Detection of GNSS Multipath with Time-Differenced Code-Minus-Carrier for Land-Based Applications

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Motivation

- *New land-based applications need an accurate and robust position solution.* →

- GNSS plays an important role as one of the main ways of navigation.

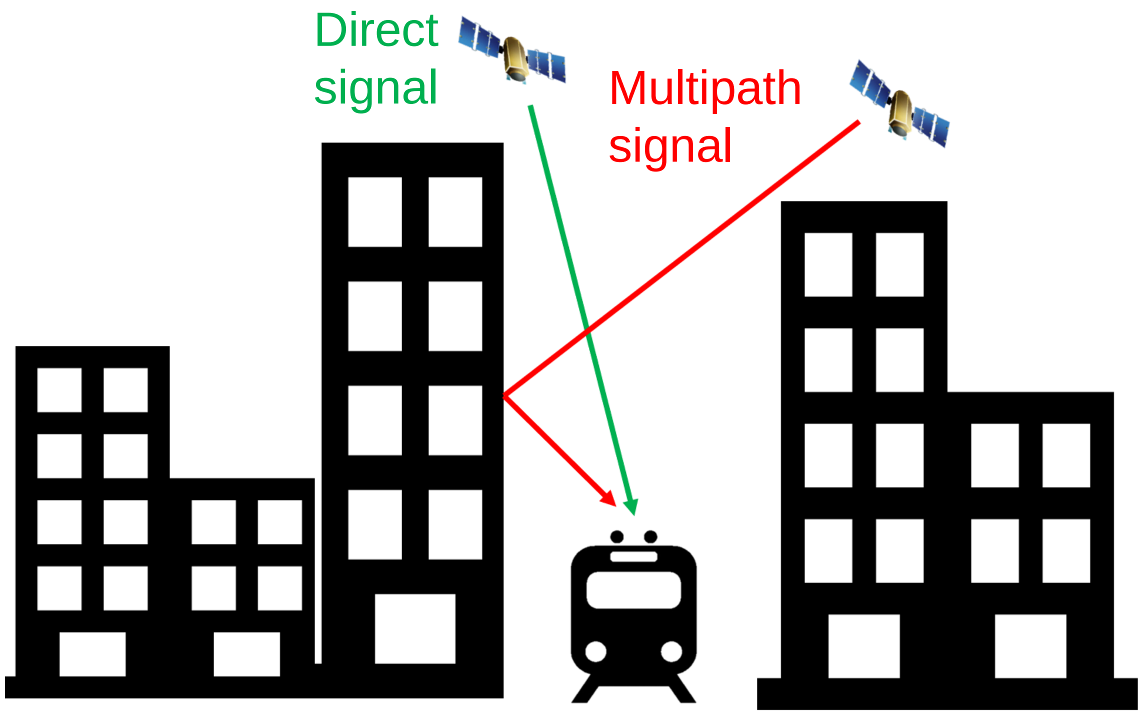
- The operation of GNSS receivers in urban environments is a challenge due to the presence of local threats (e.g. multipath).

- It is essential to equip GNSS receivers with algorithms that can detect and mitigate multipath before the position computation.

Introduction

What is the problem of multipath for real-time applications?

- **Multipath** is the reception of multiple signal replicas, which might corrupt GNSS measurements



- **Problem:** It can lead to unbounded position errors that might create hazardous situations in Safety-of-Life applications (e.g. Railway).

- **Goal:** find a suitable technique to detect the presence of multipath in urban scenarios.

Existing techniques to detect multipath

- Existing techniques can be classified according to the processing stage where they are applied in the GNSS receiver:

At the signal or correlator level

At the position level

At the raw measurement level

Existing techniques to detect multipath at the signal or correlator level

<u>Techniques:</u>

- Using different Delay Lock Loops (DLL) estimators [1,2]
- Using multicorrelators or Signal Quality Monitoring (SQM) techniques [3,4]

<u>Limitations:</u>

- Require high computational complexity
- Highly dependent on the specific receiver

[1] B. R. Townsend, et al., “Performance Evaluation of the Multipath Estimating Delay Lock Loop”, *Navigation*, vol. 42, no. 3, pp. 502–514, 1995.

[2] N. Sokhandan, et al., “An advanced GNSS code multipath detection and estimation algorithm”, GPS Solutions, vol. 20, no. 4, pp. 627–640, Oct. 2016.

