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## ABSTRACT

Galileo E1C, the pilot component of the E1 Open Service signal (CBOC(6,1,1/11) modulation), Galileo E5a and GPS L5 (BPSK(10) modulation) are signals that will be used by civil aviation receivers for pseudorange computation. 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 (TMs). Distortions incorporated in the TM are also called Evil WaveForm (EWF).
These TMs, and their associated parameter ranges, referred to as Threat Space (TS), are powerful and necessary tools to design and test the performance of Signal Quality Monitor (SQM). The SQM is a mean to detect the presence of dangerous signal distortions and is necessary to protect users with high requirements in terms of integrity, accuracy, availability, and continuity (for example civil aviation users). 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 this paper, SQMs for Galileo E1C and Galileo E5a will be designed and compared using a new representation introduced in [1]. Using this representation, different SQMs are compared and an optimized SQM is proposed to monitor signal distortions on Galileo E5a and Galileo E1C signals.

## INTRODUCTION

EWFs are distortions generated by the satellite payload and that could entail large errors on a differential GNSS user without being detected and are a burning issue for GNSS users with strict requirements. In order to represent signal distortions that could be generated by the payload, a proposition of Threat Models (TM) was made in 2001 for GPS L1 C/A [2]. The aim of this TM was to define the type of signal distortion that could be created by the GPS satellite payload and that could create a hazard for a civil aviation user. Nowadays, the proposition made in 2001 has been adopted by ICAO with the definition of three threat models for GPS L1 C/A signal [3]:

- TM-A which is associated to a digital failure,
- TM-B which is associated to an analog failure,
- TM-C which is a combination of the two first failures.

The advent of new GNSS signals requests new research in the SQM field. Indeed, new signals use different modulations. Consequently TMs have to be redefined and SQM efficiency regarding these new TMs must be assessed. A proposal for Galileo E1C and Galileo E5a signals TM is given in a previous publication [4]. These TMs will be the starting points for the work performed in this publication.

The aim of this paper, and the resulting structure is to detail the SQM process, to introduce the new representation to test SQM performance, to use this representation to estimate performance of a reference SQM on GPS L1 C/A, Galileo E5a and Galileo E1C signals and finally to propose optimal SQMs with same performance that reference SQMs. Results obtained for Galileo E5a are also valid for GPS L5, both BPSK(10)-modulated.

## CONTEXT OF THE STUDY

As a targeted requirement in this study, the maximum tolerable differential error (denoted as MERR in the literature) induced by an undetected distortion of the TM is fixed to 1.55 meters for Galileo E1C and 2.78 meters for Galileo E5a which are targeted values for civil aviation users in a dual-frequency dual-constellation context [5]. Nevertheless from results presented in this study, it is possible to assess SQM performances independently from MERR value. SQM performance is considered as acceptable if the maximum undetected differential error (MUDE) respecting the ICAO requirements for that SQM is below the MERR.

Design and performance of SQM are dependent upon:

- User (airborne) configurations to protect and reference station configurations. Receiver parameters of interest at user and reference levels are: the tracking technique (including the local replica modulation), the tracking pair correlator spacing and the RF front-end (technology, bandwidth and maximum group delay variation). The reference station configuration is fixed: its RF filter is considered as a 6-order Butterworth with a 24 MHz bandwidth (double sides) and its discriminator is an early minus late with a 0.1 chip spacing for Galileo E1C and GPS L1 C/A signals and 1 chip spacing for Galileo E5a signal. 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 and BPSK(10) for Galileo E5a signal. More configurations are tested at user level and are identical to configurations used in [1]. These configurations represent receiver architectures expected for civil aviation users. In particular, different types of filters are used, to account for the wide variety of filters encountered across multiple receiver manufacturers. All these filters satisfy ICAO requirements.
- The TM, or in other words, the distortions that have to be monitored. For Galileo E5a and Galileo E1C, performance of SQM will be evaluated from TMs proposed in [1] and [4]. Regarding GPS L1 C/A TM, the current ICAO TM is kept and is recalled in [3].

For the sake of simplicity, it is assumed in this publication that the SQM and differential corrections computation are performed by the same ground station referred to as the reference station.

