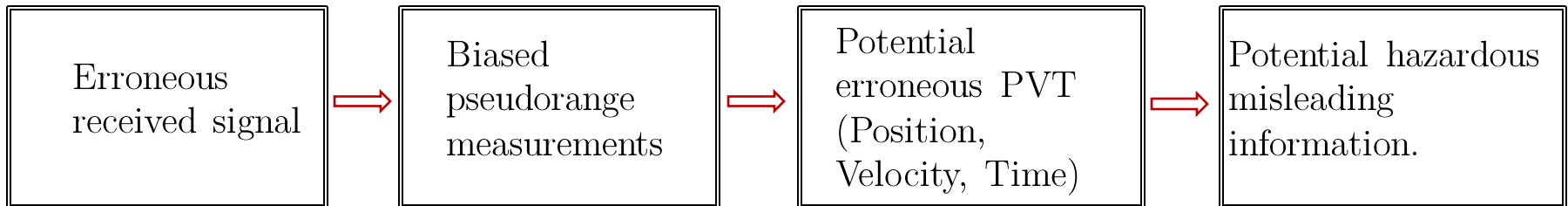


Evil Waveform Threat and Monitoring for New GNSS signals

Jean-Baptiste PAGOT
ITSNT 2016, Toulouse
November 16th

GNSS in civil aviation and signals distortions (1/3)

GNSS is used in **civil aviation** application which requires a very high quality of service for the most demanding phase of flight. The quality of the service is based on four **requirements** (integrity, accuracy, availability and continuity) defined by ICAO.



GNSS in civil aviation and signals distortions (2/3)

Augmentation systems including GBAS and SBAS are defined to improve the quality of the service. GBAS and SBAS have two main functions:

- send **differential corrections**,
- monitor signals (to detect non nominal conditions) and send timely alerts.

Differential correction concept: Pseudorange errors are estimated at known reference location and are sent to the user which can correct its own pseudorange measurements.



Differential corrections are able to correct errors that affect in the same way the reference and the user.

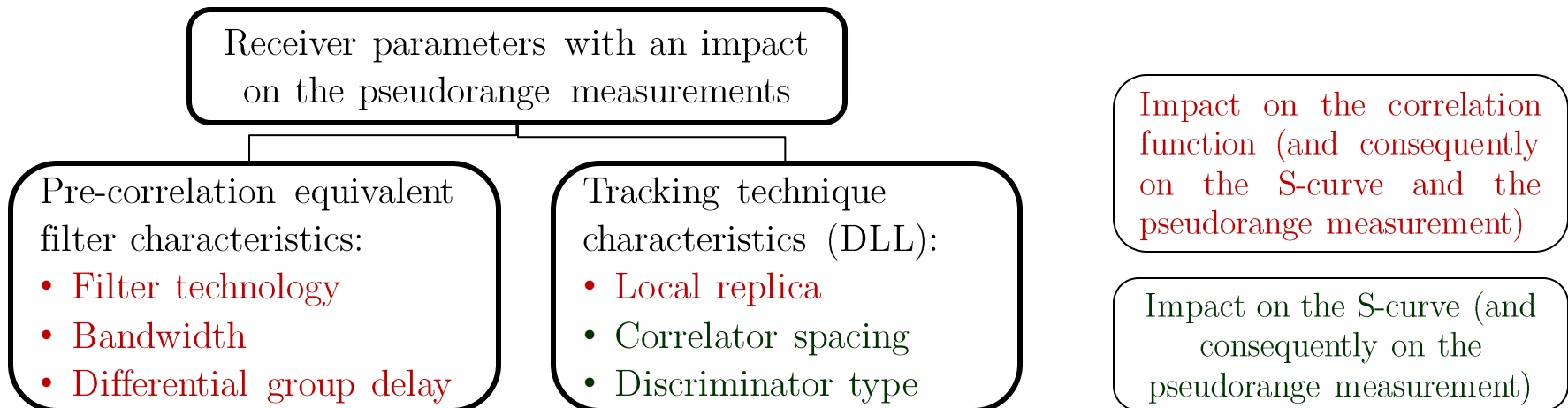
To meet stringent requirements (especially integrity) it is necessary to monitor any source of potential degradation of the service especially when they cannot be corrected differentially because having an impact which depends upon the receiver configuration.

GNSS in civil aviation and signals distortions (3/3)

Signal distortions generated by the satellite can degrade the quality of the GNSS service and are classified in two categories:

- Nominal distortions generated by healthy satellites due to payload imperfection.
- Non-nominal distortions (**Evil Waveform**) that are triggered by a satellite payload failure.

Signal distortions are a threat for differential users because their impact on receiver is dependent upon the receiver configuration.



Evil WaveForm (EWF) problem (1/2)

The first and largest EWF was observed on SV19 (GPS) in 1993 [Mitelman, 2004].

Power Spectral Density:

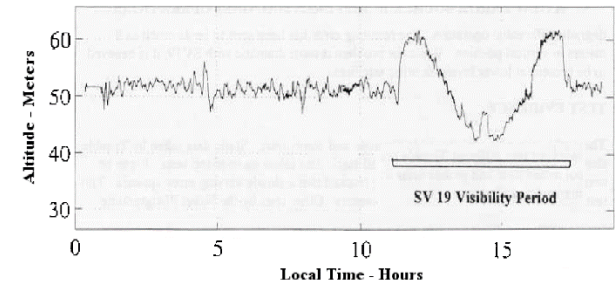
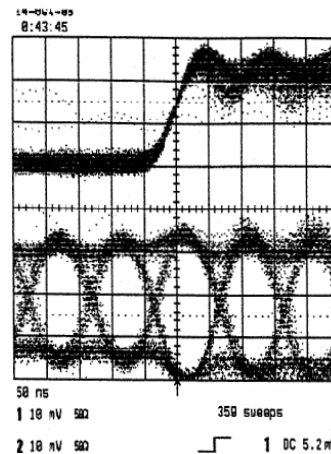
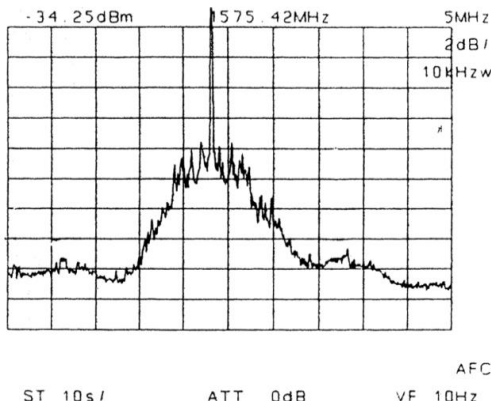
- Asymmetry
- Central peak

Time domain:

- Zero crossings not aligned (I and Q not in phase)
- Small ringing distortions

Position domain:

- error up to 8 meters



Other GNSS signal distortions were observed [Brenner et al., 2009], [FAA, 2016], and it can be difficult to make the difference between a nominal and a non-nominal distortions.

