Signal Quality Monitoring for New GNSS Signals

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ABSTRACT: *To meet stringent requirements defined for civil aviation GNSS receivers, the characterization of distortions which could affect a GNSS signal in a hazardous way is required. In particular, expected signal distortions generated at payload level are described by Threat Models, necessary tools to design Signal Quality Monitor (SQM). The SQM is a mean to detect the presence of dangerous signal distortions and to protect users requiring high integrity, accuracy, availability, and continuity. Nowadays, this monitoring task is performed by GBAS and SBAS reference stations for GPS L1 C/A to warn the user in a timely manner. In the context of GNSS signals and associated augmentation systems modernization, new modulations are envisaged. In this paper, SQMs for Galileo E1C, GPS L5, Galileo E5a and GPS L1 C/A, signals that will be used by civil aviation receivers for pseudorange computation, are designed and compared by mean of an innovative methodology.*

INTRODUCTION

Distortions generated by the satellite payload that could entail large errors on a differential GNSS user without being detected are called Evil WaveForms (EWFs) and are a burning issue for GNSS users with strict performance requirements (in terms of integrity, continuity, availability and accuracy). In order to model these signal distortions, a proposition of Threat Model (TM) was made by the civil aviation community in 2001 for GPS L1 C/A [1], which aimed at characterizing distortions that could be generated by the GPS satellite payload and that could create a hazard for a civil aviation user. Nowadays, this TM has been adopted by ICAO (International Civil Aviation Organization) with the definition of three threat categories for GPS L1 C/A signal [2]:

- TM-A which is associated with a failure in the Navigation Data Unit (NDU), the digital partition of a satellite payload. It consists of the normal C/A code signal except that all the positive chips have a falling edge that leads or lags relative to the correct end-time for that chip. The parameter describing the lead or lag is noted Δ, expressed in seconds or fraction of chips.

- TM-B which introduces amplitude modulation and models degradations in the analog section of a satellite. More specifically, it consists of the output from a second order system when the nominal C/A code baseband signal is the input. Two parameters are defined for this threat model: the damping factor σ and the ringing frequency f_d.
- TM-C which is a combination of the two first failures.

EWFs are an issue for GNSS receivers with stringent requirements (as for example in civil aviation) because they can create a large bias on the code pseudorange measurements. This bias is dependent upon the signal modulation and the receiver configuration (type of local replica used for the correlation, correlator spacing, discriminator, pre-correlation bandwidth and RF front-end filter type). The consequence is that EWF-induced biases cannot even be fully differentially corrected unless the reference station providing the corrections has exactly the same hardware and software configuration as the user receiver, which is never the case. The EWF thus has to be timely detected to avoid hazardous situations. This is the reason why GBAS and SBAS include a Signal Quality Monitor (SQM) to specifically monitor and detect this kind of threat.

The first important works on the detection of EWFs that could affect a GPS L1 C/A signal were published in early 2000's. Most of these publications are related to two PhDs, [1] and [3], but other works on SQM were also published as in [4] or [5].

The advent of new GNSS signals requests the definition of new EWF TMs. Indeed, new signals use different modulations and are generated by new payloads. Several publications have studied EWFs on new signals as in [6], [7], [8] or [9]. As an example, a proposal for Galileo E1C (the pilot component of the E1 Open Service signal), Galileo E5a and GPS L5 signals TM has been given in a previous publication from the authors [9]. These TMs will be the starting points for the work performed in this publication. Besides, until now, only few publications have investigated SQM and its performance on new signals. Some results were provided relatively to GPS L5 in [10] but a lot of work remains in particular regarding Galileo signals.

The proposal and assessment of SQM techniques adapted to the new Galileo signals in the context of the evolution of EGNOS to a Dual-Frequency Multi-Constellation (DFMC) SBAS system is the main objective of this article. In particular, Galileo E1C (CBOC(6,1,1/11)-modulated) and Galileo E5a (BPSK(10)-modulated) are the main focus as they are Galileo signals that will be used by civil aviation to estimate pseudorange measurements [11]. Note that the results obtained for Galileo E5a are also valid for GPS L5.

The article content has the following structure:

- The first section details the context of this work. Definitions of the considered EWF TMs and receiver configurations of interest will be given. Indeed, the performance of SQM is dependent upon the TM but is also dependent upon the receiver configurations to protect.
- The second section introduces different metrics used to detect the presence of a signal distortion. The methodology to assess SQM performance as a function of metric standard deviation will be described. This performance will be defined in an ideal theoretical way, considering an ideal Gaussian distribution of the noise at the correlator outputs [12] and at the metrics level. A reference SQM based on a high number of available correlator outputs compared to current SBAS SQM will be first tested on GPS L1 C/A signal, taking into account advances in receiver

technology. As a conclusion of this section, a method to adapt theoretical results to operating reference station conditions is suggested.

- In the third section, a simplified SQM obtained by reducing the number of metrics without decreasing SQM performance is proposed for Galileo E5a, GPS L5 and Galileo E1C.
- The last section concludes on the relevance of the new comparison tool (inspired from [10]) and on the performance provided by proposed SQMs.

CONTEXT OF THE STUDY

Results presented in this article are obtained in a SBAS context. As introduced, design and performance of SQM are dependent upon:

- The configurations of the user receivers to protect (certified airborne receivers) and the reference station. Receiver parameters of interest at user and reference levels are:
    - the tracking technique (including the local replica modulation used in the correlation process),
    - the correlator spacing of the tracking pair and
    - the antenna and the RF front-end (filter technology, bandwidth and maximum group delay variation).

  In this article, different allowed airborne receiver configurations, based on expected allowed civil aviation requirements (also known as User Design Space (UDS)), will be taken into account to cover all possible cases.
- The TM, or in other words, the distortions that have to be monitored.

The occurrence of an EWF entailing a (differential) pseudorange measurement error greater than the Maximum ERRor (MERR) of 1.55 m on Galileo E1, and 2.78 m on Galileo E5a and GPS L5, is here considered as a threat. The choices of 1.55 m and 2.78 m are derived from the MERR value of 3.5 m often used for an SBAS L1 mapped to the case of a DFMC SBAS that uses ionosphere-free L1/L5 measurements [10]. Note that more advanced choices for the MERR have been discussed in [4], [10], [13] and will be taken into account in later studies.

The SQM performance is considered as acceptable if the Maximum Undetected Differential Error (MUDE) for that SQM is below the MERR. The MUDE is estimated from pseudorange measurements and according to the allowed probability of missed detection (P_{md}) and probability of fault free detection (P_{ffd}, also called probability of false alarm) required by ICAO.

Receiver configurations of interest

For the sake of simplicity, the SBAS reference station configuration is here assumed fixed: its RF filter is considered as a 6th-order Butterworth with a 24 MHz bandwidth (double sided) and its discriminator is assumed to be an Early-Minus-Late (EML) discriminator with a 0.1 chip correlator spacing for Galileo E1C and GPS L1 C/A signals and 1 chip correlator spacing for Galileo E5a and GPS L5 signals [14]. Local replicas at reference level are modulated differently depending on the processed signal:

- BOC(1,1) for Galileo E1C,
- BPSK(1) for GPS L1 C/A,
- BPSK(10) for Galileo E5a and GPS L5 signals.