## THEORETICAL SQM CONCEPT

SQM methodology has already been described as for example in [6] or [7] and consists of a test to evaluate if the signal is affected by a distortion or not. This test compares to a threshold the difference between a current metric value and the metric value in the nominal case. The threshold can be chosen differently depending on the application (detect distortions or assess SQM performance). Traditionally metrics are built from outputs of the correlation function. In this document, several metrics are introduced to build the test and metrics are estimated from correlator outputs.
Mathematically, the test on one metric (noted $Test_{metric}$) is equivalent to compare the following expression to a given threshold:

$$Test_{metric} = \frac{metric_{dist}^{i} - metric_{nom}}{threshold} \tag{1}$$

where

- $metric_{dist}^{i}$ is the current value of the metric which can be affected by a distortion. The index $i$ shows that this value is estimated based on one ranging signal $i$.
- $metric_{nom}$ is the nominal value of the metric. For example, the nominal value can consist in the median of that metric across all satellites in view [8]. Another method is to estimate the nominal value of metrics from the average value of that metric for a given PRN using previous measurements known to represent nominal conditions. In the simulations considered in this document, the nominal correlation function used to estimate nominal metrics is the ideal filtered correlation function.

### Performance threshold estimation

In order to know if faulty cases are detected with adequate $P_{ffd}$ and $P_{md}$, a Neyman Pearson hypothesis test is performed. The MDE or MDR (Minimum Detectable Error/Ratio) are performance thresholds that fulfills the ICAO requirements for a test based on only one metric ($Test = Test_{metric}$). The definition of the MDE based on one metric is given in [3] as:

$$MDE_{metric} = \left(K_{md} + K_{ffd}\right)\sigma_{metric} \tag{2}$$

where

- $K_{ffd} = 5.26$ is a typical fault-free detection multiplier representing a false detection probability of $1.5 \times 10^{-7}$ per test;
- $K_{md} = 3.09$ is a typical missed detection multiplier representing a missed detection probability of $10^{-3}$per test;
- $\sigma_{metric}$ is the standard deviation of measured values of the test metric;

For the above expression to hold, it is assumed that the noise affecting metrics is white and Gaussian. The Gaussian behavior of the noise affecting correlator outputs was verified in [6].

If several metrics are used, as it is envisaged in this paper, $P_{ffd}$ and $P_{md}$ have to be computed for each individual metric. $\left(K_{md} + K_{ffd}\right)$ is assessed in this document in a conservative way which is obtained when metrics are considered as totally dependent (see [1]). It entails that even if several metrics are used to define a performance test, the MDE fulfilling the ICAO requirements in terms of $P_{md}$ and $P_{ffd}$ can be modeled in a conservative way, on each metric, as:

$$MDE_{metric} = 8.35 \times \sigma_{metric} \tag{3}$$

The three types of metrics used in this document are elementary and are presented in Eq. (4), Eq. (5) and Eq. (6). These metrics are looked at for two main reasons:

- the simple ratio and the difference ratio metrics are currently used in SQM implemented in EGNOS [9].
- the value of $\sigma_{metric}$ for these three metrics can be derived theoretically in a simple way.

*Simple ratio metric* which is the easiest metric to implement and permits to detect all kind of correlation function distortions.

$$metric_x = \frac{I_x}{P} \tag{4}$$

*Difference ratio metric* which permits to detect distortions that affect the correlation function in an asymmetric way (asymmetric from the prompt) more efficiently than the simple ratio metric.

$$metric_{x-x} = \frac{I_{-x} - I_x}{P} \tag{5}$$

*And sum ratio metric* which permits to detect distortions that affect the correlation function in a symmetric way (symmetric from the prompt) more efficiently than the simple ratio metric.

$$metric_{x+x} = \frac{I_{-x} + I_x}{P} \tag{6}$$

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. Usually $P = I_0$ ( $x = 0$).

The use of a virtual prompt for metric normalization has been reported in [7]. Nevertheless in WAAS reference stations, a prompt is used. In this publication it is decided to use the classical prompt for metrics normalization for Galileo E1C, Galileo E5a, GPS L5 and GPS L1 C/A signals. This is the main difference with results provided in [1].