Evil WaveForm (EWF) problem (2/2)

Civil aviation problem: EWF poses an integrity issue when:

- Not detected by specific monitors in augmentation systems (SBAS, GBAS)
- Leading to a threatening differential tracking bias (out of requirements)

Action 1: ICAO (International Civil Aviation Organization) created a **Threat Model** (TM) which characterizes GPS L1 C/A (expected) non-nominal signal distortions. [ICAO, 2006]

Action 2: Design at GBAS and SBAS levels **Signal Quality Monitors** (SQM) that are able to detect all threatening distortions defined in the TM leading to an hazardous impact on differential airborne users.

TM: characterize the threat

SQM: neutralize the threat

PhD Objectives

- The PhD is focused on SBAS application regarding new GNSS signals (Galileo E5a, Galileo E1 pilot component (Galileo E1C) and GPS L5 pilot component).
- PhD objectives are:
 - The investigation of nominal distortions on these new signals (not tackled in this presentation).
 - The proposition of a TM for new signals.
 - The design of a SQM robust against distortions from the TM.
 - The verification of SQM performance.

Presentation outline

I. Proposition of TM for new signals

II. SQM for new signals

III. Conclusions and future works

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1. Current GPS L1 C/A Threat Model
2. Adaptation of the current TM to new signals
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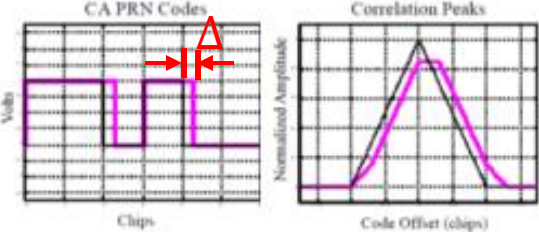
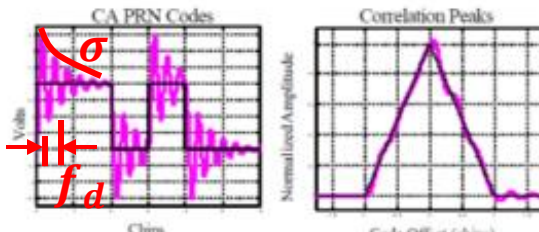
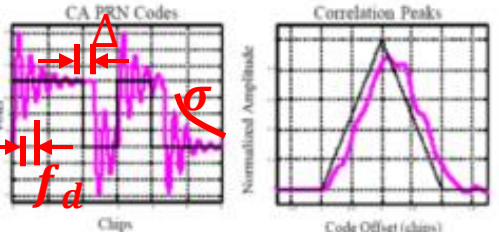
1. Current GPS L1 C/A Threat Model (1/2)

EWF causes distortions which are dependent upon the tracking technique and correlation function shape. On GPS L1 C/A signal, EWF are distortions that are able to generate on the correlation function the three threatening effects [ICAO 2006]:

- False peak
- Flat zone
- Asymmetry

I. Proposition of TM for new signals

1. Current GPS L1 C/A Threat Model (2/2)

| <p>TM-A: digital failure</p>  <p>CA PRN Codes: Shows a square wave with a zero-crossing delay Δ between rising and falling transitions. The y-axis is 'Volts' and the x-axis is 'Chips'.</p> <p>Correlation Peaks: Shows a sharp peak at the correct code offset. The y-axis is 'Normalized Amplitude' and the x-axis is 'Code Offset (chips)'.</p> | <p>TM-B: Analog failure</p>  <p>CA PRN Codes: Shows a square wave with ringing distortion. The y-axis is 'Volts' and the x-axis is 'Chips'. Parameters σ and f_d are indicated.</p> <p>Correlation Peaks: Shows a peak with a significant tail. The y-axis is 'Normalized Amplitude' and the x-axis is 'Code Offset (chips)'.</p> | <p>TM-C: Combination of TM-A and TM-B</p>  <p>CA PRN Codes: Shows a square wave with both zero-crossing delay Δ and ringing distortion. The y-axis is 'Volts' and the x-axis is 'Chips'. Parameters Δ, f_d, and σ are indicated.</p> <p>Correlation Peaks: Shows a peak with a tail. The y-axis is 'Normalized Amplitude' and the x-axis is 'Code Offset (chips)'.</p> |
|--|--|--|
| $10 \text{ ns} \leq \Delta \leq 120 \text{ ns}$ | <p>/</p> | $10 \text{ ns} \leq \Delta \leq 120 \text{ ns}$ |
| <p>/</p> | $4 \text{ Mhz} \leq f_d \leq 17 \text{ Mhz}$ | $7.3 \text{ Mhz} \leq f_d \leq 13 \text{ Mhz}$ |
| <p>/</p> | 0.8 MNepers/s $\sigma \leq 8.8 \text{ MNepers/s}$ | 0.8 MNepers/s $\sigma \leq 8.8 \text{ MNepers/s}$ |

- Δ : Zero crossing delay (lead/lag) between rising and falling transitions.
- f_d : Ringing distortion frequency.
- σ : Ringing distortion damping factor.