More configurations are tested at the airborne level as shown in Table 1. These configurations represent receiver architectures expected for future SBAS DFMC civil aviation users [14]. Different types of RF front-end filters are here considered, to account for the wide variety of filters encountered across multiple receiver manufacturers. All these filters satisfy current (but not definitive) DFMC airborne receiver requirements. In particular, the differential group delay, that has to be lower than 150 ns, is defined in [2] as:

$$\left|\frac{d\phi}{d\omega}(f_{center}) - \frac{d\phi}{d\omega}(f)\right| \qquad (1)$$

where

- f_{center} is the band pass filter center frequency in hertz,
- f is any frequency within the 3 dB bandwidth of the pre-correlation filter in hertz,
- ϕ is the band pass filter phase in radian,
- ω is equal to $2\pi f$.

The filters with the 150-ns differential group delay are assumed to be representative of a worst case:

- Filter1: 6^{th}-order Butterworth (the differential group delay is equal to 39 ns).
- Filter2: resonator filter type with a group delay equal to zero. Resonator filters represent typical filters used in GNSS receivers [15].
- Filter3: resonator filter type with a concave group delay and a 150 ns differential group delay.
- Filter4: 6^{th}-order Butterworth for the amplitude and the smallest order Butterworth filter leading to a differential group delay higher than 150 ns for the phase.

The amplitude, the phase and the differential group delay of the four filters are provided in [16].

Table 1—Tested user's configurations.

Signal and associated modulation	Galileo E1C and GPS L1 C/A signal	Galileo E5a and GPS L5 signal
Tracking technique	E-L (BOC(1,1) and BPSK(1) local replica)	E-L (BPSK(10) local replica)
Correlator spacing	0.08, 0.1 and 0.12 chip	0.8, 1 and 1.2 chip
Pre-correlation bandwidth (double sided)	12, 14, 16, 18, 20, 22, 24 MHz	
Equivalent RF filter	4 filters are tested	

Distortions of interest

As already mentioned, the SQM performance for Galileo E5a and Galileo E1C signals will be evaluated assuming the TMs proposed in [9] and recalled in Table 2. The same TM for GPS L5 signal as for Galileo E5a signal is assumed. Regarding GPS L1 C/A TM, the current ICAO TM is kept and is recalled in Table 2. Justifications about the Threat Space (TM parameters ranges) values proposed for new signals are provided in [9] and are summarized in this article. Firstly, it is noticeable that for all signals, BPSK-modulated or not, the type of distortions retained by ICAO regarding the GPS L1 C/A signal (BPSK(1)-modulated) are kept. By consequence, it means that for all signals, the analogue failure consists in the output of a second order system whereas a lead/lag on falling signal transitions (whether chip or sub-chip) characterizes a digital failure. This strategy is used because of the lack of knowledge about satellite payload and the absence of EWF observations on new signals. There is an acknowledgement that the new satellites payload would not provide different distortions, which is very unsure.

Knowing the types of distortions that can affect a GNSS signal and their associated three relevant parameters (frequency and damping factor of the ringing phenomenon and lead/lag value at every falling transition) the difficulty is to limit values that these parameters can take. To limit these values it was proposed in [9] to consider as a threat only distortions:

- with an impact higher than 1 meter on differential pseudorange measurements for the different tested users and
- with an impact smaller than 20 meters on a reference station absolute pseudorange measurement.

Definition of the TMs and associated Threat Space (TS) for the considered signals are summarized in Table 2 and in Table 3 where, as a reminder, f_d is the frequency of the ringing phenomenon, σ is the damping factor of the ringing phenomenon, Δ is the lead/lag at every falling transitions after modulation, Δ_{11} is the lead/lag at every BOC(1,1) falling transitions at signal square wave generator. Δ_{61} is the lead/lag at every BOC(6,1) falling transitions at signal square wave generator. It is noteworthy that the neper (Np) is used in official documents as the damping factor unit [2]. Like the decibel, the neper refers to as a logarithmic ratio. The relation between the two units is that 1 neper is equal to $20 \times log_{10}(exp\ (1))$ decibel where log_{10} is the logarithm with base 10 function and exp is the exponential function.

Table 2— Studied TS for new modulations

	TM-C										
	TM-B								TM-A		
	Area 1				Area 2				TM-A1	TM-A2	
	f_{d_min} MHz	f_{d_max} MHz	σ_{min} MNp/s	σ_{max} MNp/s	f_{d_min} MHz	f_{d_max} MHz	$\left(\frac{\sigma}{(f_d)^2}\right)_{min}$ $Np/s/Hz/MHz$	$\left(\frac{\sigma}{(f_d)^2}\right)_{max}$ $Np/s/Hz/MHz$	$\Delta_{max} = -\Delta_{min}$ $chip$	$\Delta_{11max} = -\Delta_{11min}$ $chip$	$\Delta_{61max} = -\Delta_{61min}$ $chip$
Galileo E1C	1	19	0	26	3	19	0.07	5	0.12	0.1	0.08
Galileo E5a	3	19	0	24	4	19	0.06	3.5	1.2	/	/
Resolution	1		1		1		0.05 (Galileo E1C) 0.075 (Galileo E5a)		0.01	0.01	0.01

Table 3— Studied TS for GPS L1 C/A signal.

	Δ $chip$	σ MNp/s	f_d MHz
TM A	$[-0.12{:}\, 0.01{:}\, 0.12]$	-	-
TM B	-	$[0.8{:}\, 1{:}\, 8.8]$	$[4{:}\, 1{:}\, 17]$
TM C	$[-0.12{:}\, 0.01{:}\, 0.12]$	$[0.8{:}\, 1{:}\, 8.8]$	$[7.3{:}\, 0.57{:}\, 13]$

THEORETICAL SQM CONCEPT

The SQM that is currently implemented on SBAS (as well as on GBAS) consists of a test (noted $Test$) based on correlator outputs to evaluate if the signal is affected by an abnormal distortion or not. The SQM methodology has already been thoroughly described in the literature as for example in [3] or [17]. This test compares the difference between a current metric value and the metric value in the nominal case (this difference is also called detector) against a threshold.

Mathematically, the test on one metric (noted $Test_{metric}$) can be expressed as:

$$Test_{metric}^{i} = \frac{D_{metric}^{i}}{threshold_{metric}} \qquad (1)$$

with:

$$D_{metric}^{i} = metric_{dist}^{i} - metric_{nom}^{i} \qquad (2)$$

where:

- $metric_{dist}^{i}$ is the current value of the metric which can be affected by a distortion. The index i corresponds to the ranging signal i that is being monitored.
- $metric_{nom}^{i}$ is the nominal value of the metric in the absence of distortion. $metric_{nom}^{i}$ can consist in the median of that metric across all satellites in view in nominal conditions [7]. $metric_{nom}^{i}$ can also be estimated for each signal i.
- $threshold_{metric}$ is the detection threshold that is determined based on a required P_{ffd}. If the test can be assumed to be Gaussian distributed, the threshold can generally be expressed easily as a function of the metric standard deviation and a multiplier related to the false alarm probability.

A distortion detector will then flag the presence of an EWF when the metric test value is higher than 1.

