Benefits from receiver clock modeling: from PPP-based GPS seismology to Navigation in harsh environment

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Introduction

In the last years, progress has been made to enable high rate (> 1 Hz) applications for GNSS in Earth observation. In addition to new receiver designs (up to 100 Hz), especially high-rate satellite clock products from the IGS and its analysis centers are now available with a data rate of up to 5 s. Geophysical and atmopheric studies (e.g. vulcano monitoring, tsunami prediction, and especially studies of co- and post-seismic displacements) benefit from these developments opening up new temporal scales for analyses.

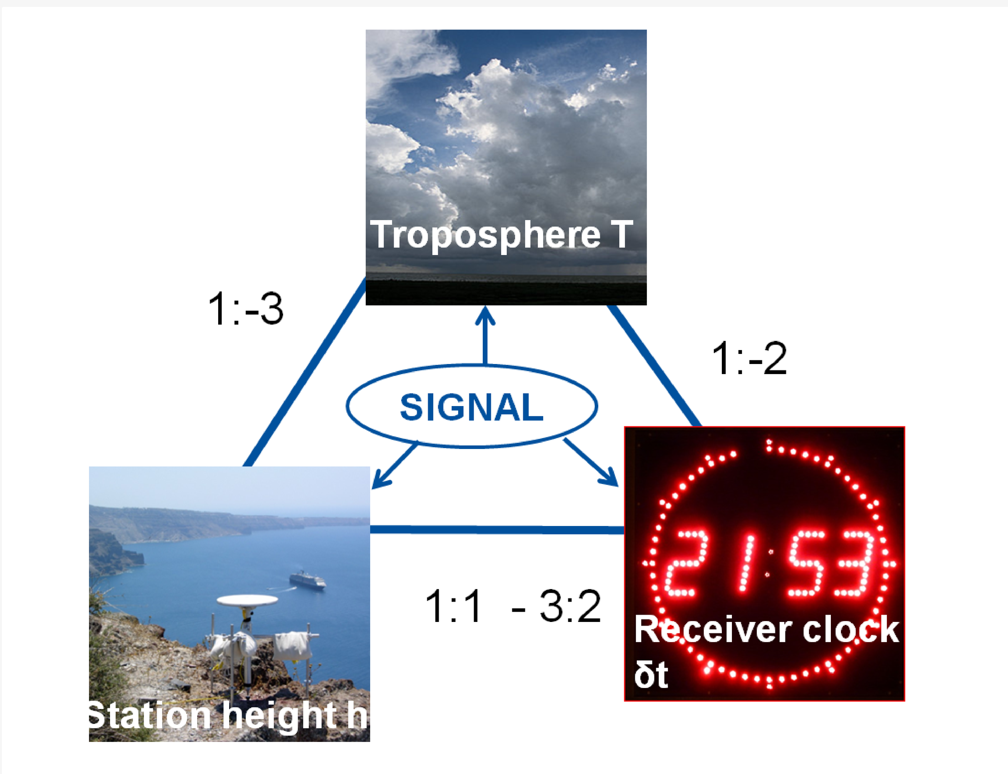

Fig. 1: Relationship between the parameter tropospheric delay, station height, and receiver clock error.

However, high correlations between the parameters of up to 0.99 occur depending on the elevation cut-off angle. This yields a significant degradation of positioning in the vertical direction and masks many valuable geophysical or atmospheric features.

Our Solution: Clock modeling improving parameter estimates by incooperation of external clock information.

Concept of clock modeling

If

- the GNSS receiver is driven by a stable oscillator,
- its accumulated time error due to random frequency fluctuations of the oscillator σ_y (in terms of the Allan deviation) is smaller than the GNSS receiver noise σ_l (e.g. 1% of the wavelength) over a significant time interval τ_p , i.e.

$$RMS_x(\tau_p) = \tau_p \cdot \sigma_y(\tau_p) < \sigma_l, \qquad (1)$$

then

- the temporal variation of the receiver clock offset can be - in a physically meaningful way - constrained over intervals τ_p where (1) is met.
- Within this interval the receiver clock error can be described by a linear or quadratic polynomial, since the random oscillator fluctuations cannot be resolved by GNSS observations because they are below the receiver noise.