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I. Proposition of TM for new signals

2. Adaptation of the current TM to new signals (1/2)

It is proposed to extend the ICAO GPS L1 C/A TM to new signals

For studied modulations and signals:

- Tracking techniques are similar (Early - Late).
- The shape of the correlation function on the tracked area is similar (triangular shape).
- The 3 correlation function effects are still a threat:
 - False peak
 - Flat zone
 - Asymmetry

- Absence of non-nominal distortion occurrence.
- Same assumptions (and lack of information) on payload failure mode.

I. Proposition of TM for new signals

2. Adaptation of the current TM to new signals (2/2)

- Same kinds of distortions as in ICAO Threat Model are adopted.
 - Analog distortions: “it consists of the output from a second order system when the nominal (C/A) code baseband signal is the input” [ICAO, 2006]. The strategy is to use the current second order filter as in TM-B, and **find a limit for parameters range (f_d and σ)**.
 - To characterize digital distortions, TM-A is more difficult to apply on a CBOC-modulated signal (Galileo E1C) because of the sub-carrier. Lead/Lag can affect code chip or sub-chip transitions.
 - Combination of analog and digital distortions are also considered (similar to TM-C).

Apply TM-B is straightforward whatever the modulation is.

Apply TM-A is more difficult on Galileo E1C, different TM-A can be envisaged.

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I. Proposition of TM for new signals

3. Concept to design the Threat Space (1/2)

- TM defines from 3 parameters: f_d, Δ, σ . Parameters range referred to as the TS cannot be limited based on same considerations as on GPS L1 C/A signal.
- Two user considerations are proposed to limit the Threat Space (TS):

1) The impact of a distortion on a receiver working with differential corrections:

If a distortion leads to small differential bias (smaller than the maximum differential error: $\Delta_{err_max} = 1$ meter in the manuscript) for all considered user/reference configurations, the corresponding TM parameters can be removed from the TS.

2) The impact of a distortion on the reference:

If a signal distortion leads to reference tracking bias higher than a limit (20 meters in this manuscript), the distortion is not included in the TS because detected by the ground segment.

I. Proposition of TM for new signals

3. Concept to design the Threat Space (2/2)

The TS depends upon user and reference receiver configurations and notably upon parameters presented in the table. Following parameters are used in the PhD and represent the expected wide variety of values used by civil aviation.

| | Galileo E1 signal (CBOC(6,1)) and GPS L1 C/A | | Galileo E5a signal (BPSK(10)) | |
|---|--|-----------------------------------|---------------------------------|-----------------------------------|
| | reference | user | reference | user |
| Tracking technique | E-L (BOC(1.1) local replica) | E-L (BOC(1.1) local replica) | E-L (BPSK(10) local replica) | E-L (BPSK(10) local replica) |
| Correlator spacing | 0.1 chip | 0.08 and 0.12 chip | 1 chip | 0.8 and 1.2 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 |
| Filter type | 4 filters are tested (6-th order Butterworth, 0-group delay resonator, 150 nsec differential group delay resonator, 150 nsec differential group delay 6-th order Butterworth). Only the 6-th order Butterworth filter is applied to the reference to estimate the tracking error. | | | |

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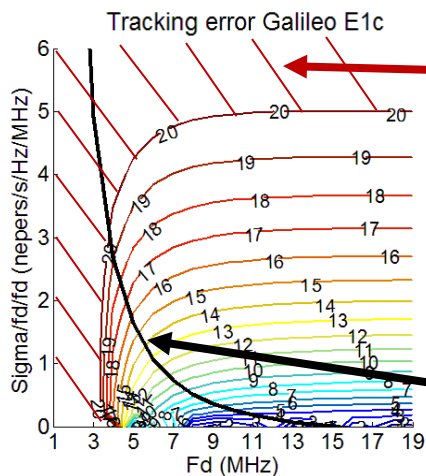
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I. Proposition of TM for new signals

4. TM-B design (1/3)

- To limit the TS, a new space is proposed to study distortions of the TM: $\frac{\sigma}{(f_d)^2}$ function of f_d space (traditionally the σ function of f_d space is used).
 - It permits to study distortion with high σ values, which were ignored in the ICAO models, while creating large differential errors.
- Impact of TM-B distortions on the reference tracking error is given in the new space (in meters). Galileo E1C.



High $\frac{\sigma}{(f_d)^2}$ distortions can be removed from the TM because detected by the reference (the tracking error is higher than 20 meters)

$\sigma = 26$ Mnepers/s as an example in the new space.

I. Proposition of TM for new signals

4. TM-B design (2/3)

$$\left(\frac{\sigma}{(f_d)^2} \right)_{max}$$

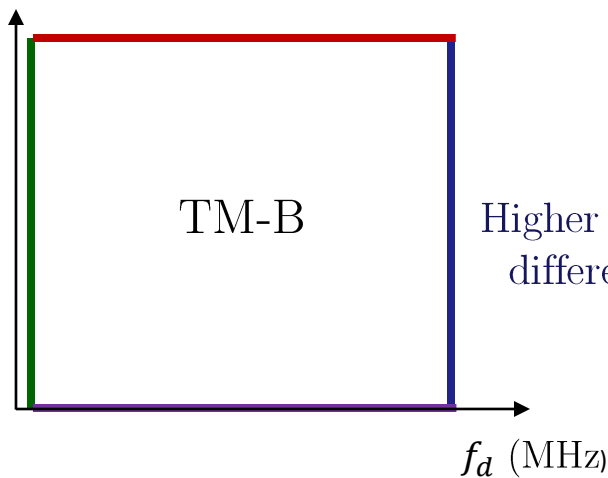
Higher ratios are detected by the ground station.
(Tracking error on the reference station higher than 20 meters)

$$\frac{\sigma}{(f_d)^2}$$

(nepers/s/Hz/MHz)

f_{d_min}

Smaller frequencies are detected by the ground station. (Tracking error on the reference station higher than 20 meters)



f_{d_max}

Higher frequencies lead to «small» differential errors (lower than 1 meter).