Performance threshold definition

In order to know if faulty cases are detected with adequate P_{ffd} and P_{md} defined by system requirements, a Neyman Pearson hypothesis test can be performed. The Minimum Detectable Error (MDE) is a parameter that provides the minimum metric bias (or distortion) that ensures that the metric test will meet the required P_{ffd} and P_{md}. The MDE definition for a given metric test $Test_{metric}^{i}$ and assuming a Gaussian distribution of $Test_{metric}^{i}$ is given in [2] as:

$$MDE_{metric} = (K_{md} + K_{ffd})\sigma_{metric} = 8.35 \times \sigma_{metric} \qquad (3)$$

where

- $K_{ffd} = 5.26$ is a typical fault-free detection multiplier representing a false detection probability of 1.5×10^{-7} per test [2];
- $K_{md} = 3.09$ is a typical missed detection multiplier representing a missed detection probability of 10^{-3} per test [2]; and
- σ_{metric} is the standard deviation of the metric test;

For the above expression to hold, it is assumed that the noise affecting metrics is white and Gaussian. In the absence of multipath, the Gaussian behavior of the noise affecting correlator outputs was verified in [12] and of the metrics tests used in the following in [18] and [19].

If several metrics tests are used to build the overall SQM detector, as it is envisaged in this paper, the global detector can then be built as:

$$Test^i = \max_{metric}\left(Test^i_{metric}\right) \tag{4}$$

In this case, the EWF is detected if any of the metrics tests flags the presence of an EWF. In this condition, P_{ffd_metric} and P_{md_metric} have to be derived for each individual metric so that the global P_{ffd} and P_{md} are in line with the ICAO requirements. Let us call P_{X_metric} $(X = ffd\ or\ md)$ the probability associated to one test based on one metric and let us assume that the same budget is allocated to each sub-test. Considering that the total test is based on N_t sub-tests and that an alarm is triggered if at least one metric exceeds its threshold, two extreme cases can be analyzed:

- All metrics are totally independent: the probabilities of one metric test (P_{X_metric}) are related to the total test probabilities (P_X) by:

$$P_{ffd} = \sum_1^{N_t}\left(\binom{N_t}{k} P^k_{ffd\_metric}\,(1 - P_{ffd\_metric})^{N_t-k}\right) \tag{5}$$

$$P_{md} = P_{md\_metric}{}^{N_t} \tag{6}$$

  where $\binom{N_t}{k}$ is the binomial coefficient.

- Metrics are totally correlated, in this case:

$$P_{ffd} = P_{ffd\_metric} \tag{7}$$

$$P_{md} = P_{md\_metric} \tag{8}$$

In real conditions, P_{X_metric} are between the two extrem cases defined by (5), (6), (7) and (8). With a more precise knowledge about the dependency relation between each metric, exact P_{X_metric} and consequenlty exact $\left(K_{md\_metic} + K_{ffd\_metric}\right)$ could be estimated for each metric. $\left(K_{md\_metric} + K_{ffd\_metric}\right)$ is assessed in this document in a conservative way which is obtained when metrics are considered as totally dependent ($K_{md\_metric} = K_{md}$ and $K_{ffd\_metric} = K_{ffd}$ i.e. there is only one metric) as shown in Figure 1.

$\left(K_{md\_metric} + K_{ffd\_metric}\right)$ is plotted in red (and is constant) in the particular case where all metrics are totally dependent and in blue the case where all metrics are totally independent. Both plots are given function of the number of metrics used by the SQM. In real conditions, $(K_{md\_metric} + K_{ffd\_metric})$ will take values between the two curves.

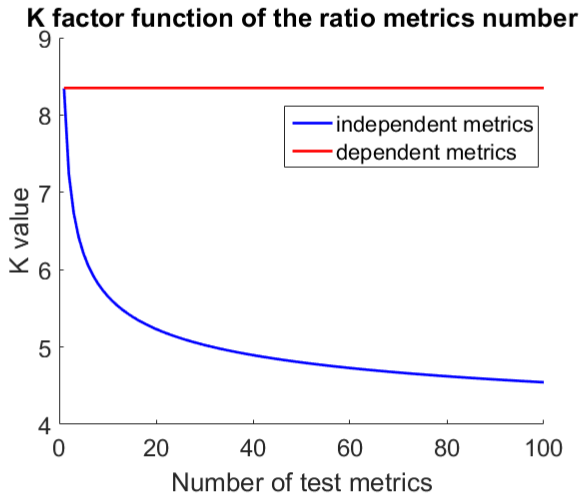

Fig. 1–($\boldsymbol{K_{md\_metric} + K_{ffd\_metric}}$) if metrics are totally dependent (red/lighter plot) or totally independent (blue/darker plot) function of the sub-tests number.

It entails that even if several metrics are used to define a test, the MDE fulfilling the ICAO requirements can be modeled in a conservative way, on each metric, as:

$$MDE_{metric} = 8.35 \times \sigma_{metric} \quad (9)$$

A specific Figure of Merit (FoM) is thus used:

$$FoM_{metric}^{i} = \frac{D_{metric}^{i}}{MDE_{metric}} \quad (10)$$

If $FoM_{metric}^{i} > 1$, this means that a given distortion is detected by the metric test with the appropriate ICAO P_{ffd} and P_{md} since it entails a metric bias larger than the MDE_{metric}. In the continuation, the superscript i associated to the monitored ranging signal will be dropped for simplicity reasons. Following the same approach as before, the global FoM can thus be written as:

$$FoM_{max} = max_{metric}[FoM_{metric}] \quad (11)$$

Then, FoM_{max} can be seen as the maximum value among all FoM_{metric}. Simulating a distortion from the considered EWF TM and comparing the resulting FoM_{max} to 1, it is possible to know if that distortion would be detected by the SQM with a given P_{ffd} and P_{md} for a given SBAS reference station configuration.

Considered Metrics

In this document, only three simple types of metric are used in the proposed SQMs:

- *Simple ratio metric* which is the easiest metric to implement and permits to detect all kinds of correlation function distortion.

$$metric_x = \frac{I_x}{P} \quad (12)$$

- *Difference ratio metric* which permits to detect correlation function distortions asymmetric from the prompt more efficiently than the simple ratio metric.

$$metric_{x-x} = \frac{I_{-x} - I_x}{P} \quad (13)$$

- *Sum ratio metric* which permits to detect correlation function distortions symmetric from the prompt more efficiently than the simple ratio metric.

$$metric_{x+x} = \frac{I_{-x} + I_x}{P} \quad (14)$$

where:

- I_x is the in phase correlator output value at a distance x (in chip unit) from the prompt,
- $P = I_0$ is the value of the prompt correlator output.

These metrics are looked at for two main reasons:

- the simple ratio and the difference ratio metrics are currently used in the SQM implemented in EGNOS [20].
- the value of σ_{metric} for these three metrics can be derived theoretically in a simple way.

Representation of SQM Performance: Example of GPS L1 C/A

Taking into account the configurations of the airborne receiver that have to be protected and of the configuration of the reference station, it is possible to assess the worst differential error induced by a given distortion of the TM. This highest differential error is called the maximum differential error and is estimated for each distortion. It is then possible to link this worst differential error experienced by the airborne user for a given distortion to the related FoM_{max} values caused by that distortion.
Let us now look at the case of a GPS L1 C/A signal and let us assume:

- The reference configuration and all airborne configurations provided in Table 1,
- A reference receiver providing access to 51 correlator outputs located at $-0.25: 0.01: 0.25$ chips. This represents a particularly favorable case since current SQM receivers only typically output 8 correlator outputs. Correlator outputs are assumed obtained using a coherent integration time equal to 1 s,
- A baseline SQM consisting of:
  - 50 simple ratio metrics $metric_x$ with $x = -0.25: 0.01: -0.01$ and $x = 0.01: 0.01: 0.25$ chips,
  - 25 sum ratio metrics $metric_{x+x}$ and 25 difference ratio metrics $metric_{x-x}$ with $x = 0.01: 0.01: 0.25$ chips.
- A C/N_0 of the incoming monitored signal assumed equal to 35 dB-Hz. This value is taken as an example in this section.