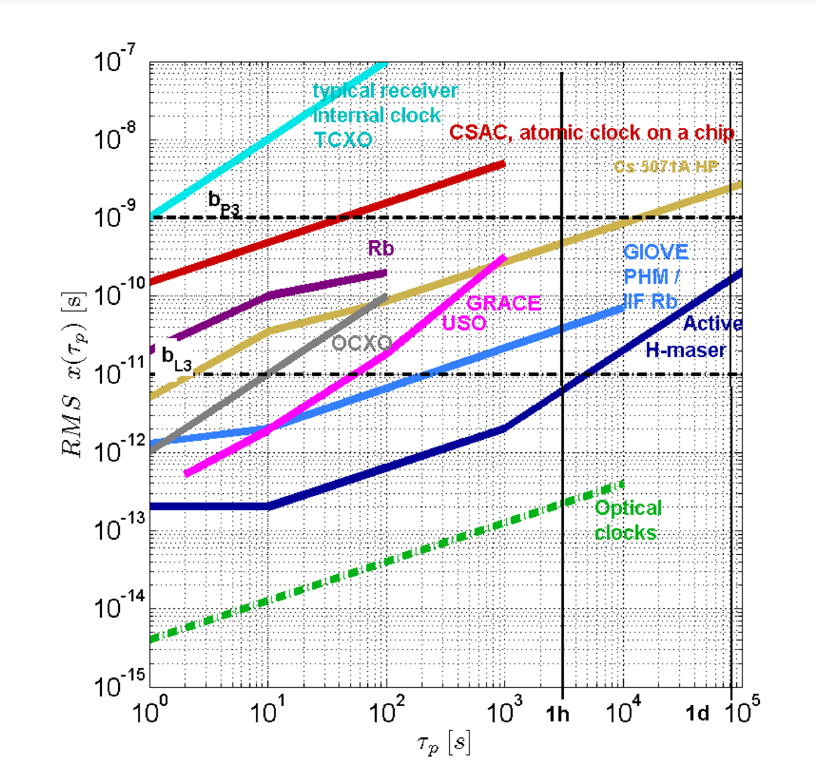

Fig. 2: Time prediction error $\tau_p \cdot \sigma_y(\tau_p)$ due to random frequency fluctuations for a number of high-precision frequency sources black dashed-lines: noise of the ionosphere-free linear combination of the code b_{P3} and carrier phase b_{L3} observations.
Currently only hydrogen maser frequency standards fulfill the condition given by equation (1) and can be modeled over extended time intervals (up to several hours) in GNSS solutions based on carrier phase observations. About 65 stations in the IGS network are equipped with hydrogen maser clocks and typically more than 20 of these reliably deliver frequency stabilities that meet or outperform the specifications given above.
Some chips scaled atomic clocks, like e.g., the CSAC can be used for clock modeling in code-based navigation.

Application of clock modeling to the Chile 2010 Earthquake

GPS Data and analysis concept

- 1 Hz GPS data of the IGS station CONZ made available by BKG
- 3 hours data before and after earthquake included for reliably estimating the float carrier phase ambiguities
- GPS receiver (CONZ) connected to well-maintained hydrogen maser frequency standard
- processed with PPP software developed at Institut für Erdmessung
- linearly interpolated 5 s GPS satellite clocks, provided by CODE, (Bock et al. 2009)
- epoch-wise independent receiver clock offsets or piece-wise linear segments (5 min) intervals.