$$\left(\frac{\sigma}{(f_d)^2} \right)_{min}$$

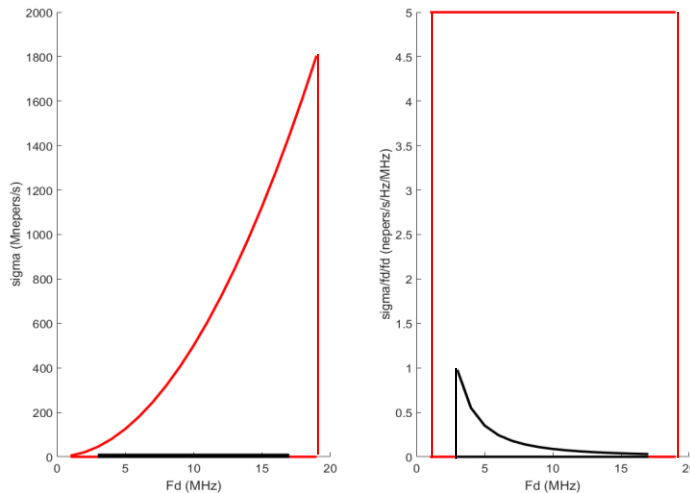
Lower ratios lead to divergent signals

I. Proposition of TM for new signals

4. TM-B design (3/3)

- TM-B proposition in a new distortion space: the $(\frac{\sigma}{f_d}^2; f_d)$ system which gives the possibility to run through high σ values quickly.
- High σ values are included in the proposed TMs compared to the ICAO TM-B (represented in black in the classical $(\sigma; f_d)$ representation).

TM proposition in two spaces



Classical $(\sigma; f_d)$ space

$(\frac{\sigma}{f_d}^2; f_d)$ space

| | Galileo E1C | Galileo E5a and GPS L5 |
|---|-------------|------------------------|
| f_{d_min} MHz | 1 | 3 |
| f_{d_max} MHz | 19 | 19 |
| $(\frac{\sigma}{f_d}^2)_{min}$ nepers/s/Hz/MHz | 0 | 0 |
| $(\frac{\sigma}{f_d}^2)_{max}$ nepers/s/Hz/MHz | 5 | 3.5 |

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I. Proposition of TM for new signals

5. Conclusion (1/2)

Proposition of two threats models (Galileo E5a and Galileo E1C signals) based on current ICAO threats established for the GPS L1 C/A signal.

| | | | Galileo E1C | Galileo E5a GPS L5 |
|---------------------------|-----------|---|-------------|-----------------------|
| TM-C like | TM-B like | $f_{d \min}$ (MHz) | 1 | 3 |
| | | $f_{d \max}$ (MHz) | 19 | 19 |
| | | $\left(\frac{\sigma}{(f_d)^2}\right)_{\min}$ (nepers/s/Hz/MHz) | 0 | 0 |
| | | $\left(\frac{\sigma}{(f_d)^2}\right)_{\max}$ (nepers/s/Hz/MHz) | 5 | 3.5 |
| | TM-A like | $\Delta_{\min} = -\Delta_{\max}$ (chips) | 0.12 | 1.2 |
| | TM-A2 | $\Delta_{11\max}$ (chips) | 0.1 | / |
| $\Delta_{11\max}$ (chips) | | 0.08 | / | |

I. Proposition of TM for new signals

5. Conclusion (2/2)

- The approach to limit the Threat Space is based on keeping only signal distortions with:
 - An impact higher than 1 meter on differential users in a specific receiver configuration range. This value is fixed by requirement.
 - An impact smaller than 20 meters on a reference station using an E-L discriminator with a correlator equal to 0.1 chip and an equivalent RF filter modelled by a 6-order Butterworth with a 24 MHz bandwidth.
- Bring forward that second orders distortions with high damping factors, not included in the current designed ICAO GPS L1 C/A TM-B, could be critical.
- Presentation of an new space to study signal distortions: $(\frac{\sigma}{(f_d)^2}; f_d)$

The next step is then to design and test performance of a SQM related to the proposed TM

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2. SQM definitions
3. SQM new representation
4. SQM on new signals and optimization

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II. SQM for new signals

1. Proposed constraints to design and test the SQM (1/2)

SQM is based on test on metrics which use correlator outputs to estimate if a distortion affects the correlation function (i.e. the signal).

SQM performance is dependent upon:

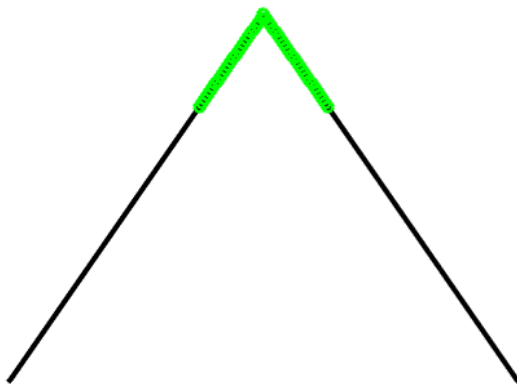
- The considered signal: GPS L1 C/A and Galileo E1C results are shown in this presentation. (Galileo E5a and GPS L5 results are available in the PhD)
- The considered TM: TMs presented in previous slides are used.
- The considered reference/user receiver configurations: configurations used to define the TM are reused, the main difference is that only the 6-order Butterworth filter is used at reference level (as to estimate reference tracking error).
- The signal quality (multipath, C/N_0)

II. SQM for new signals

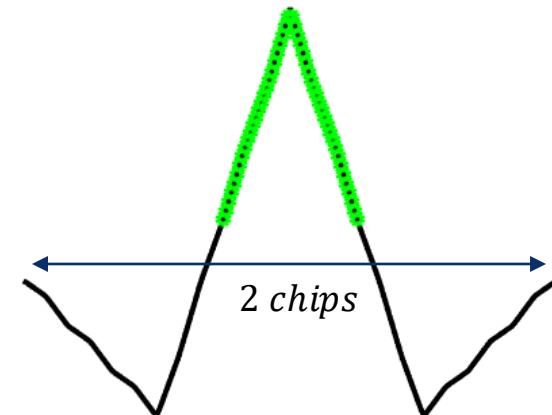
1. Proposed constraints to design and test the SQM (2/2)

GPS L1 C/A correlation function (on the left) and Galileo E1C correlation function (on the right) are monitored.

