Analysis of the Carrier Phase Multipath Error in the Context of Correction Maps for Urban Navigation

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Motivation

Accuracy, precision and availability requirements are very stringent in urban navigation and autonomous driving. The GNSS (Global Navigation Satellite System) sensor provides self-localization in a global coordinate system.

Main Challenge: Poor signal propagation conditions in urban areas.

- To meet high accuracy requirements at few cm to dm level, carrier phase observations must be used and the multipath (MP) error (LOS + reflection) modeled and corrected.

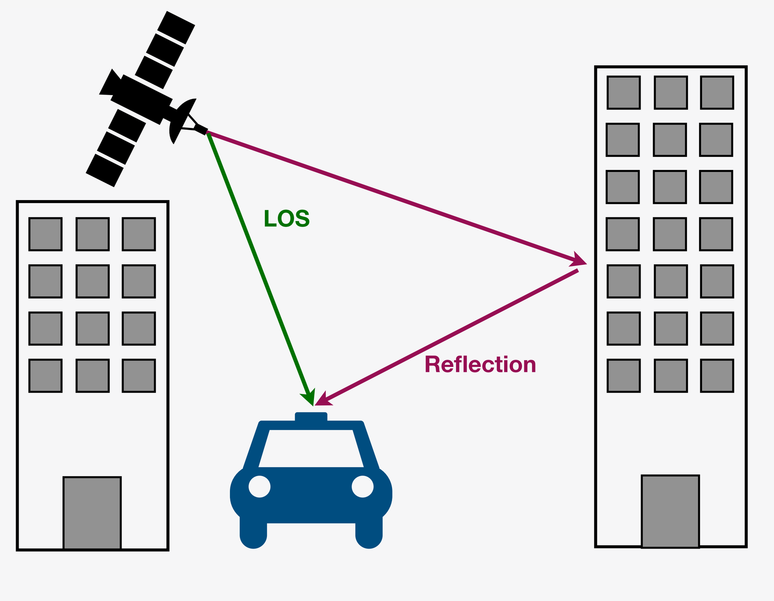

Figure 1: Possible GNSS signal propagation in multipath (LOS + single-reflection) condition.

Carrier Phase Multipath Errors

The carrier phase MP error can be expressed as explained in (Braasch, 2017)

$$\Theta_c = \arctan\left(\frac{\alpha \sin(\varphi_m)}{1+\alpha\cos(\varphi_m)}\right), \quad \varphi_m = \frac{2\pi\delta}{\lambda}.$$

The extra path delay δ parameterized by the horizontal distance to the reflector d_h and elevation and azimuth angles from the satellite and normal vector of the reflector is

$$\delta = 2d_h \cos(\mathrm{El}_{sat} - \mathrm{El}_{\vec{n}}) \cos(\mathrm{Az}_{sat} - \mathrm{Az}_{\vec{n}})$$

Goal: Computation of one cycle of the MP error when changing d_h.
The change of the extra path delay is set to the signals wavelength λ, satellite positions remain unchanged.

$$\Delta d_h = \frac{\lambda}{2\cos(\mathrm{El}_{sat} - \mathrm{El}_{\vec{n}}) \cos(\mathrm{Az}_{sat} - \mathrm{Az}_{\vec{n}})}$$