Figure 2 shows the worst differential error induced by the distortions from the entire GPS L1 C/A EWF TM as a function of the FoM_{max} value. A total of 1326 distortions (each represented by one point) are represented: 12 from TM-A, 126 from the TM-B and 1188 from the TM-C. The continuous line corresponds to the maximum differential error for a given FoM_{max} value.

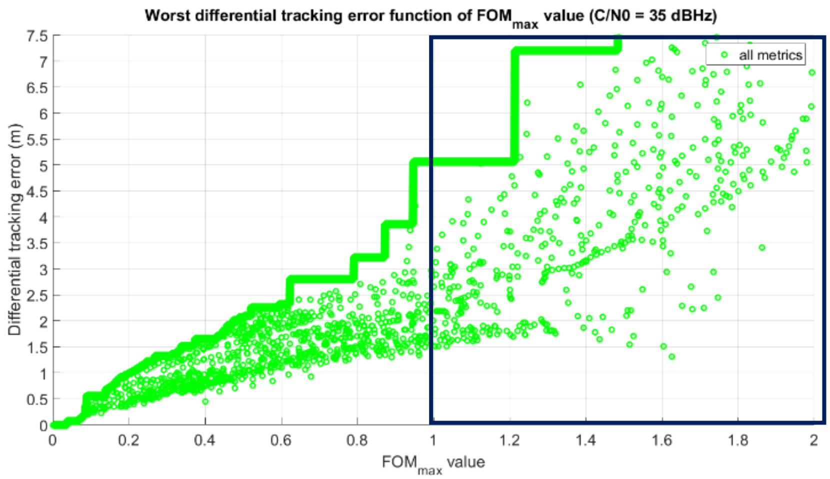

Fig. 2–Example of worst differential tracking error function of $\boldsymbol{FoM_{max}}$.

Distortions included in the blue square of Figure 2 ($FoM_{max} > 1$) are distortions detected by the defined SQM with the ICAO P_{ffd} and P_{md} requirements. The Maximum Undetected Differential Error (MUDE) can then been read by taking the worst differential tracking error for $FoM_{max} < 1$. To ensure that the SQM is suitable for SBAS use, it is then critical to ensure that the MUDE is below the targeted MERR. In Figure 2, the MUDE is equal to 5.1 m.

Alternative representation of the SQM theoretical performance: Example of GPS L1 C/A signal

As seen in (3), the MDE depends upon the metric test standard deviation. This means that, among other things, the MDE and FoM_{max} depend upon the monitored signal C/N_0 at the reference station. As a consequence, the MUDE is also dependent upon the C/N_0 which is a drawback operationally. In this document it is proposed to adapt the scale on the x-axis in order to have a SQM performance representation that is visually related to the C/N_0 at the monitoring station.

The relation between the C/N_0 in dB-Hz and σ_{metric} is given by:

$$\sigma_{metric} = C_{metric}\sqrt{\frac{1}{T_{int} \times 10^{\frac{C/N_0}{10}}}} \quad (15)$$

where

- T_{int} is the coherent integration time chosen for the tracking ($T_{int} = 1$ s),
- C_{metric} is a parameter that does not depend on the C/N_0 but depends only on the metric.

From (16), it is possible to apply a change of x-axis on Figure 2 in order to transform the value of FoM_{max} for a given distortion in the value of the minimum C/N_0 that creates a FoM_{max} equal to 1 for that same distortion. This transformation is detailed in [16]. Figure 3 shows the same results as on Figure 2 with the x-axis change. The blue square now encloses the distortions detected by the SQM according to the ICAO requirements when the C/N_0 of the monitored signal is equal to 35 dB-Hz.

One interest of the representation shown in Figure 3 is that the MUDE can be assessed as a function of the monitored signal C/N_0 at the reference station. For instance, the MUDE of a reference station operating with a C/N_0 equal to 40 dB-Hz would be 2.8 m.

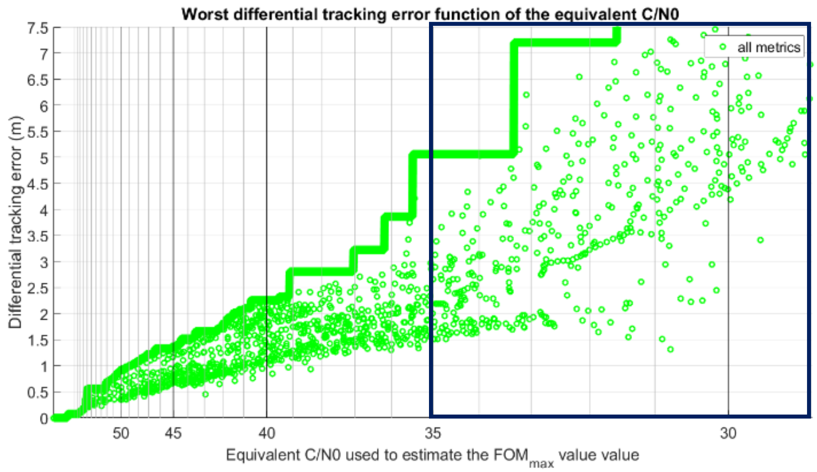

Fig. 3–Example of worst differential tracking errors function of the equivalent $\boldsymbol{C/N_0}$.

A second interest of the representation is that performance of different SQMs can be compared. Let us introduce for instance a second SQM, referred to as SQM2b. This SQM was studied around 2000 in [21] or [22], and is still used nowadays in EGNOS RIMS-C stations [20]. Originally SQM2b consisted of 11 metrics even if only 4 metrics are used by EGNOS RIMS-C stations:

- 2 simple ratio metrics: $metric_{-0.075}$, $metric_{0.075}$
- 2 difference sum ratio metrics: $metric_{0.075-0.075}$, $metric_{0.1-0.1}$.

Figure 4 gives in red (crosses) the results obtained using the SQM2b and in green (circles) the results obtained using the reference SQM. From these plots, it is clear that MUDE is higher for the SQM2b than for the reference SQM whatever the C/N_0 is. This was expected since the reference SQM relies on 100 metrics whereas SQM2b relies on only 4 metrics.

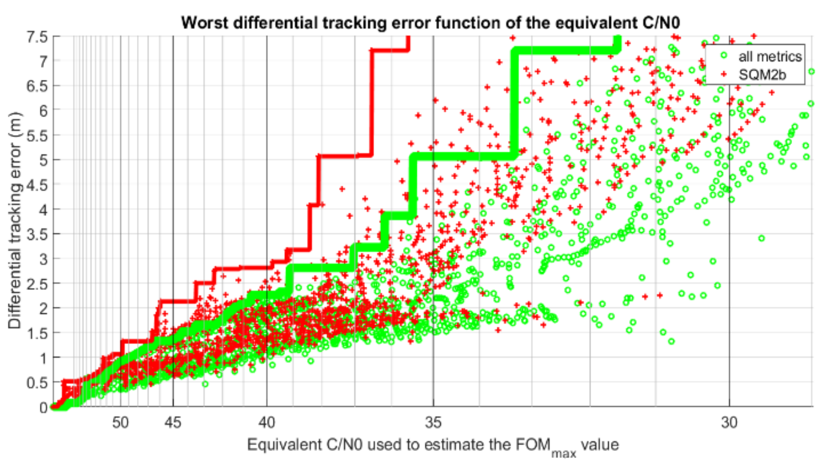

Fig. 4–Comparison of two SQMs performance.