SQM are based on 51 monitored correlator outputs I_x with $x = -0.25:0.01:0.25$ in GPS L1 C/A chip unit.



○ Correlator outputs used for the SQM



Three types of metrics are tested (simple $metric_x$, difference $metric_{x-x}$ and sum $metric_{x+x}$ ratio metrics) for all monitored correlator outputs.

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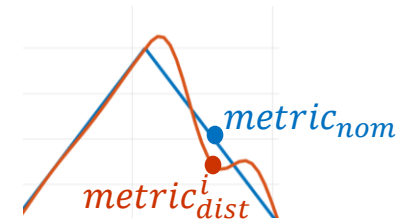
III. Conclusions and future works

II. SQM for new signals

2. SQM definitions – Test on metrics

For a given metric the test is modeled by:

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



Where

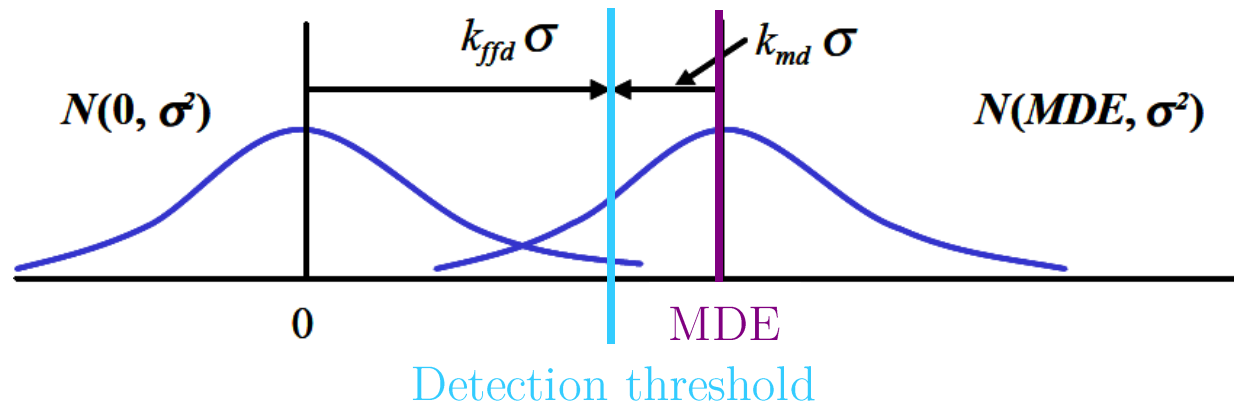
- $metric_{dist}^i$ is the current value of the metric and can be affected by a distortion. The index i shows that this value is estimated based on one ranging signal i .
- $metric_{nom}$ is the nominal value of the metric.
- MDE_{metric} is the threshold associated to the metric performance. MDE is defined by ICAO for a test based on only one metric as [ICAO, 2006]:

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

- $K_{ffd} = 5.26$ is a typical fault-free detection multiplier representing a false detection probability of 1.5×10^{-7} per test;
- $K_{md} = 3.09$ is a typical missed detection multiplier representing a missed detection probability of 10^{-3} per test;
- σ_{metric} is the standard deviation of measured values of the test metric; It is assumed that the noise distribution on metrics is Gaussian.

II. SQM for new signals

2. SQM definitions – Test on metrics



Performance threshold (MDE (Minimum Detectable Error)): Threshold not implemented on SQM. Tool to test SQM performance for a given P_{md} and P_{ffa} .

Detection threshold: Threshold implemented on SQM. Above this threshold a distortion is considered as detected. The P_{md} is not necessarily met.

$$Test_{metric} \geq 1$$

*A distortion is detected with the right
 P_{md} and P_{ffa}*

$$Test_{metric} < 1$$

*A distortion may not be detected with the
right P_{md} and P_{ffa}*

II. SQM for new signals

2. SQM definitions – Metrics

- *Simple ratio metric*

$$metric_x = \frac{I_x}{I_0}$$

- *Difference ratio metric* (more sensitive to distortions asymmetric from the prompt)

$$metric_{x-x} = \frac{I_{-x} - I_x}{I_0}$$

- *And sum ratio metric* (more sensitive to distortions symmetric from the prompt)

$$metric_{x+x} = \frac{I_{-x} + I_x}{I_0}$$

Where

- I_x is the in phase correlator output value at a distance x (in chip unit) from the prompt.

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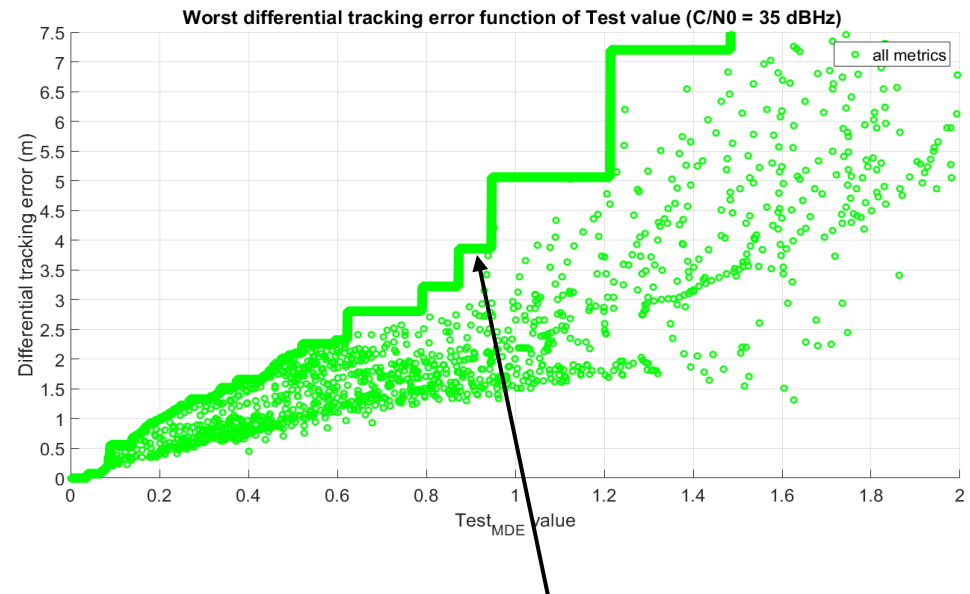
3. SQM new representation (1/3)

Test and associated maximum differential error values can be estimated for each distortion of the ICAO TM (GPS L1 C/A) as presented on the figure inspired from [Phelts et al., 2013].

one point = one distortion

Y-axis: the differential tracking error corresponds to the highest differential error obtained among user/reference configurations.