Mainshock

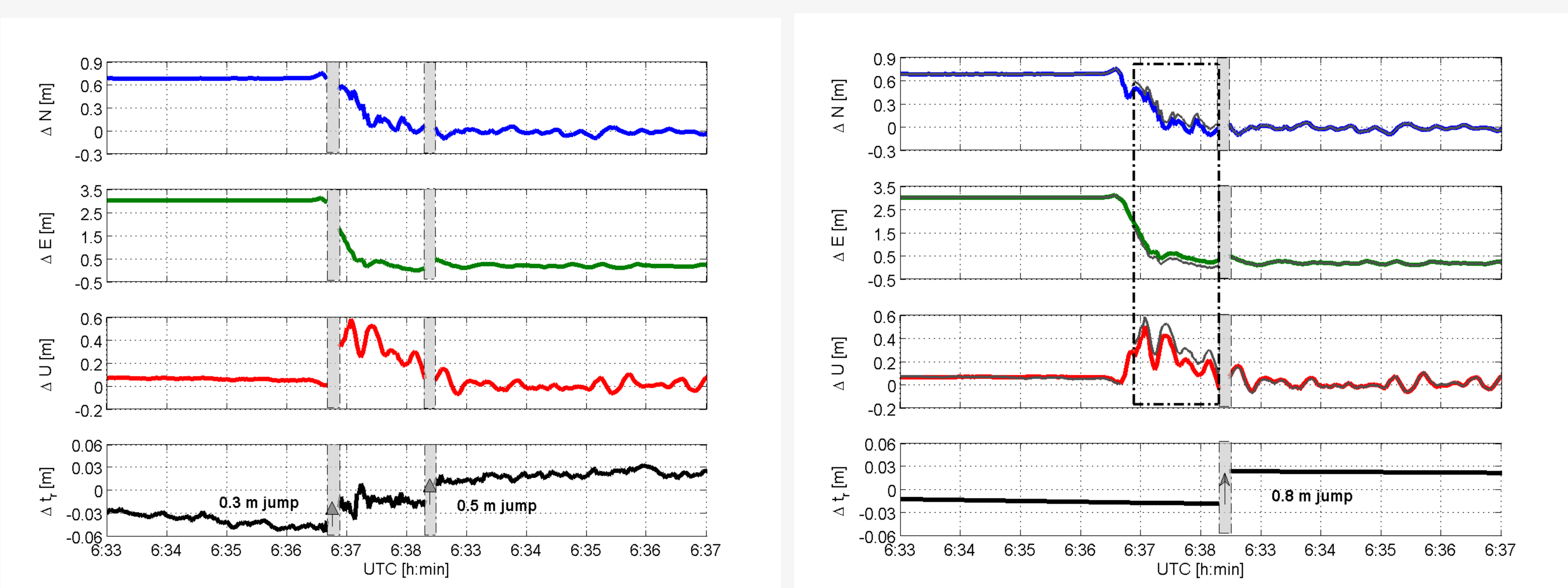

Fig. 3: Kinematic PPP position estimates and receiver clock error during the main shock of the 8.8 magnitude 2010 Chile earthquake (a) using epoch-wise clock estimation, (b) using clock modeling taking the h-maser performance at CONZ into account
Benefits: less jumps, continuous and reliable time series