[3] N. Blanco-Delgado et al., “Multipath Estimation in Multicorrelator GNSS Receivers using the Maximum Likelihood Principle”, IEEE Transactions on Aerospace and Electronic Systems, vol. 48, no. 4, pp. 3222–3233, Oct. 2012.

[4] A. Iliopoulos, et al., “Multicorrelator signal tracking and signal quality monitoring for GNSS with extended Kalman filter”, in 2017 IEEE Aerospace Conference, Mar. 2017, pp. 1–10.

Existing techniques to detect multipath at the position level

Techniques:
- Using adaptation of ARAIM algorithms from civil aviation [5,6]
- Using position robust estimators [7,8]

Limitations:
- Difficult to choose right models for the measurements
- Quantification of the performance is an open issue

[5] N. Zhu, et al., “GNSS Position Integrity in Urban Environments: A Review of Literature”, IEEE Transactions on Intelligent Transportation Systems, vol. 19, no. 9, pp. 2762–2778, Sep. 2018.

[6] A. Grosch, et al, “Snapshot residual and Kalman Filter based fault detection and exclusion schemes for robust railway navigation”, in 2017 European Navigation Conference (ENC), May 2017, pp. 36–47.

[7] N. L. Knight and J. Wang, “A Comparison of Outlier Detection Procedures and Robust Estimation Methods in GPS Positioning”, Journal of Navigation, vol. 62, no. 4, pp. 699–709, Oct. 2009

[8] O. Garcia Crespillo, et al., “Design and Evaluation of Robust M-estimators for GNSS Positioning in Urban Environments”, in Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, Jan. 2020.

Existing techniques to detect multipath at the raw measurement level

Techniques:

- Using difference between the code and carrier-phase measurements (CMC) [9,10]
  - Used in civil aviation for multipath modelling (GBAS).

[9] M. S. Braasch, et al. "Isolation of GPS Multipath and Receiver Tracking Errors", Navigation, vol. 41, no. 4, pp. 415–435, 1994.

[10] A. Beitler, et al, "CMCD: Multipath Detection for Mobile GNSS Receivers", in 2015 International Technical Meeting of The Institute of Navigation, Jan. 2015.

Limitations:

- Removal of the carrier-phase ambiguity requires long statellite observation period without losing the signal
- Difficult to find suitable thresholds

Advantage:
NOT dependent on the GNSS receiver

Adaptation of CMC techniques for urban scenarios

Estimation of multipath and noise with Code-Minus-Carrier techniques

- Code and carrier-phase observables for frequency *i*, satellite *s* and epoch *k*:

$$\rho_{i,k}^{s} = R_k^s + c\left(\delta t u_k - \delta t_k^s\right) + I_{i,k}^s + T_k^s + MP_{i,k}^s + \epsilon_{i,k}^s$$

$$\phi_{i,k}^{s} = R_k^s + c\left(\delta t u_k - \delta t_k^s\right) - I_{i,k}^s + T_k^s + N_{i,k}^s\lambda_i + mp_{i,k}^s + \zeta_{i,k}^s$$

Common terms with same sign:
R: geometric range
c: speed of light
δtu: user clock bias
δt^s: satellite clock bias
T: tropospheric delay

Common terms with different sign:
I: ionospheric delay

Non-common terms:
N: carrier-phase ambiguity
λ: wavelenght
MP: code multipath
ϵ: code noise
mp: carrier-phase multipath
ζ: carrier-phase noise

Estimation of multipath and noise with Code-Minus-Carrier techniques

- To remove the common terms, the code and carrier-phase measurements are subtracted to form the Code-Minus-Carrier (CMC) observable:

$$CMC^s_{i,k} = \rho^s_{i,k} - \phi^s_{i,k} = \boxed{2I^s_{i,k} + N^s_{i,k}\lambda_i} + MP^s_{i,k} - \cancel{mp^s_{i,k}} + \epsilon^s_{i,k} - \cancel{\zeta^s_{i,k}}$$

Carrier-phase multipath and noise negligible in comparison with the code terms

The ionospheric delay and the carrier-phase ambiguity terms still need to be removed to obtain the pseudorange multipath and noise.

Estimation of multipath and noise with Code-Minus-Carrier techniques

State-of-the-art: how to remove the carrier-phase ambiguity and ionospheric terms?