As mentioned earlier, the targeted MERR for SBAS users using GPS L1 C/A is equal to 3.5 m. It can be seen that the MUDE is lower than 3.5 m with the SQM2b only if the C/N_0 at the reference station is at least equal to 38.5 dB-Hz. This result puts forward that with this simulation setup, SQM2b does not reach the required performance for signals observed with a C/N_0 lower than 38.5 dB-Hz at the reference station. This can be interpreted as a reason why a supplementary step in SQM design was proposed in the early 2000's [17]. In order to decrease the metrics standard deviation, it was proposed to smooth metrics values by means of a low pass digital filter with a time constant equal to or shorter than 100 s [2]. Such smoothing was implemented on reference stations as mentioned in [17], [22] or [23]. Assuming a Gaussian metric noise, this smoothing gives the possibility to divide the metrics tests standard deviation by a factor of 10. However in practice, especially because of multipath, such improvement is not reachable. In the next section, a method is developed to estimate at which equivalent theoretical C/N_0 a reference station is operating.

Equivalent theoretical C/N_0 for a reference station in operational conditions

The results presented in the previous section were obtained assuming that:

- The noise distribution on metrics is white and Gaussian.
- The coherent integration time is equal to 1 s.
- No multipath is affecting the incoming signal.
- A 6^{th}-order Butterworth (24 MHz double sided) is implemented at the reference level.

It is possible to continue to use the same methodology to assess the SQM performance in non-ideal conditions if it can be assumed that the presence of multipath or other sources of errors does not modify the Gaussian nature of the metric test. This will be assumed in this section. Note that the case in which the metrics tests noise distribution is not Gaussian is discussed in the next section.

The relation between σ_{metric_x} (for any correlator location) and the C/N_0 value at the monitoring station is known theoretically when thermal noise is the only source of error [18], [24]. As a consequence, from known values of σ_{metric_x} obtained at the reference station site, it is possible to associate a corresponding C/N_0 value. This C/N_0 value estimated theoretically is not necessarily representative of the C/N_0 seen by the reference station regarding the monitored signal. Indeed, the theoretical C/N_0 is deduced from σ_{metric_x} values assuming that the noise on metrics is white and Gaussian, that the coherent integration time is equal to 1 s and that no multipath is affecting the incoming signal. For that reason, the C/N_0 estimated theoretically is called, in the following, the equivalent theoretical C/N_0.

On Figure 5, three examples of σ_{metric_x} are highlighted and represent some real reference stations conditions. Note that each continuous line represents the theoretical values of σ_{metric_x} as a function of a specific C/N_0 assuming a coherent integration time of 1 s and no metric smoothing.

- The two first cases correspond to a data collection performed at Stanford University with a LAAS integrity test-bed on SV 5 with a 5° elevation angle [21]. Red large stars correspond to unsmoothed metrics and green stars to metrics smoothed by a 100 s moving average.
- The last case illustrates σ_{metric_x} obtained from a data collection made by Cap Gemini with a Novatel GIII receiver. The data collection was 1 hour long and σ_{metric_x} were estimated from all satellites in view. The worst σ_{metric_x} among satellites is represented by blue dots. The worst case

was observed on SV 62. Its elevation angle was equal to 9° at the beginning of the data collection and 33° at the end.

From Figure 5, it can be approximated that the LAAS receiver is working at an equivalent theoretical C/N_0 equal to 35.1 dB-Hz in the worst case if metrics are unsmoothed whereas the equivalent theoretical C/N_0 is equal to 39 dB-Hz with smoothed metrics (keep in mind that the equivalent C/N_0 is associated to a relation between σ_{metric_x} and C/N_0 that assumes a coherent integration time of 1 s and no metric smoothing). With unsmoothed metrics, Cap Gemini's σ_{metric_x} correspond in the worst case to a theoretical C/N_0 equal to 35.9 dB-Hz. This value of 35.9 dB-Hz obtained in the case of the Cap Gemini's data collection is consistent with C/N_0 values estimated by the receiver (the signal C/N_0 was equal to 32.8 dB-Hz at the beginning of the data collect and 42.0 dB-Hz at the end). It confirms that equivalent C/N_0 derived from mathematical formula is a good approximation of the true signal C/N_0 estimated by a receiver.

One important remark is that the 100-second smoothing has entailed, on data collected by Stanford, only a 4 dB improvement whereas a 10 dB improvement is expected, in theory, if only thermal noise is present. In practice, notably because of multipath, the smoothing improvement factor was observed having values between 1.5 and 2.3. To be conservative, the value of 1.5 (4 dB) is considered in the continuation.

Same plots as Figure 5 for Galileo E5a, GPS L5 and Galileo E1C signals have also been computed but are not provided in this article.

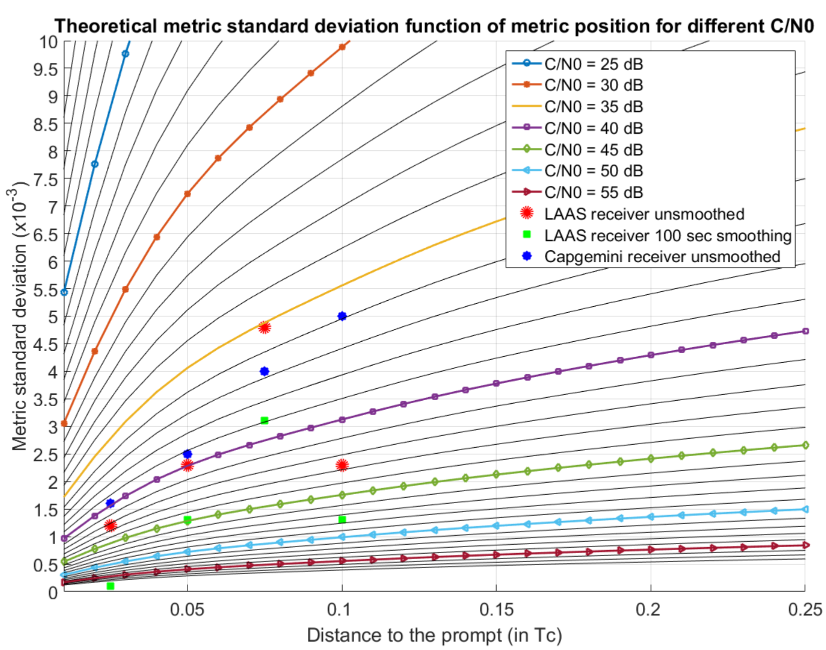

Fig. 5–Example of reference station metric standard deviations compared to theoretical values assuming only thermal noise.

Generalization to non-Gaussian noise distribution on metrics

The methodology exposed in the previous section to assess the equivalent operating C/N_0 of a reference station was based on the assumption that the noise distribution on metrics was white and Gaussian. In real conditions, this is generally not true [8]. One of the consequences is that, at each reference station, the MDE of each metric has to be adjusted to satisfy P_{md_metric} and P_{ffd_metric}, and especially avoid too many false alarms. Indeed in non-Gaussian conditions, it is not possible to easily estimate the MDE_{metric} by multiplying $\sigma_{metric,j}$ by a multiplier derived from a normal law.

