IGS 2026 WORKSHOP
SANTIAGO DE CHILE
33°26' S 70°39' O

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UNIVERSITY OF WARMIA AND MAZURY IN OLSZTYN

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Exploring the potential of smartphone GNSS and accelerometer observations for displacement monitoring

ORGANIZING INSTITUTIONS

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Exploring the potential of smartphone GNSS and accelerometer observations for displacement monitoring

Motivation

- Limited effectiveness of high-quality GNSS receivers and strong-motion accelerometers due to insufficient spatial coverage.
- High costs and challenges associated with densifying traditional sensor networks.
- Widespread availability of low-cost, mass-produced GNSS and IMU MEMS sensors, including smartphones.
- Potential of smartphones as an alternative source of observational data for high-precision applications due to the promising accuracy of the observations.

Research hypothesis

➢ Android smartphones can serve as a low-cost source of information on high-frequency displacement, potentially aiding early warning systems in seismology, SHM, and geohazards

Goal

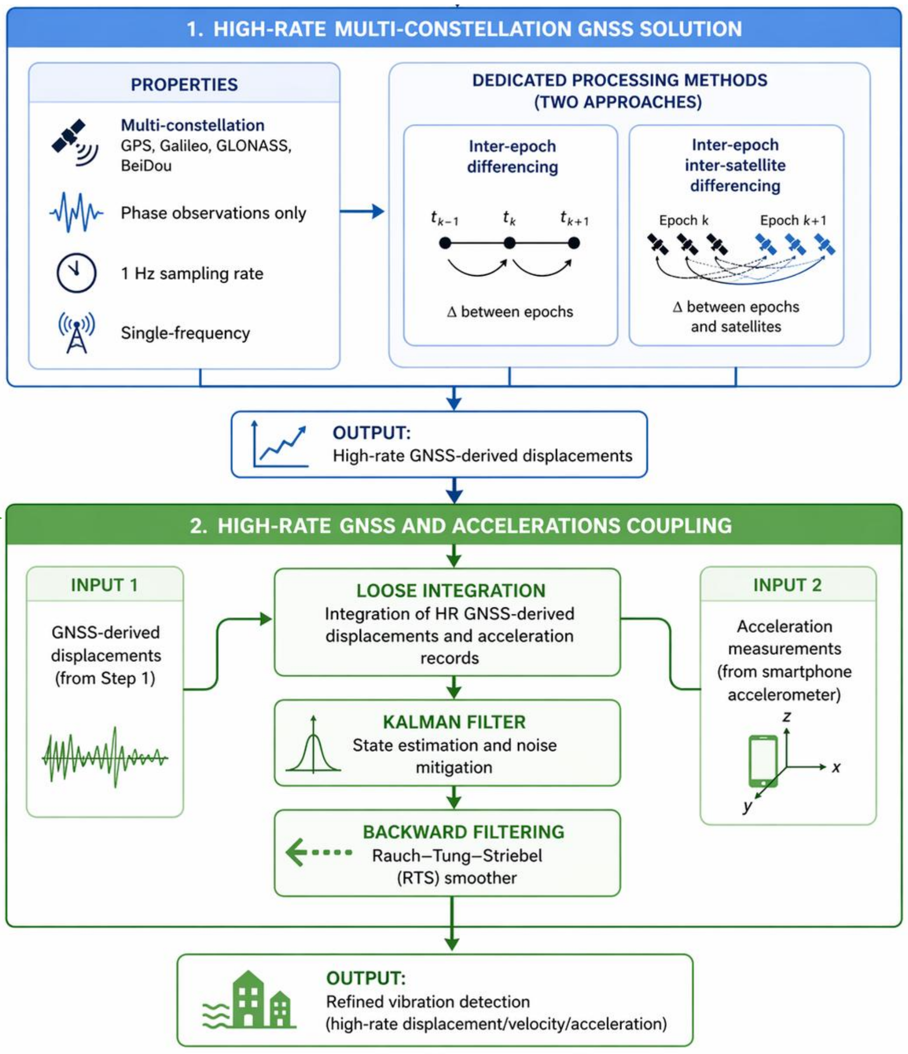
➢ *to develop a data-processing technique to make smartphone GNSS and accelerometer sensors suitable for geoscience applications – with millimeter-level precision*

Method
for recapturing dynamic displacement with smartphone GNSS & acceleration data

Two-step procedure for a high-rate smartphone-based solution for vibration detection

1. HIGH-RATE MULTI-CONSTELLATION GNSS SOLUTION

2. HIGH-RATE GNSS AND ACCELERATIONS COUPLING



Method
for recapturing dynamic displacement with smartphone GNSS & acceleration data