Removal of ionospheric term:

- The ionospheric delay is estimated with dual-frequency measurements.

$$\hat{I}^s_{i,k} = \frac{f_j^2}{f_i^2 - f_j^2}\left(\phi^s_{i,k} - \phi^s_{j,k}\right)$$

- CMC_{Dfree}: calculated by substracting twice the ionospheric delay from the CMC.
- This method introduces additional carrier-phase ambiguity error terms.

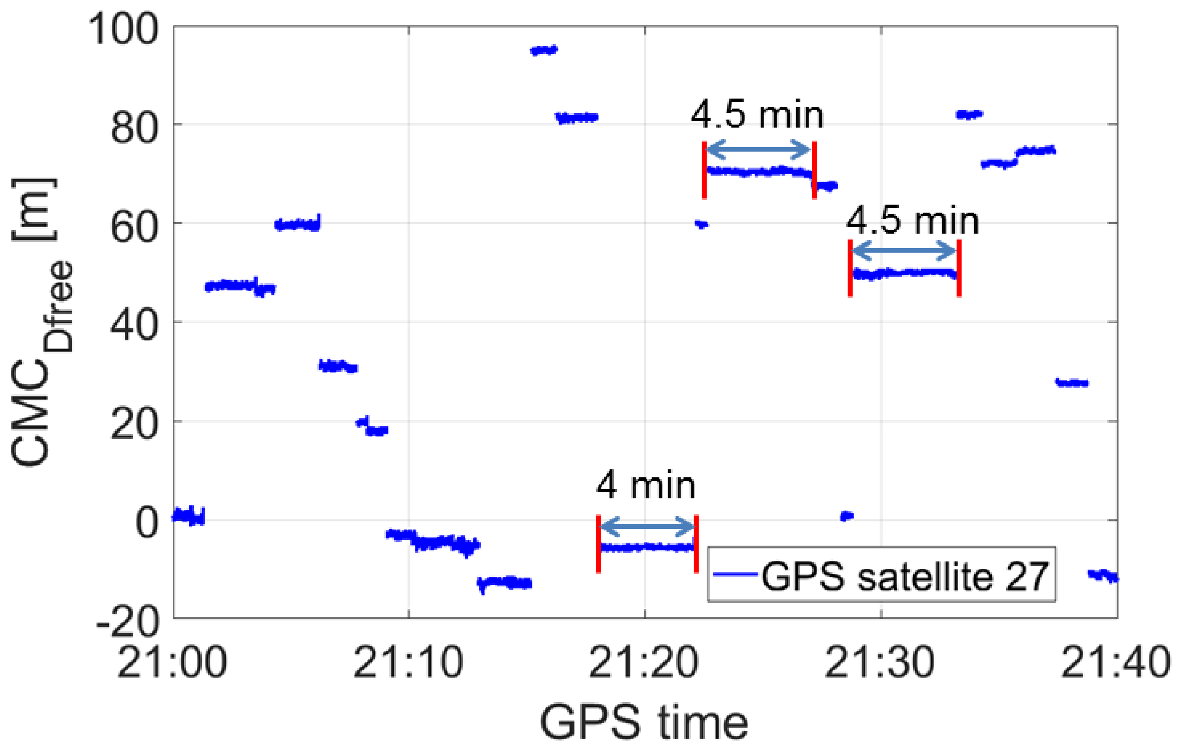
Removal of carrier-phase ambiguity terms:

- The carrier-phase ambiguity terms are constant and can be removed by subtracting the mean of the CMC_{Dfree} over a time window *K*, where the data was continuously tracked.

$$\widehat{\mathrm{MP}}_k = CMC_{Dfree,k} - \frac{1}{K}\sum_{p=k-K}^{k} CMC_{Dfree,p}$$

Can we use this CMC-based technique in Urban scenarios?

- CMC_{Dfree} calculated with GNSS data recorded in a dynamic scenario in the railway domain.
- Signals could only be tracked continuously for a few minutes.



- When the size of *K* is that small, multipath cannot be properly estimated (e.g. in aviation windows with *K*=60 minutes are used).

- This technique is not suitable for urban scenarios and real-time applications.

Detection of multipath with Time-differenced Code-Minus-Carrier

The estimation of the absolute value of multipath is not needed for detecting it.

Removal of the carrier-phase ambiguity term:

- Use as a multipath metric the rate of change of multipath and noise.

$$\Delta CMC_k = \frac{1}{\Delta t}(CMC_k - CMC_{k-1}) \approx 2\dot{I}_k + \dot{MP}_k + \dot{\epsilon}_k$$

- The carrier-phase ambiguity error terms are removed.
- Two times the rate of the ionospheric delay remains.