X-axis: *Test* is the value of the highest $Test_{metric}$ if several metrics are used on the SQM.



The line corresponds to the differential tracking error upper-bound.

II. SQM for new signals

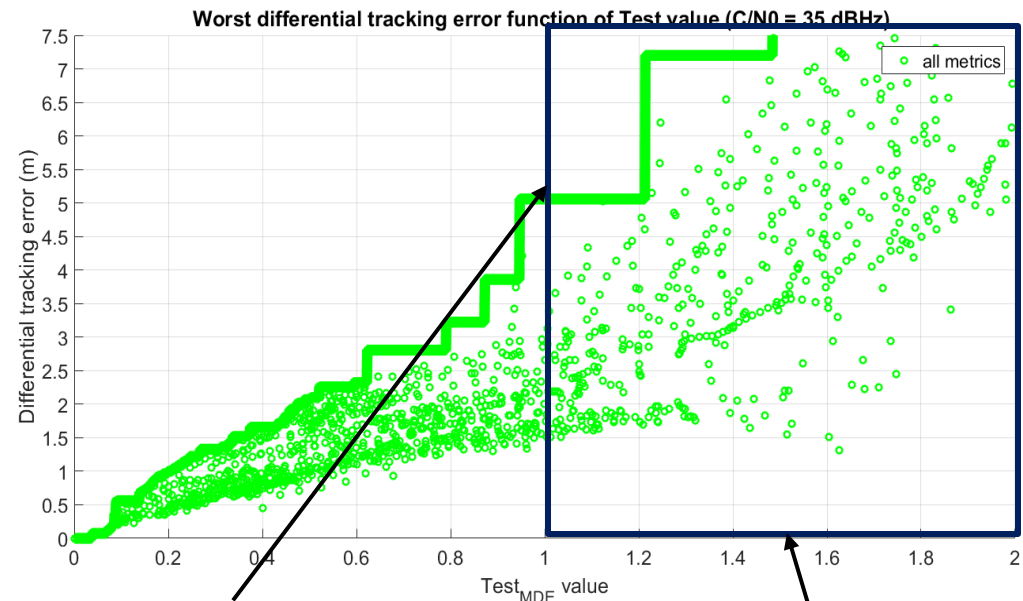
3. SQM new representation (2/3)

The figure (and the MUDE) is dependent upon:

- The considered signal
- The considered TM
- The considered reference/user receiver configurations
- The tested SQM
- The $C/N_0 = 35 \text{ dBHz}$

The tested SQM is based on :

- 50 $metric_x$
for $x = -0.25:0.01:-0.01$ and
 $x = 0.01:0.01:0.25$.
- 25 $metric_{x+x}$
for $x = 0.01:0.01:0.25$.
- 25 $metric_{x-x}$
for $x = 0.01:0.01:0.25$.



The Maximum Undetected Differential Error (MUDE) is equal to 5.1 meters.

Distortions detected by the SQM

The MUDE fulfills ICAO P_{md} and P_{ffd} requirements.

II. SQM for new signals

3. SQM new representation (3/3)

MUDE is dependent upon the C/N_0 but a relation exists between C/N_0 and the value of $Test_{metric}$:

$$Test_{metric} = \frac{C_{dist}}{MDE_{metric}} = \frac{C_{dist}}{8.35 \times C_{metric} \times 10^{\frac{-C/N_0}{20}}}$$

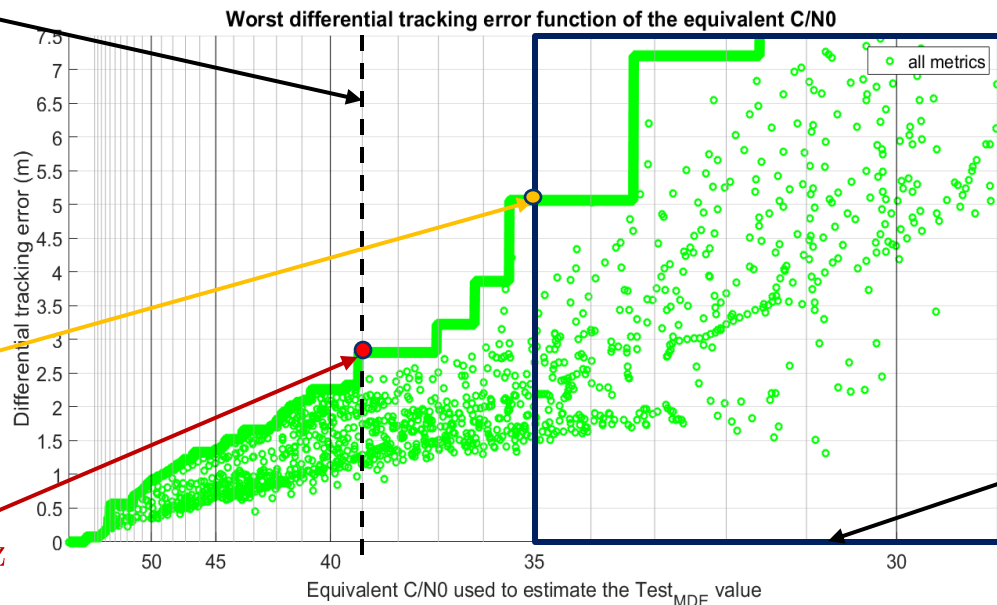
C_{dist} constant for a given distortion.

C_{metric} constant for a given metric.