Application of clock modeling to the Chile 2010 Earthquake

Aftershock

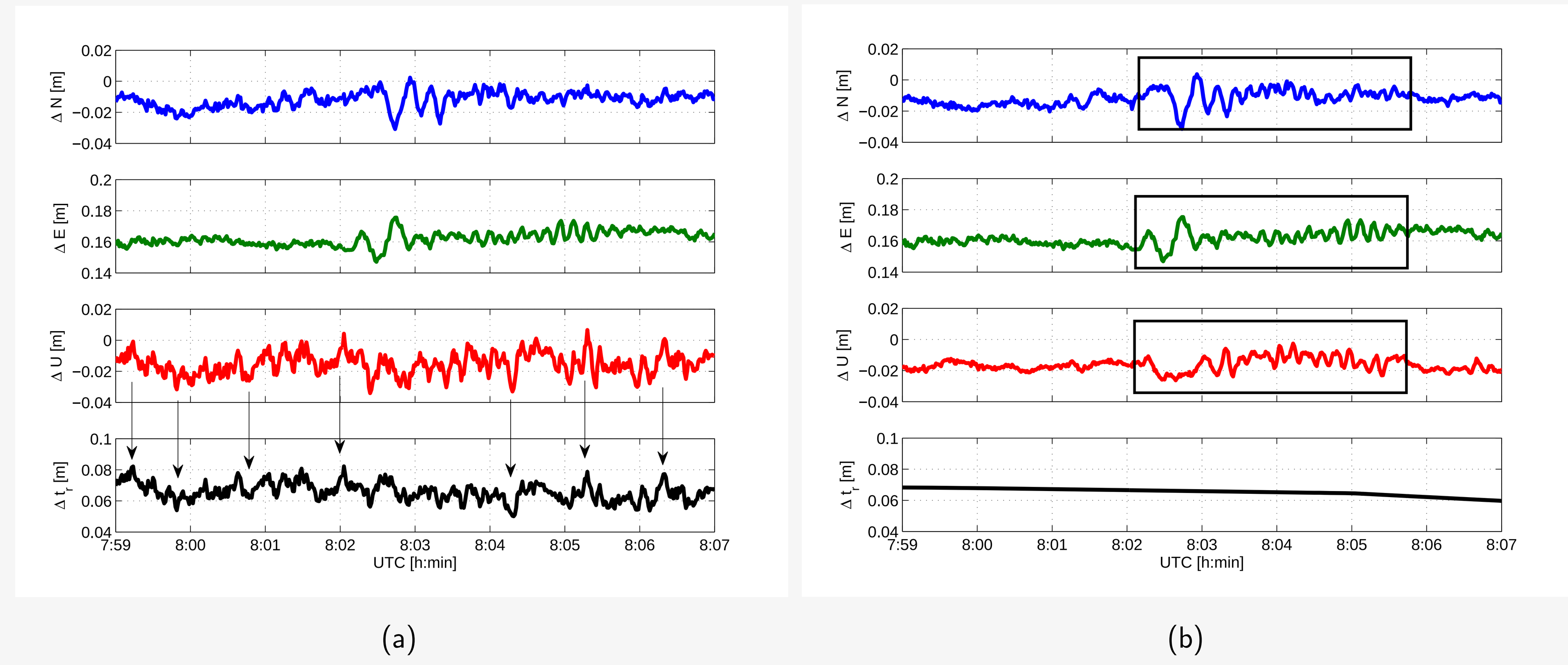

Fig. 4: Kinematic PPP position estimates and receiver clock error during a 6.9 magnitude aftershock (a) using epoch-wise clock estimation, (b) using clock modeling taking the h-maser performance at CONZ into account

- Vertical station displacements hidden in the noise of the kinematic height estimates (Conventional PPP solutions Fig.5(a))
- High mathematical correlation (here about 89.6%) expressed by the similarity of the vertical position time series and the epoch-wise receiver clock offsets (cf. arrows, Fig.5(a))
- Tightly constraining the receiver clock according to the physical clock performance, the signature of the earthquake becomes clearly visible also in the height component (Fig.5(b))
- The standard deviation of height time series is improved by 37% from 12 mm to 7.5 mm.