Removal of ionospheric term:

- It can be removed with DF measurements, which introduces dependencies on a second frequency tracking.
- The ionospheric rate in nominal conditions can be considered negligible in comparison to the rate of multipath and noise.

Experimental Setup

- GNSS measurements recorded at 10 Hz sampling rate during a measurement campaign in Sardinia (Italy) for H2020 ERSAT GGC project (*).
- Considered scenarios: open-sky static and dynamic in the line *Cagliari-San Gavino* with a line length of 50 km.
- The GNSS antenna was installed on the roof of the commercial train.

Commercial Train ALn668-3136 (Trenitalia)

GNSS antenna installation on train roof

(*) ERSAT GGC Website: http://ersat-ggc.eu/

Test detection and threshold derivation in Railway scenarios

Selected test statistic → ΔCMC

↓

Characterization of nominal expected multipath and noise level → $\sigma_{\Delta CMC}$

Nominal conditions: low multipath environment

- The multipath and noise level present due to the specific installation of the antenna and the permanent environment of the roof of the train
- Open-sky static scenario

Calculation of $\sigma_{\Delta CMC}$:

- Based on ΔCMC samples calculated for all satellites and all epochs
- Different values for different elevation bins to consider the higher level of multipath and noise expected in the measurements from low elevation satellites

↓

$\sigma_{\Delta CMC}(\theta_k^s)$

Test detection and threshold derivation in Railway scenarios

Selected test statistic → ΔCMC

↓

Characterization of nominal expected multipath and noise level → $\sigma_{\Delta CMC}(\theta_k^s)$

↓

Calculation of a detection threshold → $T = f(\sigma_{\Delta CMC})$

Definition of acceptance level α :

- Number of standard deviations allowed for no detection.

$$T_k = \alpha \cdot \sigma_{\Delta CMC}(\theta_k^s)$$

- α can be calculated either empirically or assuming a certain underlying model

- Based on the application considered, the detection threshold was selected empirically as:

$$T_k = 5 \cdot \sigma_{\Delta CMC}(\theta_k^s)$$

Test detection and threshold derivation in Railway scenarios

Selected test statistic → ΔCMC

Characterization of nominal expected multipath and noise level → $\sigma_{\Delta CMC}(\Theta_k^s)$

Calculation of a detection threshold → $T_k = 5 \cdot \sigma_{\Delta CMC}(\Theta_k^s)$

Definition of the test detection → $Detection\ occurs\ when\text{: } |\Delta CMC_k^s| \geq T_k\ (\Theta_k^s)$