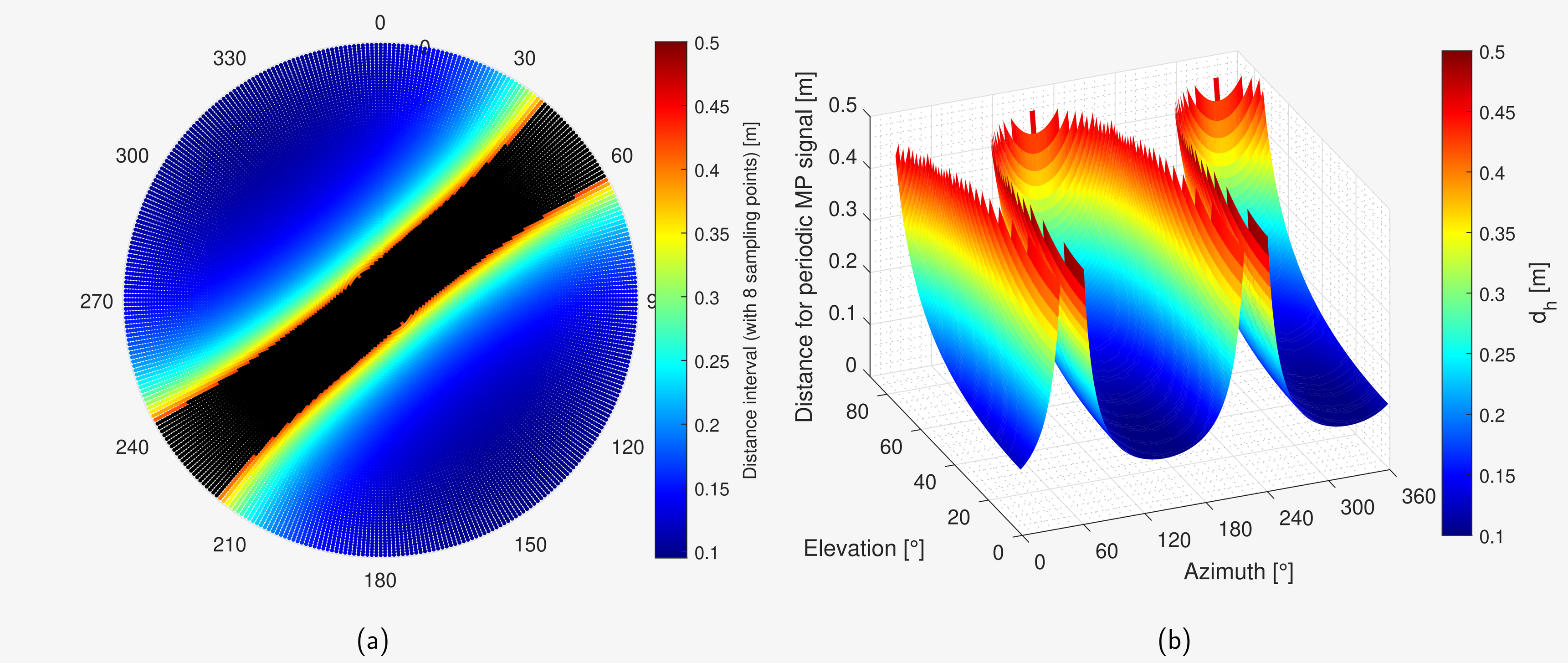

Figure 2: Simulations to determine the change of the horizontal distance to the reflector in order to receive one cycle of the periodic carrier phase MP error. The orientation of the vertical reflector is $\mathrm{Az}_{\vec{n}} = 320°$.

Pseudo-kinematic Experiment Design

- Location selection based on ray tracing simulations to ensure a high number of MP receptions.
- Surrounding environment representative as a one-sided street in urban areas but without frequent dynamic changes due to cars or pedestrians.
- Tallysman TW7272 antenna mounted on the roof of a car connected to a Septentrio PolaRx5e receiver.
- Static measurements of 24 h with 1 s time interval.
- Shifting of the car 2 cm per day for 10 consecutive days to cover most of the periodicities, which are below 20 cm (cf. Fig. 2).

Figure 3: Location of the pseudo-kinematic experiment.

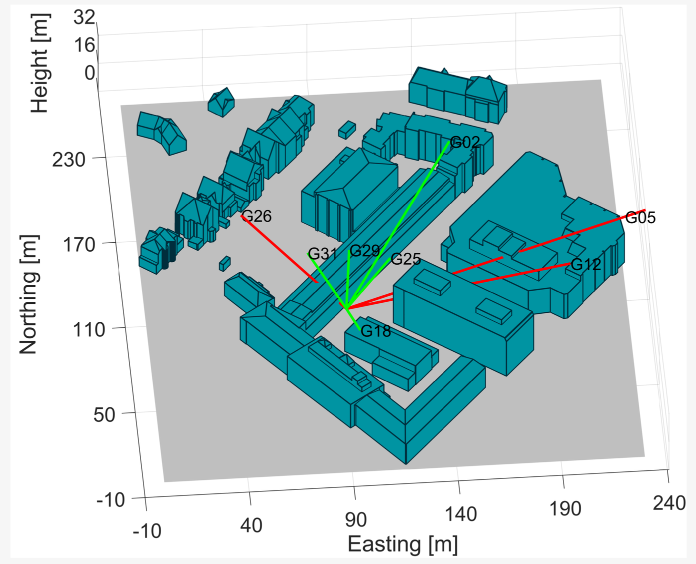

Figure 4: Antenna position in the building model using our ray tracing approach (green: LOS, red: NLOS).