Metrics value can then be compared to its nominal value and finally divided by the MDE associated to that metric. Let us define the performance test $Test_{metric\_MDE}$ as:

$$Test_{metric\_MDE} = \frac{metric_{dist}^{i} - metric_{nom}}{MDE_{metric}} \tag{7}$$

As discussed previously, $MDE_{metric}$ is a function of $\sigma_{metric}$ making the assumption that the noise distribution on metrics is Gaussian. $\sigma_{metric}$ can be estimated theoretically for the three introduced metrics. Mathematical $\sigma_{metric}$ expressions are provided [1]. These expressions are valid when the noise distribution on correlator outputs is Gaussian (as assumed in [6], [10] or [11]) and when the $C/N_0$ is high enough as it can be considered at reference station level.

**Representation to Assess Theoretical Performance of SQM, example of GPS L1 C/A**

In this document, performance of SQM is assessed based on the highest differential error entailed by an undetected distortion from a given TM considering only the steady state (the transient state is not considered). Knowing the distortion

and the value of $MDE_{metric}$ it is possible to assess $Test_{metric\_MDE}$ for each metric and by consequence $Test_{MDE}$ which is the performance threshold test of a SQM based on several metrics.
Let us denote:

$$Test_{MDE} = max_{metric\_MDE}\left[Test_{metric\_MDE}\right] \tag{11}$$

Comparing $Test_{MDE}$ to 1, it is possible to know if a distortion from the TM is theoretically detected with a given $P_{ffd}$ and $P_{md}$ by a SQM for a given reference station configuration. Moreover, assuming user receiver configurations that have to be protected and the reference station configuration, the highest differential error induced by a given distortion of the TM between different users and the reference can be assessed independently from the SQM. This highest differential error is also called the maximum differential error.

Using simulations, $Test_{MDE}$ and maximum differential error values can be estimated for each distortion of the TM. $Test_{MDE}$ is independent from users to protect and depends upon, the reference receiver configuration, the SQM design implemented on the reference, the $C/N_0$ of incoming signals which will have a direct impact on $\sigma_{metric}$ and consequently on $MDE_{metric}$ and $Test_{metric\_MDE}$.

A reference SQM, based on a large number of correlator outputs, is used. This reference SQM is expected to have redundant metrics, and is probably to "expensive", from a computational point of view, to be implemented in operational reference receivers. However, thanks to its complexity, it is supposed to give the best performance for distortion monitoring. The reference SQM consists of:

- 50 $metric_x$ with $x = -0.25{:}\,0.01{:} -0.01$ and $x = 0.01{:}\,0.01{:}\,0.25$ in GPS L1 C/A chip unit,
- 25 $metric_{x+x}$ and 25 $metric_{x-x}$ with $x = 0.01{:}\,0.01{:}\,0.25$ in GPS L1 C/A chip unit.

The Fig. 1 left plot shows the maximum differential error induced by distortions from the TM defined by ICAO for GPS L1 C/A signal among the tested user configurations, as a function of the $Test_{MDE}$ value. The $C/N_0$ of the incoming signal is equal to 35 dBHz. This representation is comparable to the representation proposed in [8] except that in this document, the value of $Test_{MDE}$ is based on the $P_{md}$ and $P_{ffd}$ whereas in [8] the value of $Test_{MDE}$ is derived only from the $P_{ffd}$. Each point of the graph corresponds to one distortion of the TM with on the y-axis the highest impact on tested users and on the x-axis the value of $Test_{MDE}$. 1650 distortions are represented (12 from TM-A, 126 from the TM-B and 1512 from the TM-C). The continuous line corresponds to the higher bound.