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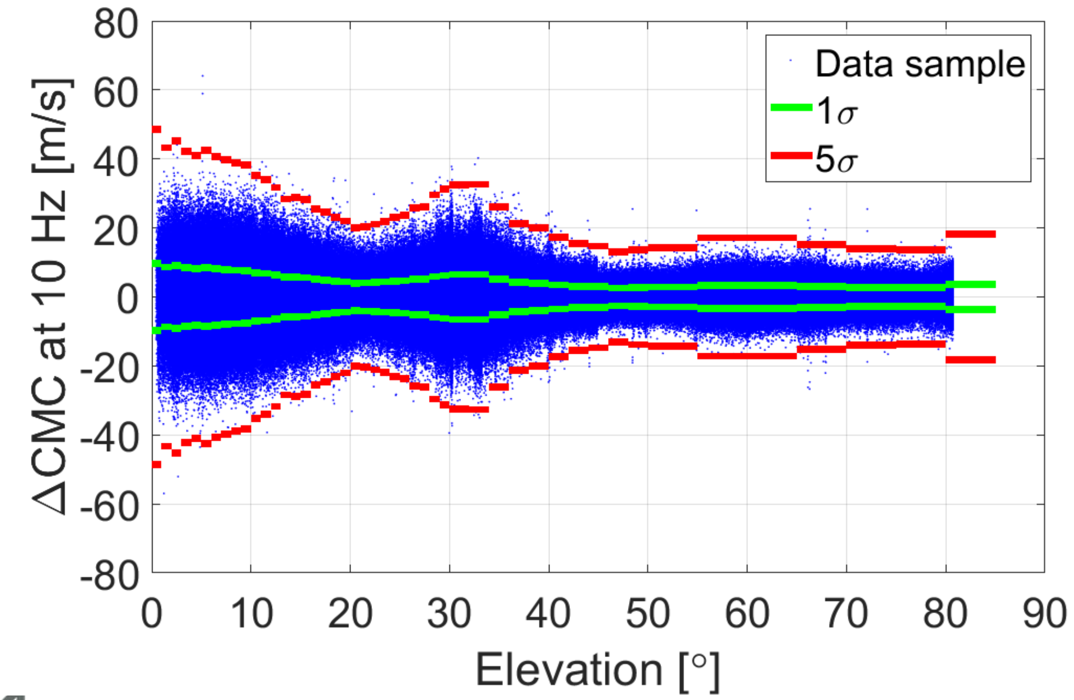
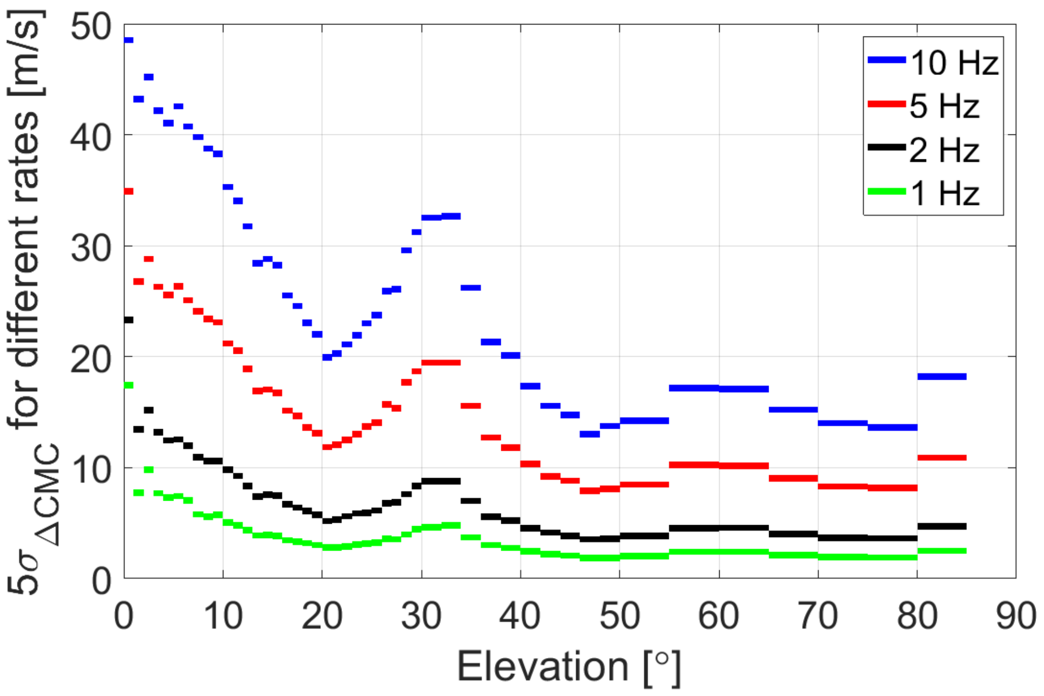
Test detection and threshold derivation in Railway scenarios