Application of clock modeling to code-based navigation

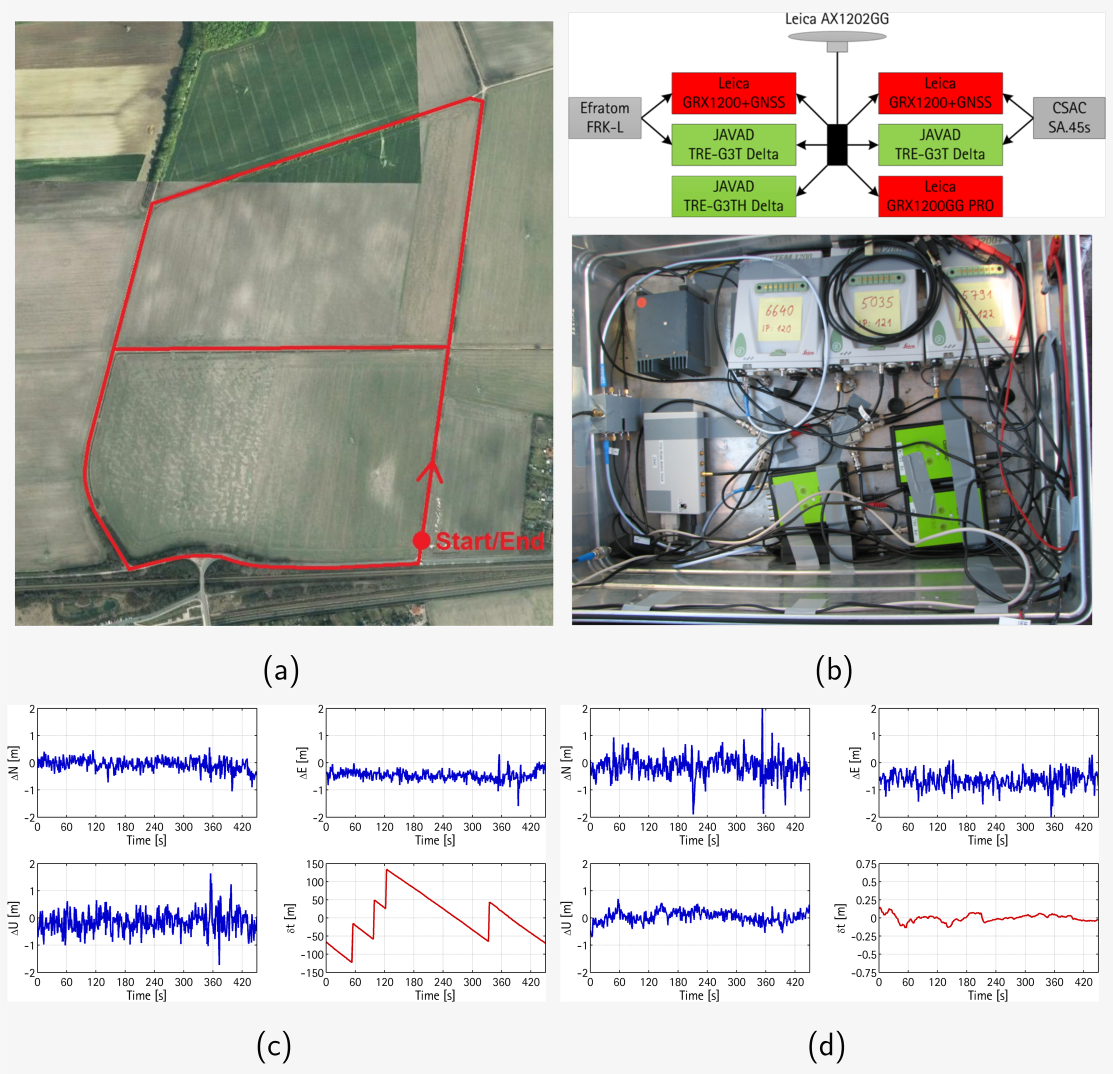

Fig. 5: Kinematic code-based position estimates and receiver clock error during a kinematic test drive (a) Test trajectory (b) receiver set up with three identical receivers, (c) Results with internal clock, (d) Results from clock modeling

- Clock modeling with two states (offset, drift) Kalman model.
- Again, the noise of the height component is reduced (Static positioning up to 23%, kinematic positioning up to 50%).
- Height component less vulnerable w.r.t. systematics, since correlations between the parameters are reduced.
- Availability improved, since positioning with only three satellites in view is possible.
- Vibrations may degrade the results.

Conclusions

- The usage of highly stable GNSS receiver oscillators allows to improve the accuracy of kinematic vertical position estimates by a factor of 2-3.
- Co-seismic few mm vertical displacements of a stand-alone GPS receiver connected to a hydrogen maser frequency standard can be detected using the PPP approach with enhanced clock modeling.
- More accurate height variations can be derived from Precise Point Positioning using IGS orbit and clock products. This is interesting for high-frequency deformation monitoring such as GPS seismology.
- Chip-scaled atomic clocks together with clock modeling improve the availability, continuity and precision of code-based navigation solutions in harsh environments.

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