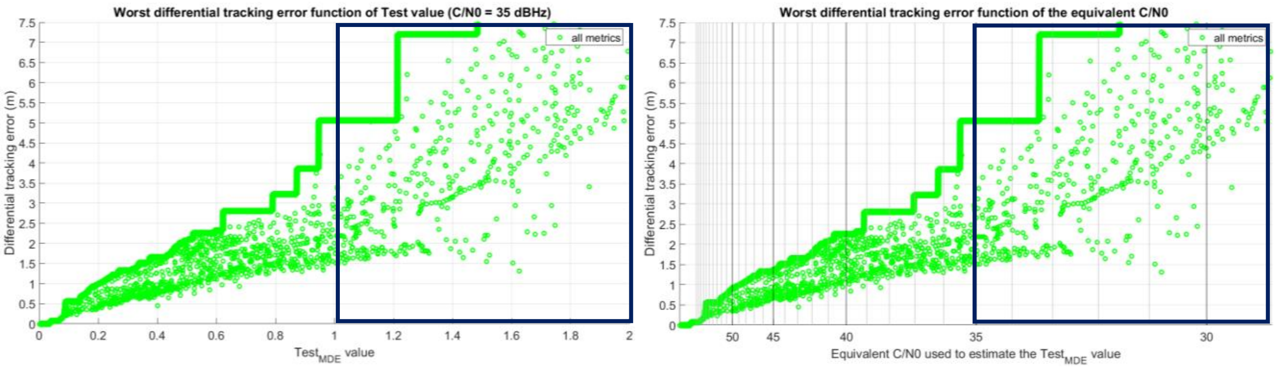


**Fig. 1**. *Example of worst differential tracking error function of* $\boldsymbol{Test_{MDE}}$.

Distortions included in the blue square of Fig. 1 are distortions detected by the reference SQM ($Test_{MDE} > 1$). The Maximum Undetected Differential Error (MUDE) can then been read by taking the largest differential tracking error for $Test_{MDE} < 1$. On the Fig. 1 left plot, the MUDE is equal to 5.1 m.

It is noticeable that MUDE is dependent upon the $C/N_0$ which is a drawback because MUDE has to be re-estimated depending on the $C/N_0$ at which a reference station is operating. Nevertheless, a relation exists between $C/N_0$ and the value of $Test_{MDE}$. Indeed, $C/N_0$ has an impact on $\sigma_{metric}$ which can be theoretically estimated. Then a relation exists between $\sigma_{metric}$ and $MDE_{metric}$, and therefore between $\sigma_{metric}$ and $Test_{MDE}$. The relation between $C/N_0$ in dBHz and $\sigma_{metric}$ is given by:

$$\sigma_{metric} = C_{metric}\sqrt{\frac{1}{T_{int} \times 10^{\frac{C/N_0}{10}}}} \tag{12}$$

Where $T_{int}$ is the coherent integration time chosen for the tracking ($T_{int} = 1$ sec). $C_{metric}$ is a parameter that does not depend upon the $C/N_0$ but depends upon the metric.
By consequence, it is possible to apply a scale change on the Fig. 1 left plot in order to have the worst differential tracking bias function of $Test_{MDE} = 1$ for different $C/N_0$. Fig. 1 right plot shows same results as on Fig. 1 left plot with a simple scale change. The blue square is still representing distortions detected by the SQM considering $C/N_0$ equal to 35 dBHz. One interest of the representation shown in the Fig. 1 right plot is that MUDE can be assessed for different $C/N_0$ from one figure.

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

To estimate the performance of SQM at a given reference station, it is necessary to know at which $C/N_0$ the MUDE has to be assessed. In this document, it is assumed that the noise distribution on metrics is white and Gaussian. In [1] a strategy to estimate SQM performance if the noise distribution is not Gaussian is developed.

Fig. 2 represents, through the dots, some $\sigma_{metric_x}$ (standard deviation of simple ratio metric $metric_x$) values that have been measured in real conditions. Three examples are proposed:

- 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 [12]. Red dots correspond to unsmoothed metrics and green dots to metrics smoothed by a 100 sec moving average.
- The last case in blue illustrates $\sigma_{metric_x}$ obtained from a data collection made by Capgemini with a Novatel GIII receiver. The data collection was one hour long and $\sigma_{metric_x}$ was estimated from all satellites in view. The worst $\sigma_{metric_x}$ 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.

Fig. 2 also shows the theoretical link between $\sigma_{metric_x}$ and the $C/N_0$ assuming that only thermal noise is present, according to relations presented in [1]. One curve corresponds to one $C/N_0$.
From Fig. 2, it can be approximated that the LAAS receiver is working at an equivalent $C/N_0$ of 35.1 dBHz in the worst case if metrics are unsmoothed whereas the equivalent $C/N_0$ is equal to 39 dBHz with smoothed metrics. With unsmoothed metrics, standard deviations reported from the Capgemini's data collection correspond in the worst case to an equivalent $C/N_0 = 35.9$ dBHz.