In this case, $MDE_{metric,j}$ can be determined based on data collections at a given reference station. Indeed, even if the noise distribution on metrics is not Gaussian, it is possible to estimate K_{md_metric} and K_{ffd_metric} (and as a consequence MDE_{metric}) from the cumulative distribution function. With the knowledge of MDE_{metric}, it is then possible to evaluate the equivalent σ_{metric} that would lead to the same MDE_{metric} if the metric was Gaussian-distributed. Finally, from this equivalent σ_{metric} and an tool like the one provided in Figure 6, it is possible to determine an equivalent theoretical C/N_0 at the reference station. Figure 6 represents the value of the MDE as a function of the equivalent C/N_0 at the reference station and the location of the correlator used in the simple ratio metric (Figure 5 multiplied by $K = 8.35$).

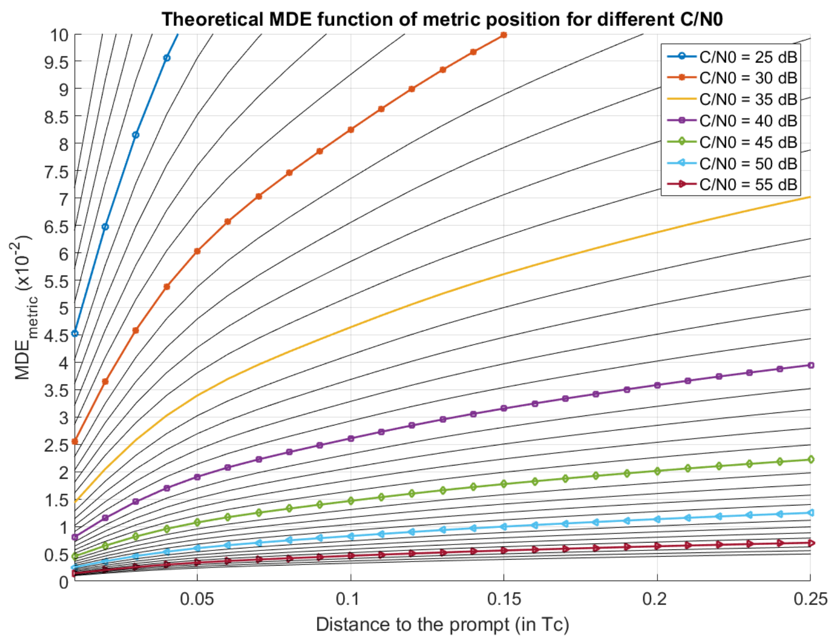

Fig. 6–Simple ratio metric performance thresholds for different C/N_0 and different distances to the prompt.

As a consequence, even if at a reference station the noise distribution on metrics is not Gaussian, it is possible to find an equivalent theoretical C/N_0 that permits to reduce the problem to an ideal theoretical case. It is then possible to use the new SQM performance representation and compare it against the estimated equivalent theoretical C/N_0. Nevertheless, if the noise distribution on metrics is far from Gaussian, it might be necessary to ensure that the results correctly bound the actual SQM performance. Due to the lack of data, this is not used in this article but could be of interest for future works.

Conclusion about SQM performance assessment methodology

As a conclusion of this section a new methodology to assess an SQM performance as a function of the equivalent theoretical C/N_0 at which a reference station operates was proposed. Note that this methodology is based on a number of assumptions on the setting of the airborne and reference receivers, and on the way the metrics tests are computed.

Considering that the coherent integration time to obtain the correlator outputs is 1 s, and that no smoothing is applied on metrics, the equivalent theoretical C/N_0 at the reference station can be as bad as 35 dB-Hz (from different results used in this article). In this condition, the MUDE is higher than 7.5 m with SQM2b and is equal to 5.1 m with the reference SQM, which is way above the targeted MERR of 3.5 m. If a 100-second moving average window is used to smooth metrics, the equivalent theoretical C/N_0 at the reference station would then be improved by 4 dB, leading to a MUDE of 3.2 m with the SQM2b and 2.8 m with the reference SQM.

Finally, note that results provided in this document are conservative:

- Conservative airborne filters with different bandwidths are assumed.
- The metrics tests composing the global SQM are considered as totally correlated.
- The global SQM assumes the use of only 1 reference station instead of a network of reference stations

Finally, SQM performance could be improved by a better mitigation of the multipath and/or station siting and/or the setting of a mask angle and/or increase the benefit of smoothing.

PERFORMANCE OF THE REFERENCE SQM ON NEW SIGNALS

Until now, only a GPS L1 C/A SQM has been investigated in order to show the methodology based on current signals and compare it against the open literature. Let us know look at new GNSS signals.

The tested reference SQM for Galileo E1C signal consists of 100 metrics:

- 50 $metric_x$ with $x = -0.25{:}\,0.01{:} -0.01$ and $x = 0.01{:}\,0.01{:}\,0.25$ in E1C chip unit,
- 25 $metric_{x+x}$ and 25 $metric_{x-x}$ with $x = 0.01{:}\,0.01{:}\,0.25$ in E1C chip unit.

The tested reference SQM for Galileo E5a and GPS L5 signals consists of 40 metrics:

- 20 $metric_x$ with $x = -1{:}\,0.1{:} -0.1$ and $x = 0.1{:}\,0.1{:}\,1$ in E5a chip unit,
- 10 $metric_{x+x}$ and 10 $metric_{x-x}$ with $x = 0.1{:}\,0.1{:}\,1$ in E5a chip unit.

The limitation of the location of the correlator outputs is justified by three main reasons:

- ICAO TM like distortions are more visible around the prompt. It is not necessary to monitor the correlation function at an important distance from the prompt.
- Correlator outputs located at an important distance from the prompt are more subject to multipath. With the selected correlator outputs range, the multipath impact is limited.
- A time delay of 10 ns between two correlator outputs is nowadays reachable.

Reference SQM performance for Galileo E1C

More distortions are tested on new signals because of the larger threat space presented in Table 2. For Galileo E1C, 39455 distortions are generated (12 TM-A1, 80 TM-A2, 1022 TM-B on area1, 1717 TM-B on area2, 14303 TM-C on area1 and 22321 TM-C on area2). Figure 7 shows the reference SQM performance for Galileo E1C. The dashed line represents the targeted MERR for DFMC SBAS on L1 (1.55 m). It can be seen that to satisfy the ICAO requirements, the equivalent C/N_0 of a monitored Galileo E1C signal must be at least equal to 38.5 dB-Hz. This value can be considered as reached assuming that a 100-second moving average window is applied on the metrics tests based on the evaluation proposed in the previous section.

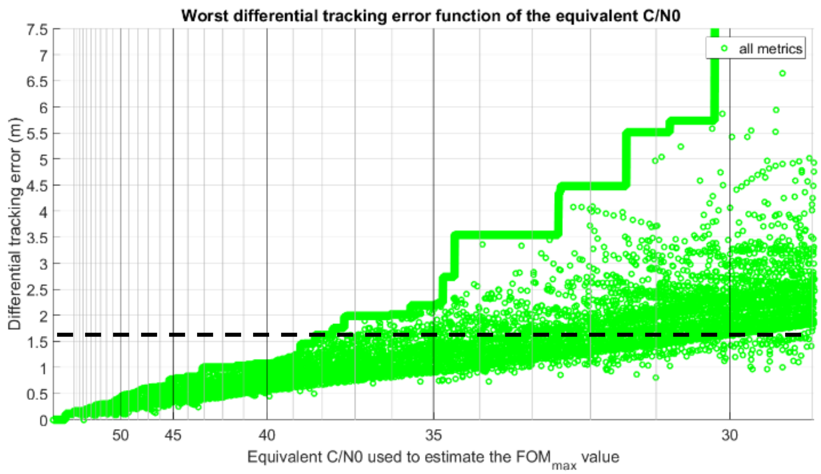

Fig. 7–Reference SQM performance considering the proposed Galileo E1C TM.