We employ two models fed with phase-only multi-constellation data to retrieve displacements from high-rate GNSS observations collected by smartphones and geodetic receivers:

➤ **Inter-epoch differenced multi-GNSS solution (*TimeDiff*)**

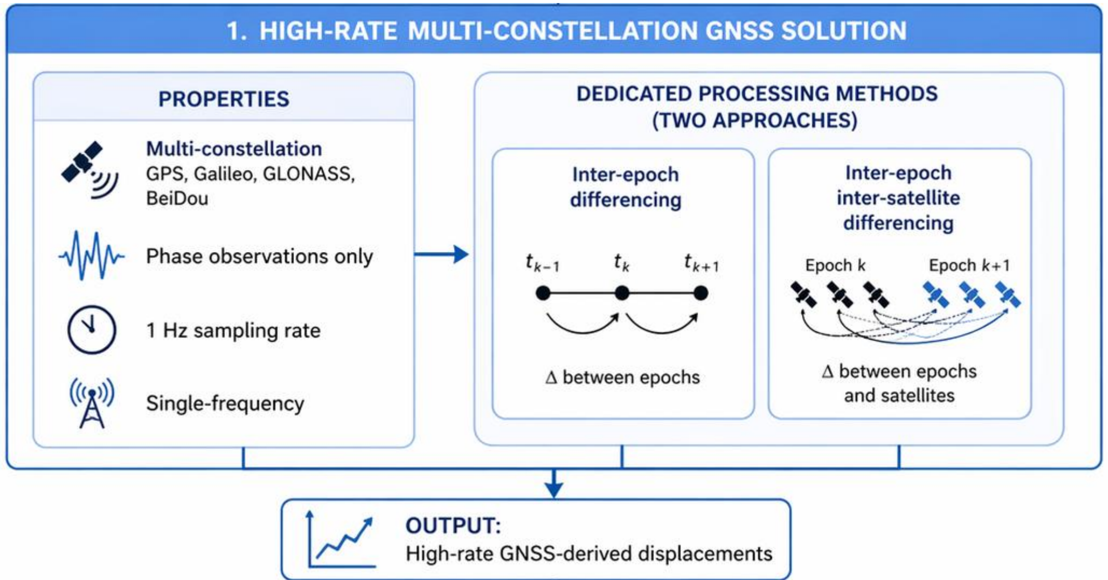
$$\bar{L}_{j,r}^{s}\,(t+\Delta t, t) = e_r^s \cdot \delta\xi_r(t+\Delta t, t) + c dt_r(t+\Delta t, t)$$

where: e_r^s is the line-of-sight vector and $\delta\xi_r$ is the vector of the coordinate components' changes between epochs t and $t+\Delta t$, i.e., mean velocity between epochs, $L_{j,r}^{s}$ denotes the carrier phase observation in the units of metres, an overbar denote that the phase observation were corrected with corrections and a priori parameters; c is the speed of light; $dt_r(t+\Delta t, t)$ represent the change in receiver clock error between epochs ($t+\Delta t$ and t).

Differencing the time-differenced observations between two satellites, s^1 and s^2, reduces the number of unknowns in the model by excluding the change in the receiver clock error term:

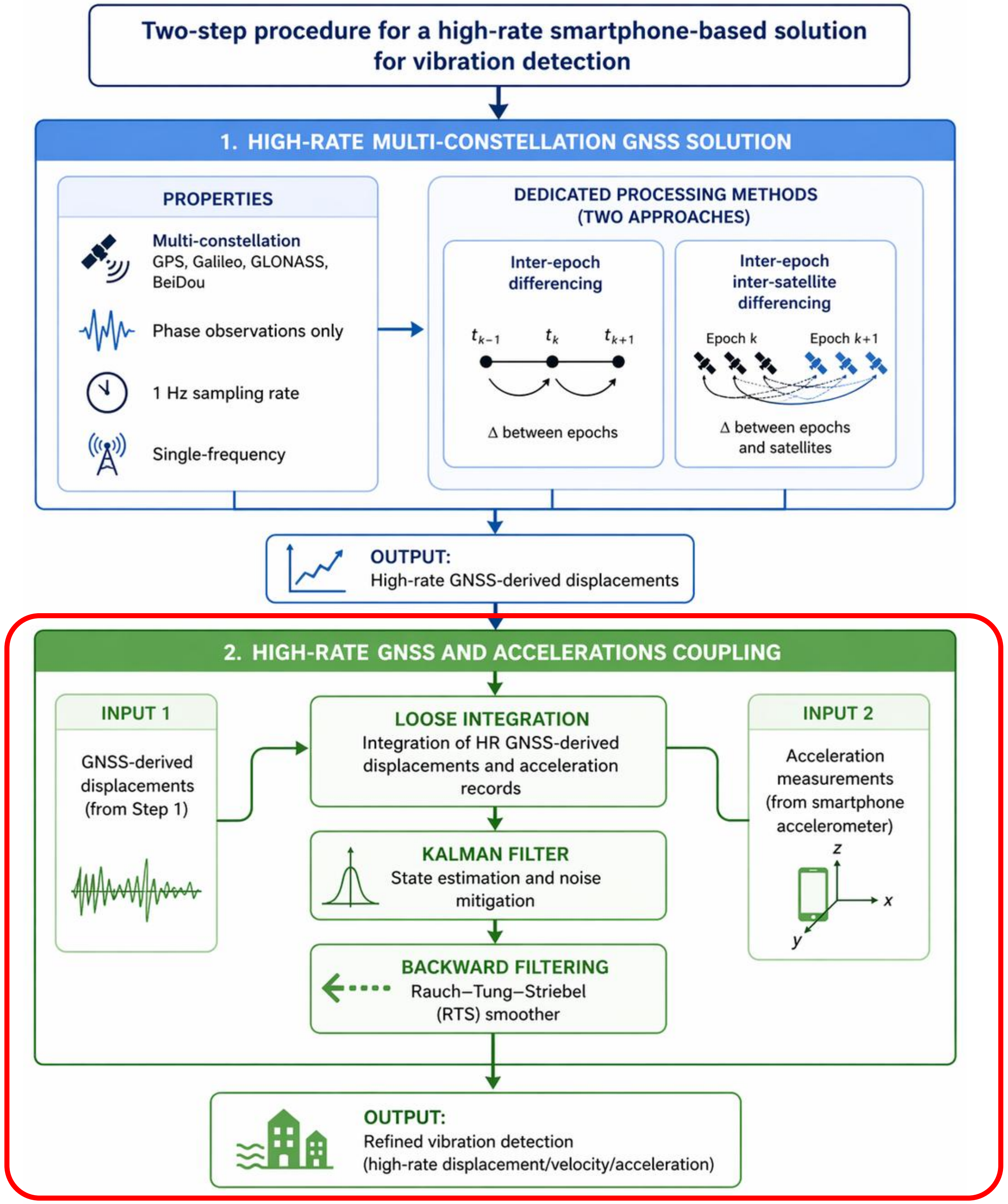
➤ **Inter-satellite inter-epoch differenced multi-GNSS solution (*SatTimeDiff*)**

$$\bar{L}_{j,r}^{s^1 s^2}(t+\Delta t, t) = e_r^{s^1 s^2} \cdot \delta\xi_r(t+\Delta t, t)$$



Method
for recapturing dynamic displacement with smartphone multi-GNSS & acceleration data

- High-rate smartphone GNSS-derived displacements and smartphone accelerometer data are combined in a Kalman filter.
- A **loose integration approach** based on the Kalman filter, including prediction and correction steps, is used to couple the multi-rate data from the smartphone's embedded sensors: **1 Hz GNSS-derived displacements** and **100 Hz accelerometer records**.
- **Backward filtering** is used to refine previous epoch solutions (the Rauch-Tung-Striebel smoother).



Experiment design

- Validation of the derived displacements against the ground-truth displacements provided by the Quanser I-40 **shake table**.
- Several **sine wave motions** at amplitudes of **20-5 mm** and frequencies of **0.1-0.5 Hz**, reflecting possible structural vibrations in SHM.
- Seismic waveforms of two preloaded real **earthquakes**, **the Cape Mendocino** and **El Centro** events, with a single degree of freedom.

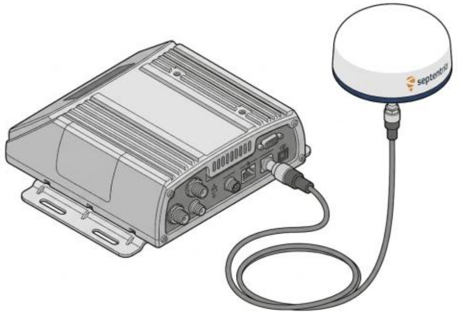
Sine wave motion	Frequency [Hz]	Amplitude [mm]
Sine wave #1	*0.1*	*20*
Sine wave #2	*0.5*	*20*
Sine wave #3	*0.1*	*10*
Sine wave #4	*0.5*	*10*
Sine wave #5	*0.1*	*5*
Sine wave #6	*0.5*	*5*
Scaled earthquake waveform	**Peak displacement [mm]**	
El Centro seismic	*18*	
Cape Mendocino seismic	*18*	

Experiment design

Equipment

- The **Quanser I-40 shake table** to simulate single-axis sine wave motions and scaled seismic waveforms (linear stage position with a resolution of 1.22 μm and at a sampling rate of 500 Hz). Provider of ground truth displacements.