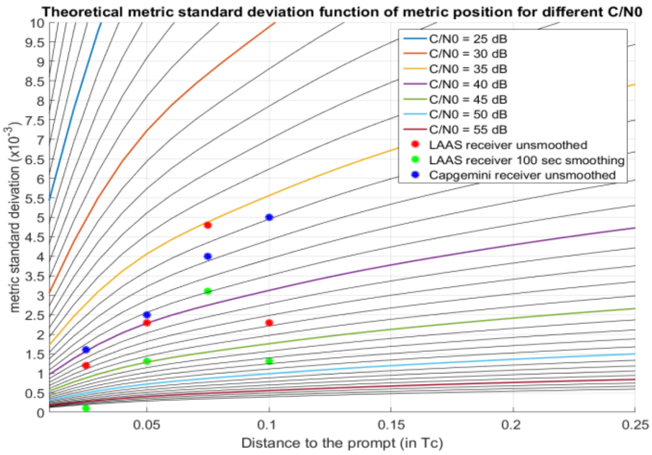


Fig. 2. *Example of reference station metrics standard deviations compared to theoretical values. One curve corresponds to one iso-$C/N_0$.*

One important remark is that the 100 sec smoothing of the metrics seems to entail only a 4 dB improvement in the equivalent $C/N_0$ in the real data whereas a 10 dB improvement would be expected if the raw metrics were uncorrelated in time.

### PERFORMANCE OF THE REFERENCE SQM ON GALILEO E5A AND E1C

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 signal 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.

On the left of Fig. 3 is shown the maximum differential error entailed by distortions of the Galileo E1C TM as function of the equivalent theoretical reference $C/N_0$ for the E1C reference SQM. On the right, same results for a Galileo E5a signal are shown based on the E5a reference SQM.

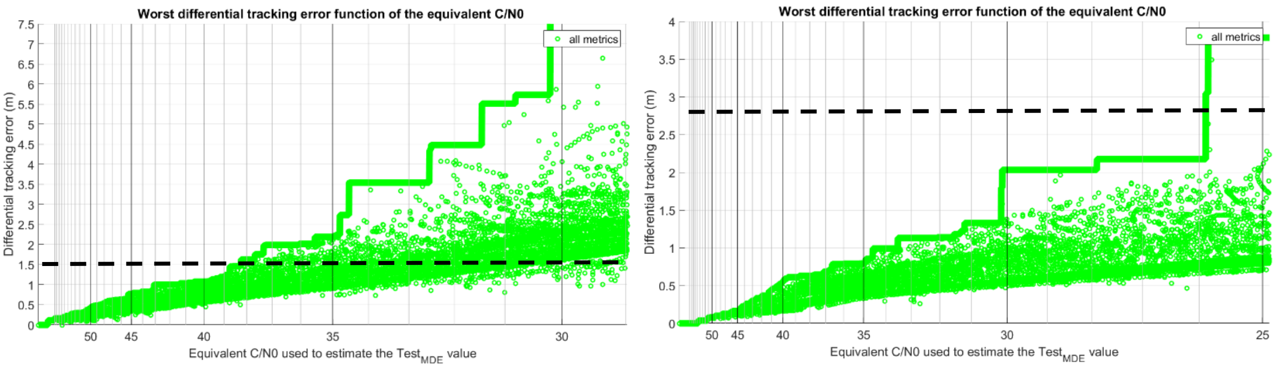


Fig. 3**.** *Reference SQM performance considering the proposed Galileo E1C TM (left) and Galileo E5a TM (right).*

From Fig. 3, it can be seen that to satisfy the requirement on the MUDE of 1.55 meters (represented by the black dashed line), the equivalent $C/N_0$ must be higher than 38.5 dBHz. This value of 38.5 dBHz is considered as reached assuming that a 100-sec moving average window is applied on metrics even if a small margin is observed. Indeed it was seen in the previous section that the equivalent theoretical $C/N_0$ estimated in real conditions was equal to 39 dBHz. To satisfy the requirement on the MUDE of 2.78 meters on Galileo E5a and GPS L5, the $C/N_0$ can be as low as 26 dBHz.

It appears that SQM performance is slightly better on Galileo E1C than on GPS L1 C/A using in both cases the reference SQM. Moreover, SQM required performance is clearly easier to reach on Galileo E5a than on GPS L1 C/A and Galileo E1C. The fact that SQM performance is better on one modulation than on another one 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. Therefore, it is easier to detect distortions on sharp correlation function peak.

