peak. Figure 15 shows two examples of the zero crossing points (green crosses) obtained with the user filter 4 when its center frequency is shifted by 20% of its 3dB bandwidth. In these figures, the correlation functions and the discriminators obtained with filter 4 (red and blue lines) at a bandwidth of 12 (right) and 20 MHz (left) are compared to the ones obtained with baseline reference filter (in black and dotted purple lines). It appears clearly that in the right figure (filter 4 with 12MHz bandwidth), the implemented DLL is not tracking the right zero crossing (represented by the red circle). Then, the obtained bias is not due to the tested EWF, but to the limitation of the DLL design. This DLL anomaly is only observed with one tested user filter (filter 4 at 12MHz bandwidth). It also appears that if the right zero crossing is chosen, the obtained differential bias will be in the same order of magnitude than the ones obtained with Δ below $0.14 \mu\text{s}$. Therefore, this is not changing the conclusion of the study.

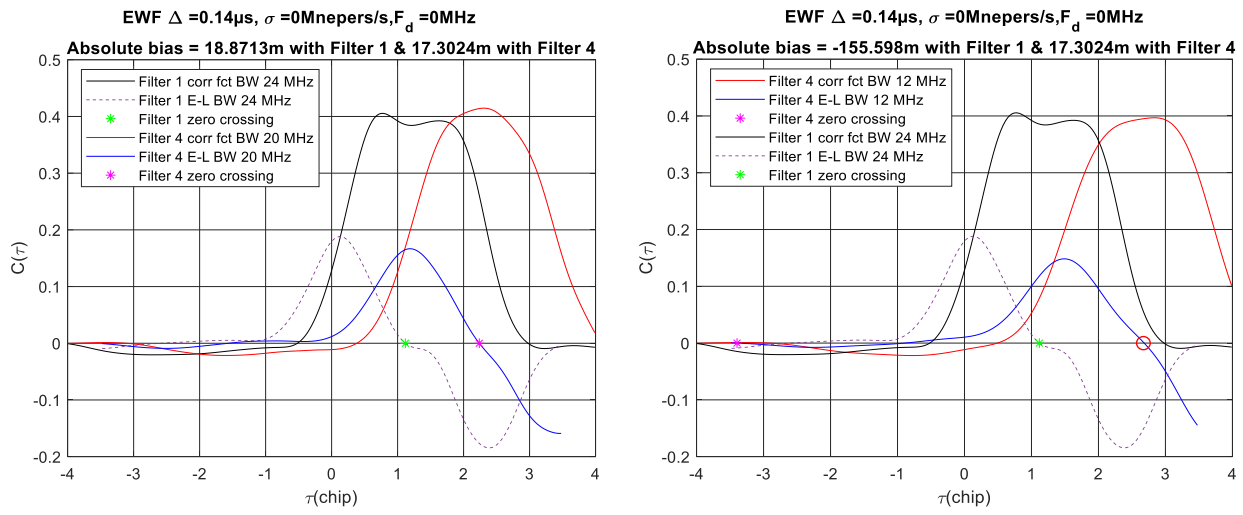


Figure 15. Correlation function and discriminator functions for a TM-A with $\Delta = 0.14 \mu\text{s}$ with the baseline reference filter (both figure) and the user filter 4 with a frequency shift of 20% of the filter bandwidth set to 12 (right) and 20 MHz(left).