Mapping Function Estimation

- Idea: map the carrier phase MP error w.r.t. the horizontal reflector distance.
- Phase shift φ_m is calculated by ray tracing and the approximation values for the relative amplitude are taken from material properties (ITU-R, 2019).

Observations:

- Carrier phase residuals from the Geo++ positioning engine using a single-difference approach:

$$\Delta l = [r_1, \ \ldots, \ r_n]^T$$

Parameter:

- Relative amplitude α

Functional Model:

$$f(\alpha) = \frac{\alpha\sin(\varphi_m)}{1+\alpha\cos(\varphi_m)}$$

$$A = \left[\frac{\partial f_1}{\partial \alpha} \ldots \frac{\partial f_n}{\partial \alpha}\right]^T$$

Estimation:

$$\Delta\hat{x} = \left(A^T A\right)^{-1} A^T \Delta l$$

Results

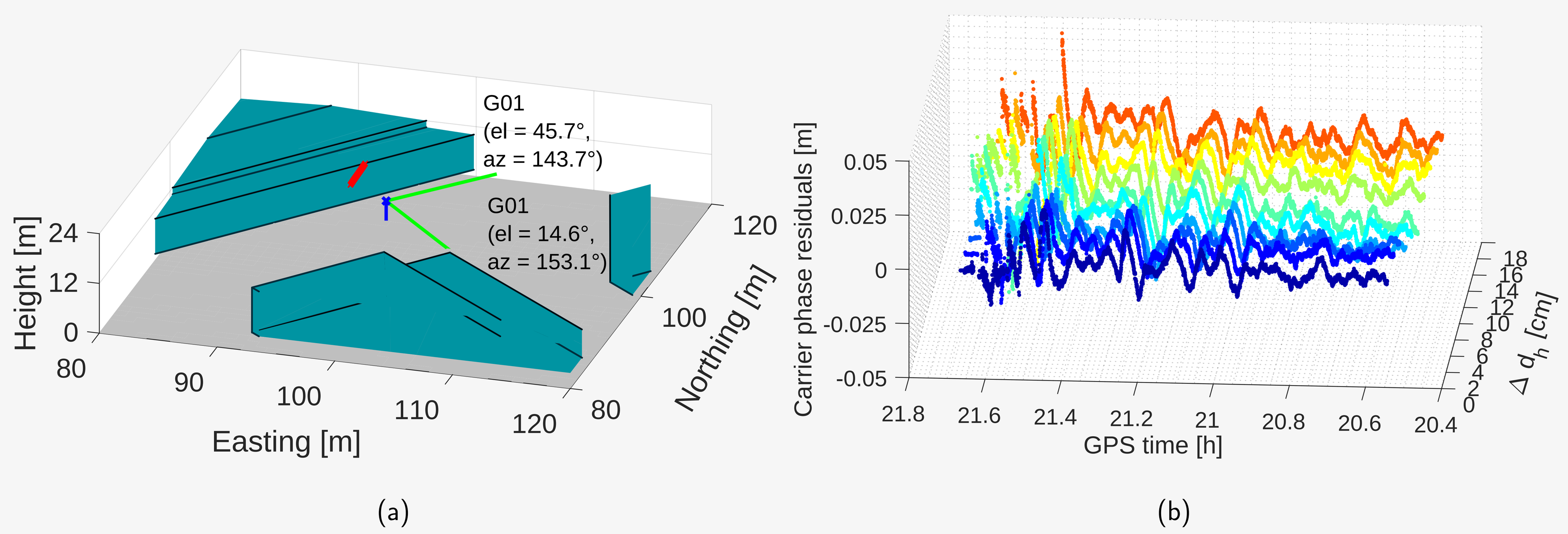

Figure 5: PRN 1: Geometric conditions at the beginning and end of the MP time series with all determined reflection points (red dots) at antenna position 1 (a). In (b) the shifted MP time series colored by each location are depicted.