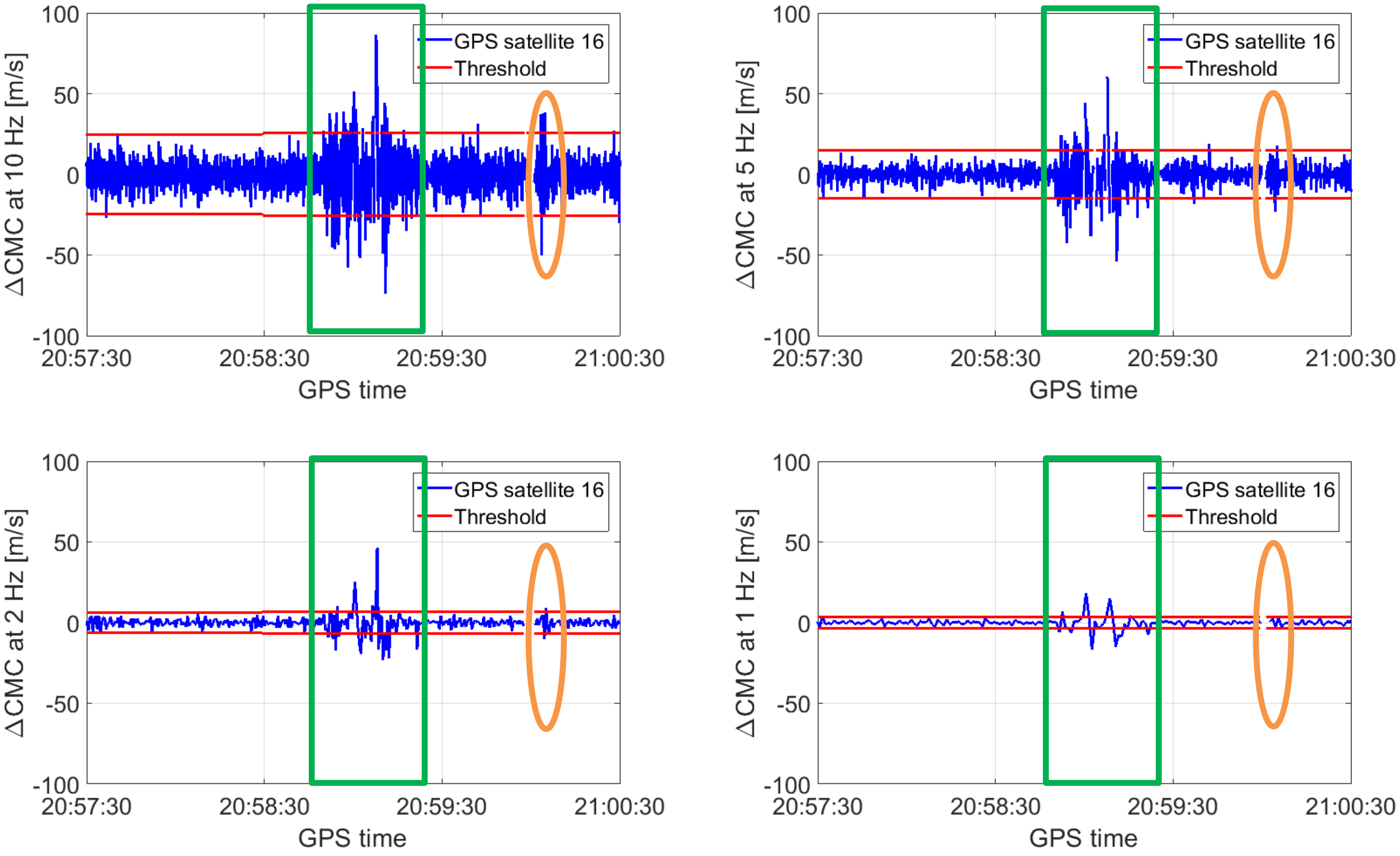
- The detection threshold calculated with the recorded data at 10 Hz is suitable for our application.
- The detection thresholds were also calculated for different sampling rates assuming that the receiver was not using the intermediate samples.
- Depending on the sampling rate, different nominal noise levels are expected in the observables used as test statistics.





Results: multipath detection in the time domain

- Thresholds suit the test statistics calculated with the different sampling rates of the data.
- When the source of multipath is strong, the detections with different sampling rates are consistent.
- Some multipath effects might not be captured by the observable. But they may also not impact the error of the measurements at that rate. ⟶ Future work!



Use case: classification of railway areas suitable for the use of GNSS

- In the frame of the H2020 ERSAT GGC project, this technique was used to classify railway tracks suitable for the use of GNSS.

- Results from time domain were mapped into space domain by combining detections from all visible satellites, multiple days and multiple train runs.
- Red indicated significant multipath detections, yellow not enough samples collected and green no multipath.
- The proposed method showed to be a strong option for the detection of multipath in real-time land-based applications.

For more details see presentation in ENC2020:

- "**Framework to Classify Railway Track Areas According to Local GNSS Threats**", D. Gerbeth, O. García Crespillo, F. Pognante, A. Vennarini and A. Coluccia (session D2 Rail)

Conclusions and future work

- We showed that state-of-the-art absolute CMC-based multipath detection techniques are not suitable for land-based applications.
- We provided a methodology to detect multipath based on the rate of change of CMC.
- Our methodology can be applied to both real-time scenarios, as shown with the results in the time domain, and to non real-time applications as the classification of areas in the railway scenario.
- Future work will investigate how the internal processing of the receiver used, the speed of train and the type of environment affect the performance of our methodology.

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Thank you for your attention!

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