Equivalent theoretical C/N_0 of a reference station in operational conditions (estimated to 39 dBHz in the manuscript)

Equivalent $C/N_0 = 35$ dBHz
MUDE = 5.1 m

Equivalent $C/N_0 = 39$ dBHz
MUDE = 2.8 m



Same plot with a x-axis scale change

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II. SQM for new signals

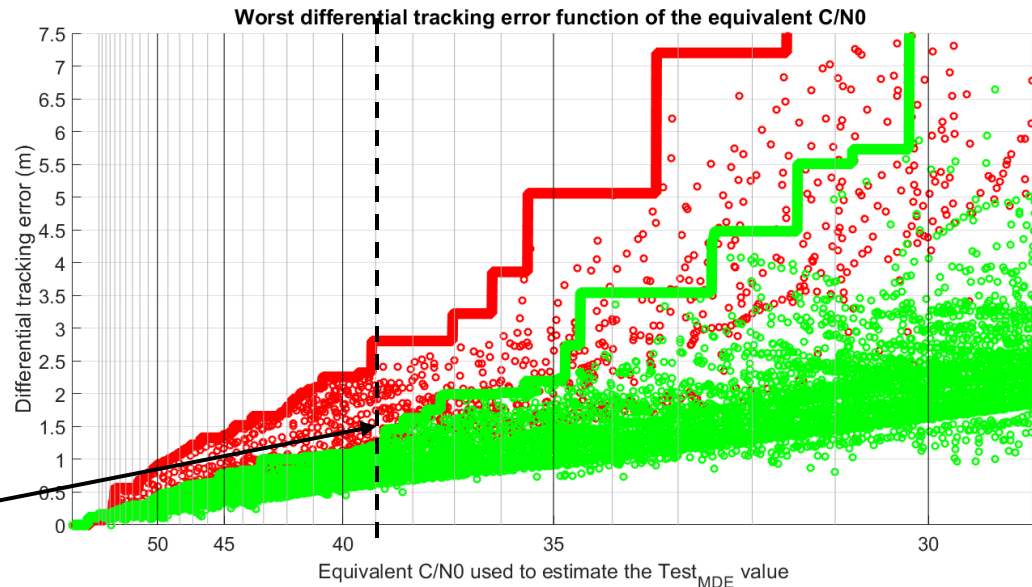
4. SQM on Galileo E1C

Comparison of **GPS L1 C/A reference SQM** with the **Galileo E1C reference SQM**.

The tested SQM is based on :

- 50 $metric_x$
for $x = -0.25:0.01:-0.01$ and
 $x = 0.01:0.01:0.25$.
- 25 $metric_{x+x}$
for $x = 0.01:0.01:0.25$.
- 25 $metric_{x-x}$
for $x = 0.01:0.01:0.25$.

Equivalent $C/N_0 = 39$ dBHz
MUDE = 1.3 m



The comparison has to be interpreted carefully, threat models and correlation functions are different.

SQM performance on Galileo E1C is better than on GPS L1 C/A.

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1. Conclusions
2. Perspectives

III. Conclusion and future works

1. Conclusion

In this presentation:

- Two threat models (Galileo E1C, Galileo E5a and GPS L5 signals) are proposed. It is based on current ICAO threats established for the GPS L1 C/A signal.
- A new space is proposed to study EWF: the $(\frac{\sigma}{(f_d)^2}; f_d)$ space. It put forward that highly attenuated distortions can be threatening even if not considered in the current ICAO TM.
- SQM on Galileo E1C signal is proposed and its performance is assessed theoretically and conservatively in a new representation.

Provided results are dependent upon user/reference configurations and TMs.

III. Conclusion and future works

2. Future works

- Find an alternative to threat models which are assuming a deformation pattern making approximations.
- Estimate σ_{metric} (and SQM performance) in real environment with particular reference receiver filters.
- Test additional metrics and not only the simple ratio, the sum ratio and the difference ratio metrics.
- The approach developed in the PhD could be applied to other modulations.

For the curious, in addition in the manuscript:

- A strategy to find an optimal quantification grid to test distortions of the TM is introduced. The concept is to:
 - reduce the number of distortions to test
 - Don't miss any dangerous behavior.
- SQM results regarding Galileo E5a and GPS L5 signals are available.
- A methodology to estimate the equivalent C/N_0 in reference station operating conditions is developed and the difference between the theoretical and real conditions is discussed.
- Different SQM optimization criteria are proposed.

Thank you for your attention
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Presentation outline

I. Proposition of TM for new signals

1. Current GPS L1 C/A Threat Model
2. Adaptation of the current TM to new signals
3. Concept to design the Threat Space
- 4. TM-A design**
5. TM-B design
6. TM-C design
7. Conclusion

II. SQM for new signals

III. Conclusions and future works

I. Proposition of TM for new signals

4. TM-A design – GPS L5 and Galileo E5a

- The concept of ICAO GPS L1 C/A is kept for the BPSK(10) modulation: falling edge lead/lag relative to the correct-end time for that chip is given as Δ .
- The upper bound of Δ cannot be limited using the two proposed considerations.

- The proposed range for this parameter is given by:
$$-1.2 E5a \text{ chips} \leq \Delta \leq 1.2 E5a \text{ chips}$$

- For two main reasons:
 - Higher values should be detected by multi correlator techniques (SQM).
 - When converting into seconds, Δ limits have the same values as for Δ values used the GPS L1 C/A TM-A.