## OPTIMIZATION OF THE SQM

Reference SQMs have redundant metrics and an optimization process is proposed to reduce the number of metrics used by the SQM. The optimization criterion consists in finding the smallest metrics set that permits to reach performance of the reference SQM whatever the value of the equivalent $C/N_0$ is. To find the optimal SQM, the principle is represented in Fig. 4.

For Galileo E1C, an optimal SQM that reach performance of the reference SQM (see the Fig. 5 left plot) is reduced to 30 metrics (and 34 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 $x = 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.16, 0.24, 0.25$ in E1C chip unit,
- 4 $metric_{x-x}$ with $x = 0.11, 0.12, 0.14, 0.25$ in E1C chip unit.

For Galileo E5a, an optimal SQM that reaches performance of the reference SQM (see the Fig. 5 right plot) is reduced to 11 metrics (and 13 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.

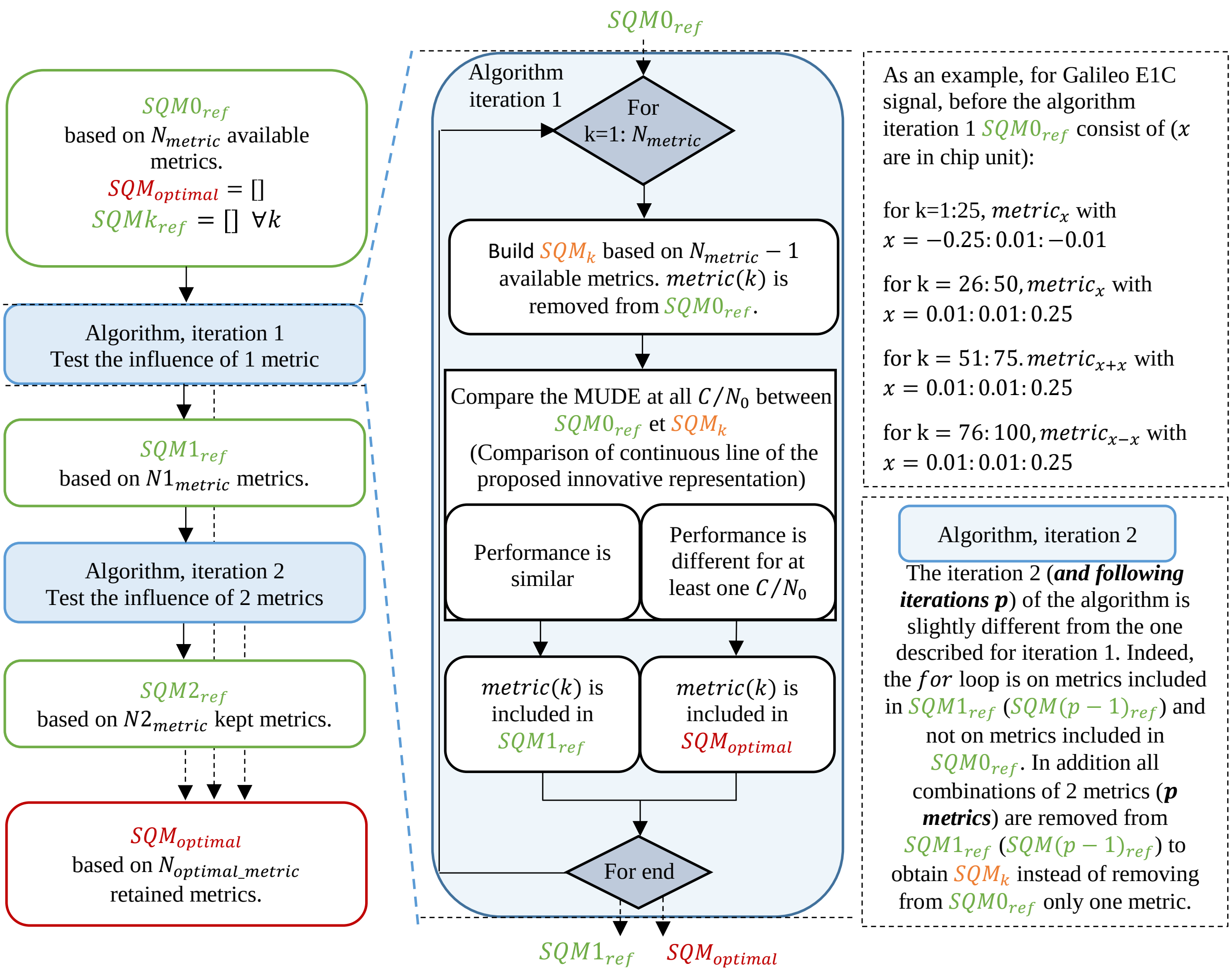


Fig. 4. *Algorithm to design an optimized SQM.*

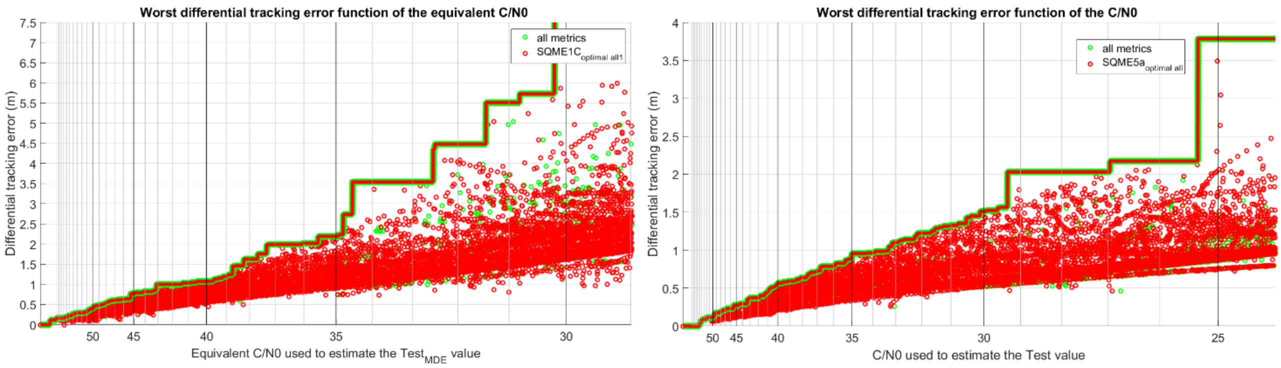


Fig. 5. *Optimal SQM (in red) compared to the baseline SQM (in green).Galileo E1C (left), Galileo E5a (right).*

For both optimal SQMs, other optimal SQMs with the same number of metrics exist. From Fig. 5 it can be seen that, as expected, the MUDE of optimized SQMs is equal to MUDE of the reference SQM whatever the equivalent $C/N_0$ is. Indeed, the two continuous lines are superimposed. From the design of the optimal 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 optimal 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