It appears that SQM performance is slightly better on Galileo E1C than on GPS L1 C/A using the same reference SQM. This can be explained by the fact that the narrower the correlation function peak is, the more the correlation function is affected by the ICAO-like distortions.

Reference SQM performance for Galileo E5a and GPS L5

For Galileo E5a and GPS L5, 21450 distortions are generated (12 TM-A, 408 TM-B on area1, 736 TM-B on area2, 5526 TM-C on area1 and 14768 TM-C on area2).

Figure 8 shows the reference SQM performance for Galileo E5a (and GPS L5). To satisfy the MERR requirement of 2.78 m on Galileo E5a and GPS L5, the equivalent theoretical C/N_0 can be as low as 26 dB-Hz. This should be easily the case at all reference stations. SQM required performance is clearly easier to reach on Galileo E5a (and GPS L5) than on GPS L1 C/A and Galileo E1C.

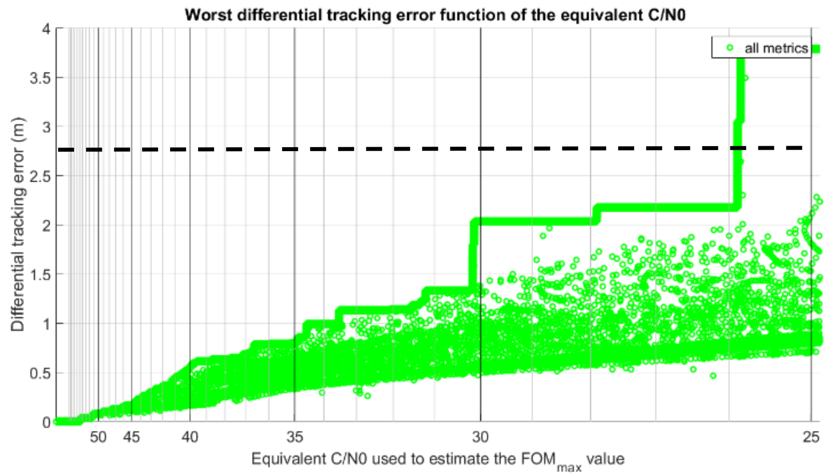

Fig. 8–Reference SQM performance considering the proposed Galileo E5a TM.

SIMPLIFICATION OF THE SQM

The considered reference SQM for each signal is quite complex in terms of number of metrics tests. It is thus interesting to see if it could be simplified. For instance, some metrics tests might be redundant to detect particular threats. Additionally, there is an interest in reducing the number of correlator outputs and metrics used to have simpler reference receivers, which can be operated more easily. Therefore, a simplification process is proposed to reduce the number of metrics used by the SQM.

General considerations

[19] shown that some metrics tests are more able to detect distortions than other. Indeed, [19] looked at the influence of three parameters on the SQM performance:

- the area covered by the correlator outputs used by the reference SQM,
- the distance between two correlator outputs used by the reference SQM ,
- the use of the difference and the sum ratio metrics.

From this study several general results were put forward:

- Distortions detection with metrics based on correlator outputs distant from the correlation function main peak (> 200 ns) is more difficult than with metrics based on correlator outputs close to the prompt. Indeed, second order analog distortions are attenuated according to a damping factor that reduces the distortion further away from the peak. Moreover, the furthest the correlator location, the more affected by multipath.
- The use of additional correlator outputs close to each other (< 10 ns) does not increase detection performance. It is due to the fact that the lowest period of ringing effects considered in this document is equal to $1/(19 \times 10^{-6}) \approx 50$ ns and that high frequency phenomena are filtered out by the airborne and reference RF filters (24 MHz maximum).
- The difference ratio metric is not able to detect symmetric distortions that can have a threatening impact on differential users.

In the following, the aim of the SQM simplification is to reduce the number of metrics (among all available metrics of the reference SQM) while obtaining suitable SQM performance. The definition of suitable performance can depend upon the application but has to be clearly defined to make the simplification relevant.

The simplification criterion consists in finding the smallest metrics tests set that allows reaching the same SQM performance as the reference SQM whatever the value of the equivalent C/N_0. The process to find the simplified SQM is represented in Figure 11. The outcome of the process is:

- For Galileo E1C, a simplified SQM that reaches performance of the reference SQM (red crosses on Figure 9) is reduced to 30 metrics (and 35 correlator outputs):
    - 12 $metric_x$ with $x = -0.24, -0.11, -0.09, -0.01, 0.02, 0.07, 0.08, 0.09, \ 0.11, 0.12, 0.13, 0.21, 0.25$ in E1C chip unit,
    - 14 $metric_{x+x}$ with $x = 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.16, 0.24$ and 0.25 in E1C chip unit,
    - 4 $metric_{x-x}$ with $x = 0.11, 0.12, 0.14, 0.25$ and 0.25 in E1C chip unit.
- For Galileo E5a, a simplified SQM that reaches performance of the reference SQM (red plot on Figure 10) is reduced to 11 metrics (and 14 correlator outputs):
    - 5 $metric_x$ with $x = -0.1, 0.1, 0.8, 0.9, 1$ in E5a chip unit,
    - 5 $metric_{x+x}$ with $x = 0.1, 0.4, 0.6, 0.7, 0.8$ in E5a chip unit,
    - 1 $metric_{x-x}$ with $x = 1$ in E5a chip unit.

Note that other simplified SQMs with the same number of metrics exist.
Figure 9 and Figure 10 show that the MUDE of the simplified SQMs are the same as the MUDE of the reference SQM for all equivalent C/N_0 values. Indeed, the two continuous lines are superimposed.

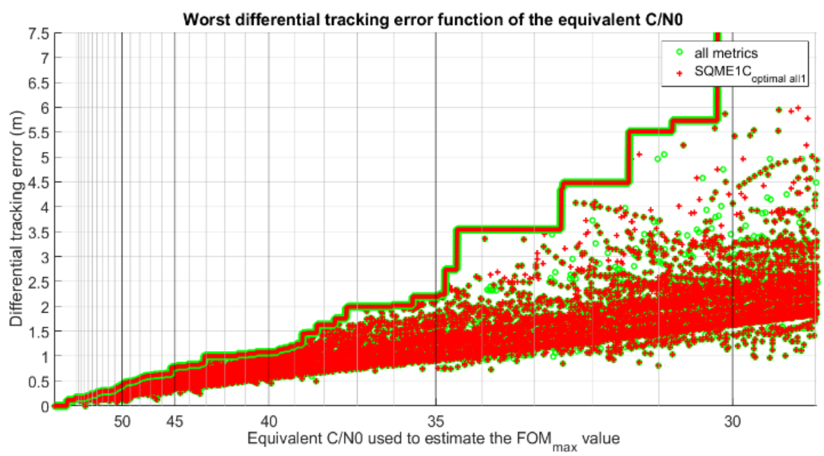

Fig. 9–Simplified SQM (red crosses) compared to the baseline SQM (green circle) for Galileo E1C.