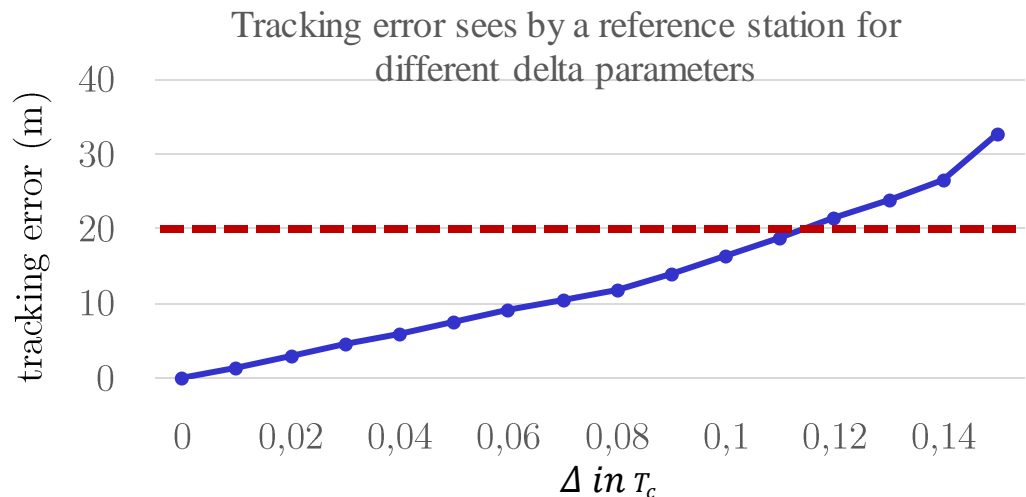
I. Proposition of TM for new signals

4. TM-A design – Galileo E1C

- Two TM-A are proposed for Galileo E1C in the PhD.
 - Lead/Lag can affect code chip or sub-chip transitions.
- Hypothesis: the signal is directly generated as the components product.
 - ↳ A simplified TM-A is proposed and is referred to as TM-A1.
- Reference station is able to detect tracking bias larger than 20 meters.
 - ↳ $|\Delta|$ can be limited to **0.12 chips** as illustrated.

By consequence, for TM-A1,
following parameter values
are envisaged:

$$-0.12 \text{ chips} \leq \Delta \leq 0.12 \text{ chips}$$



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6. TM-C design

- In the current ICAO TM:
 - the TM-C is a TM-A and TM-B combination.
 - parameter ranges choose for TM-C are smaller than individual parameters range for TM-A and TM-B.

To be conservative and without more knowledge, the proposed TM-C takes parameters range established for the TM-A and the TM-B.

II. SQM for new signals

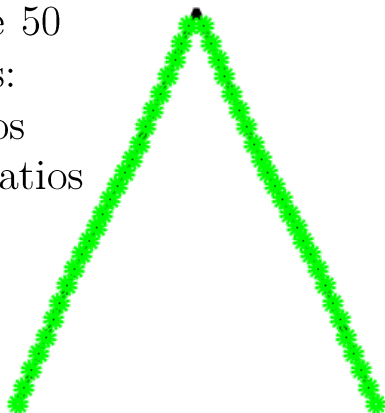
4. SQM on new signals – Proposition of optimal SQMs

An algorithm is applied to find the smallest set of metrics which is able to reach performance of SQM1 (based on all available metrics) whatever the value of the C/N_0 is.

SQM1: 100 metrics are

used based on the 50
correlator outputs:

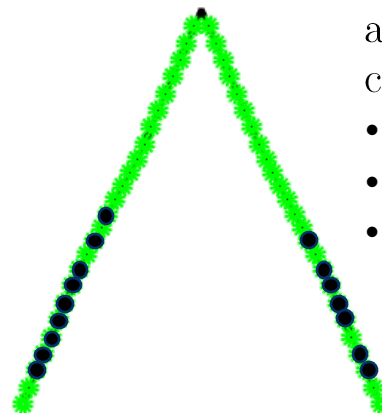
- 50 simple ratios
- 25 difference ratios
- 25 sum ratios



SQM_{optimal}: 30 metrics

are used based on 32
correlator outputs:

- 12 simple ratios
- 14 sum ratios
- 4 difference ratio

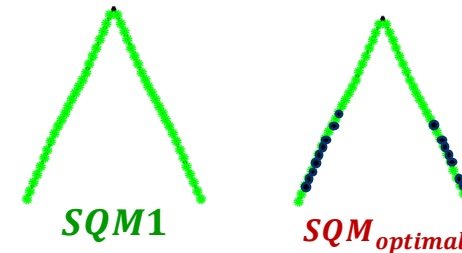


- Correlator outputs un-used in the optimal SQM because « redundant »

II. SQM for new signals

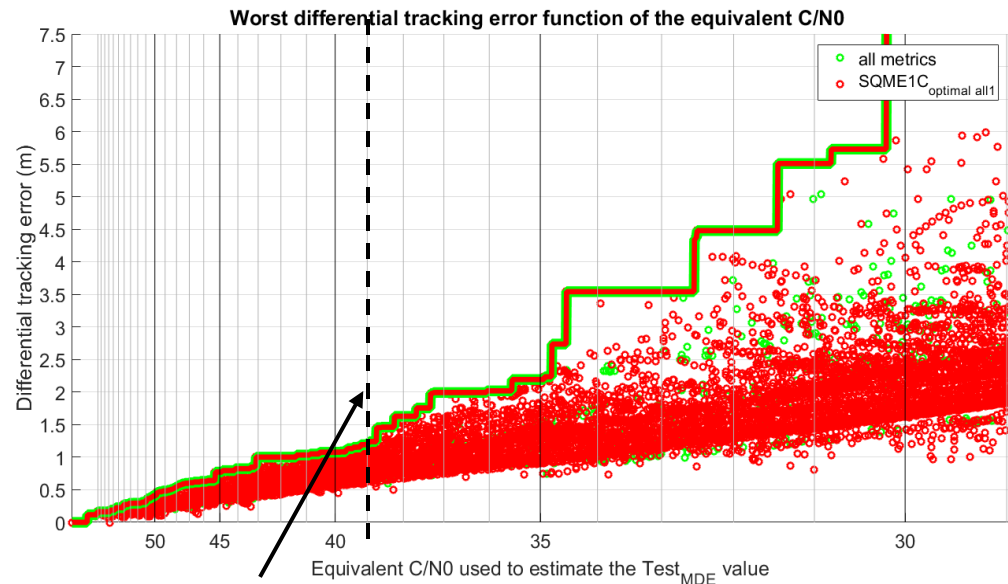
4. SQM on new signals – Proposition of optimal SQMs

Comparison of performance between **SQM1** (including all metrics) and the **SQM_{optimal}**



The two upper bounds (continuous lines) are superimposed.

Performances of both SQMs are equal (even if less metrics are used in the optimal SQM)



The MUDE is equal to 1.3 meters for an equivalent theoretical $C/N_0 = 39 \text{ dBHz}$ (for the two SQMs).