This paper tackles the design of SQM regarding new GNSS signals: Galileo E5a and Galileo E1C. SQM performances are assessed theoretically for reference SQMs defined in the publication. SQM performance is dependent upon, distortions from the TM that have to be detected, user and reference configurations under discussion and the type of metrics used to design the SQM. The concept of the representation used to estimate SQM performance is introduced in [1] and reused in this paper. Compared to [1], new results are provided: a prompt is used to normalize metrics instead of a virtual prompt and an optimization process is proposed. The purpose of the optimization is to decrease the number of metrics on which the SQM relies, while still reaching performance of the reference SQM.

SQM based on all available metrics shows better performance on Galileo E5a signal than on Galileo E1C and GPS L1 C/A signals. Moreover, SQM performance is slightly better on Galileo E1C than on GPS L1 C/A. These results can be explained by the different shapes of the correlation function for the different modulations. The narrower the correlation function peak is, the more the correlation function is affected by the ICAO-like distortions. Therefore, it is easier to detect distortions on sharp correlation function peak.

It was established from real measurements that the equivalent theoretical $C/N_0$ at reference station level can be assumed as equal to 39 dBHz considering that metrics are smoothed. The value of 39 dBHz is particularly high but it is reminded that it does not correspond to the true $C/N_0$ observed from signals but to an equivalent theoretical $C/N_0$ that takes into account the effect of the smoothing. For this $C/N_0$ the MUDE is lower than 1.55 meters on Galileo E1C and lower than 2.78 meters on Galileo E5a.

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