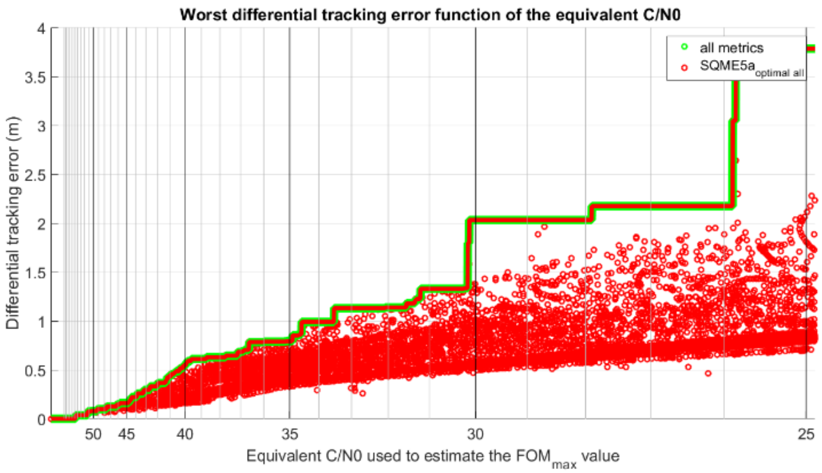

Fig. 10–Simplified SQM (in red) compared to the baseline SQM (in green) for Galileo E5a.

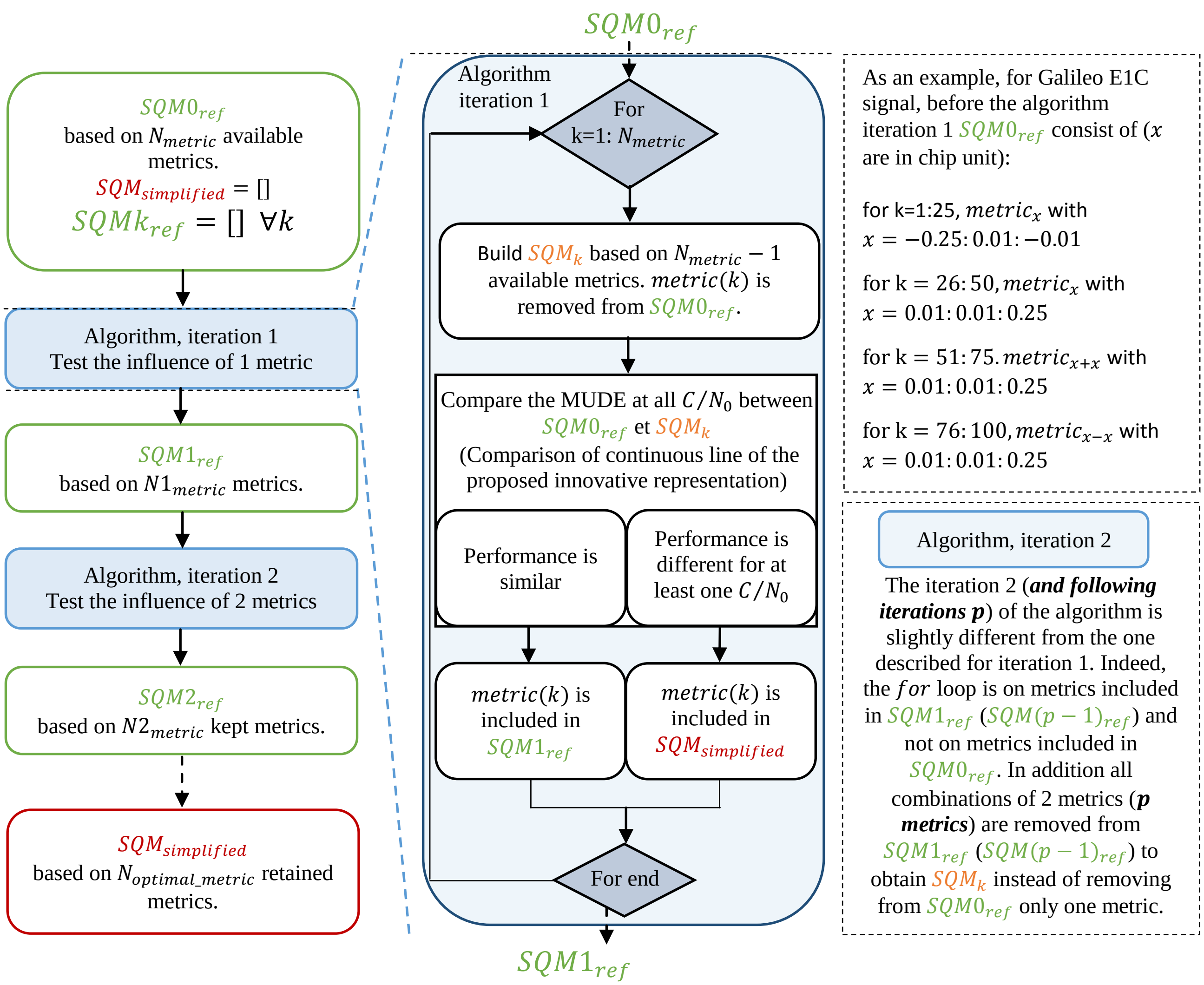

Fig. 11–Algorithm to design a simplified SQM.

From the design of the simplified SQM on Galileo E1C signal, it can be seen that:

- the most used correlator outputs are situated around $0.1\,T_c$ from the prompt and not necessarily close to the prompt,
- the least used metric is the difference ratio metric,
- some metrics based on correlator outputs far away from the prompt (around $0.25\,T_c$) are present in the proposed simplified SQM,
- the same correlator outputs can be used by several metrics,
- less metrics and correlator outputs are necessary to monitor Galileo E5a and GPS L5 signals. This is mainly justified because, on these signals, the reference SQM is based on less metrics than to monitor Galileo E1C signal.

CONCLUSION AND FUTURE WORKS

This article tackles the design of SQM able to detect EWF that could occur on the new GNSS signals that will be used by civil aviation: Galileo E5a, GPS L5 and Galileo E1C. The proposed SQM performance was assessed theoretically taking into account the distortions from the assumed TM for each new signal, the expected DFMC user and reference configurations and specific types of metrics tests.

The main issue in SQM performance study is the determination of performance thresholds. This work proposed a new way of visualizing the SQM performance that directly links the SQM MUDE to an equivalent C/N_0 at the reference station (this equivalent C/N_0 is defined with respect to a reference configuration and might not be directly related with the actual C/N_0). This new evaluation of the SQM performance was shown to be adaptable to the cases in which the metrics tests are assumed Gaussian or not.

It was also established from the literature that the typical worst case equivalent theoretical C/N_0 of monitored signals at the reference station can be assumed as equal to 39 dB-Hz considering that metrics tests are smoothed over 100 s. In these conditions, the proposed reference SQM, based on a large number of correlator outputs, could reach the foreseen targeted ICAO performance for Galileo E5a and GPS L5 in DFMC conditions. The reference SQM for Galileo E1C was able to meet the assumed MERR requirement of 1.55 m (with almost no margin though), while this was not the case for GPS L1 C/A.

A simplification process of the reference SQM based on the limitation of metrics tests number was proposed. This simplification process allowed reduction of the SQM complexity to 30 metrics (based on 35 correlator outputs) on Galileo E1C and 11 metrics (based on 14 correlator outputs) on Galileo E5a and GPS L5 without degrading the SQM performance.

Future work will consist in:

- estimating accurately the statistical properties of the correlator output of a typical reference station in order to adapt the results found in this article,
- investigating the notion of time-varying SQM performance,
- studying other SQM simplification and optimisation processes following the example of the alpha metric concept [21],
- extending the proposed methodology to other signals (e.g. GLONASS, Beidou signals).

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