Results

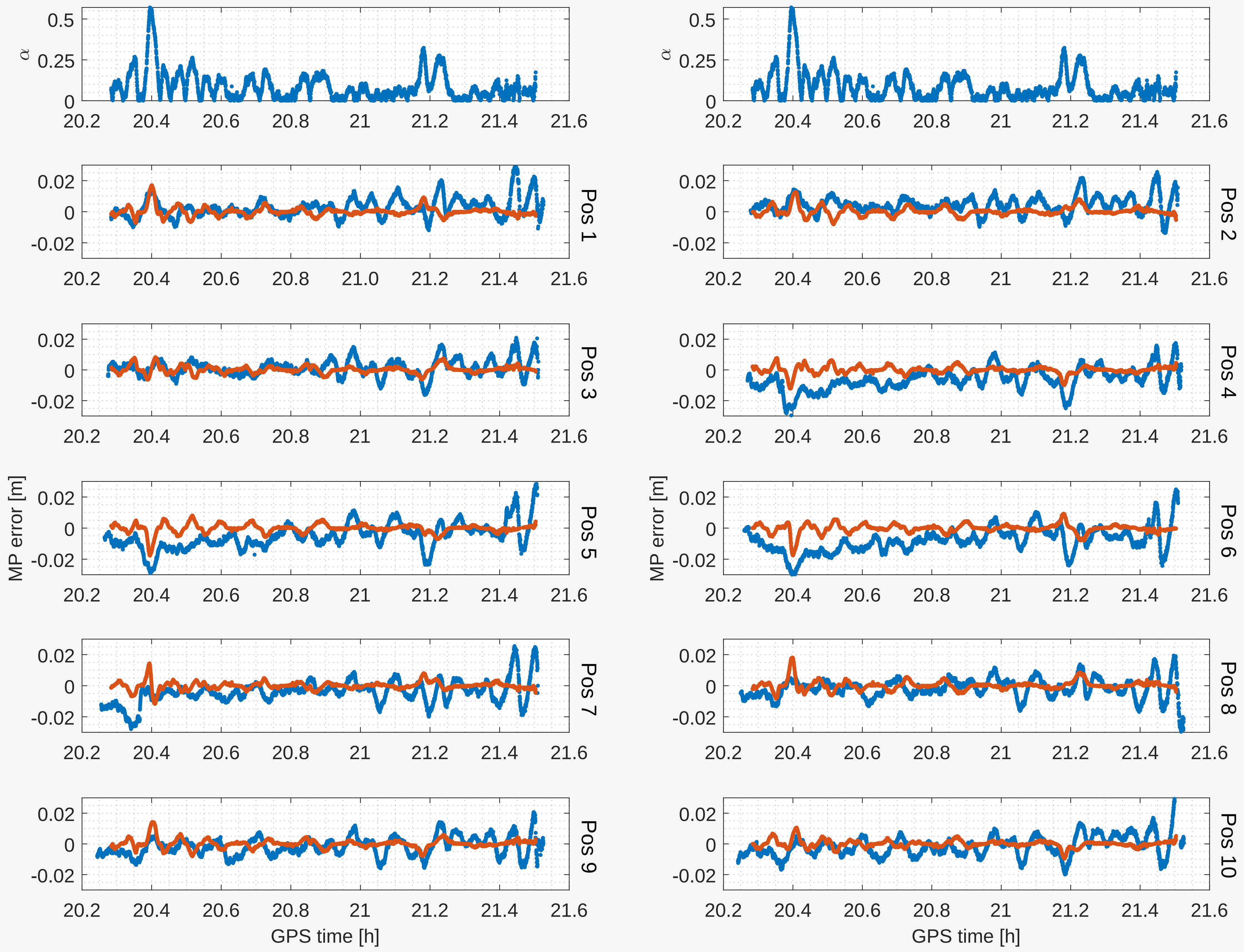

Figure 6: Estimation results for satellite PRN 1: the first row shows the relative amplitude α, in rows 2 to 6 the observed MP error (blue) together with the estimated MP error (orange) are depicted.

- The time series of PRN 1 show similar patterns at the 10 antenna locations.
- In the first half, the estimation fits to some of the observed amplitudes.
- In the second half, α cannot be reliably estimated from the residuals due to additional systematical errors resulting in values close to zero.

Conclusions

- The estimation requires clear MP conditions, e.g. full coverage of the Fresnel ellipsoid on the reflection surface.
- The horizontal reflector distance has to be known precisely to match the estimation with the observed MP errors.
- The MP error is highly dynamic and complex and its estimation is additionally influenced by many factors, e.g. satellite time shifts, irregularities of the facade and the noise and further systematical effects in the residuals.

References

Braasch, M. S. (2017). *Springer Handbook of Global Navigation Satellite Systems*, chapter 15. Multipath, pages 443–468. Springer.

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