- **Xiaomi 13T Pro smartphone** (model 23078PND5G) running Android 14, with a MediaTek Dimensity 9200+ chipset to record 1 Hz multi-GNSS observations and ~100 Hz accelerations.



- **Trimble Alloy receiver** + Septentrio PolaNt* MC.v2 antenna to record benchmark multi-GNSS data with 20 Hz.

Software:

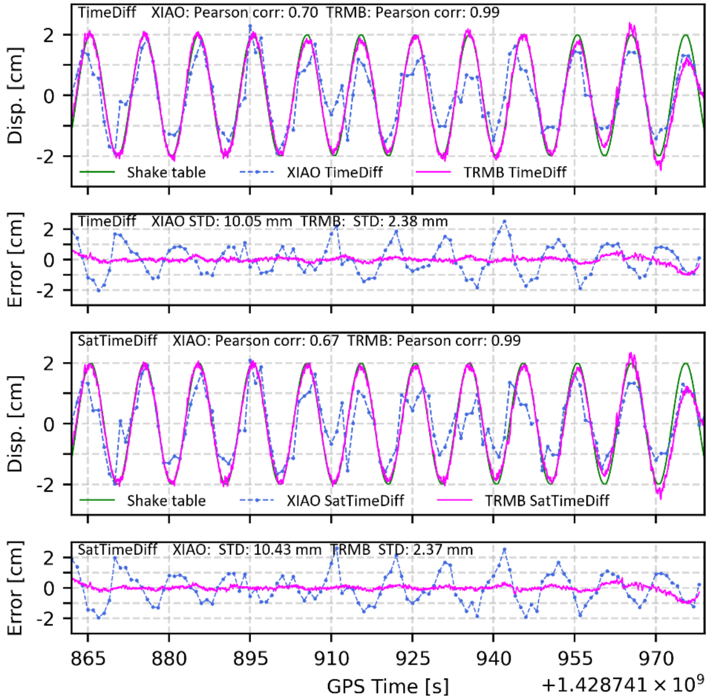
- Smartphone data acquisition software - Google GNSS Logger Android.
- Processing software – in-house-developed for GNSS and accelerometer processing and coupling.

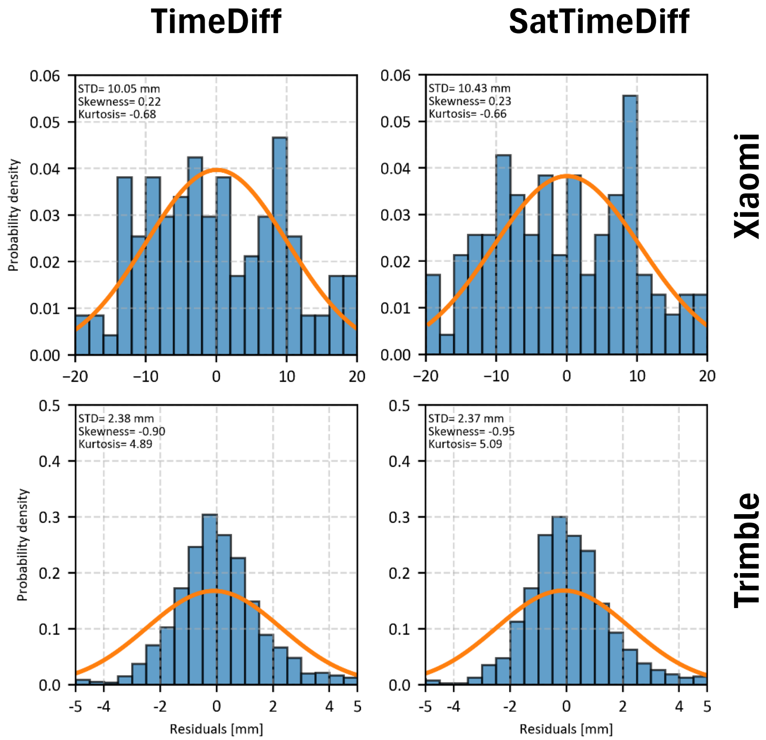
Experiment results: smartphone GNSS-only solution

Sine-wave motion amplitude: 20 mm, frequency: 0.1 Hz

High-rate GNSS-only solution assessment:

- Android smartphone (***Xiaomi***) vs high-grade GNSS receiver (***Trimble Alloy***)
- Inter-epoch differenced GNSS solution (***TimeDiff***) vs Inter-satellite inter-epoch differenced GNSS solution (***SatTimeDiff***)



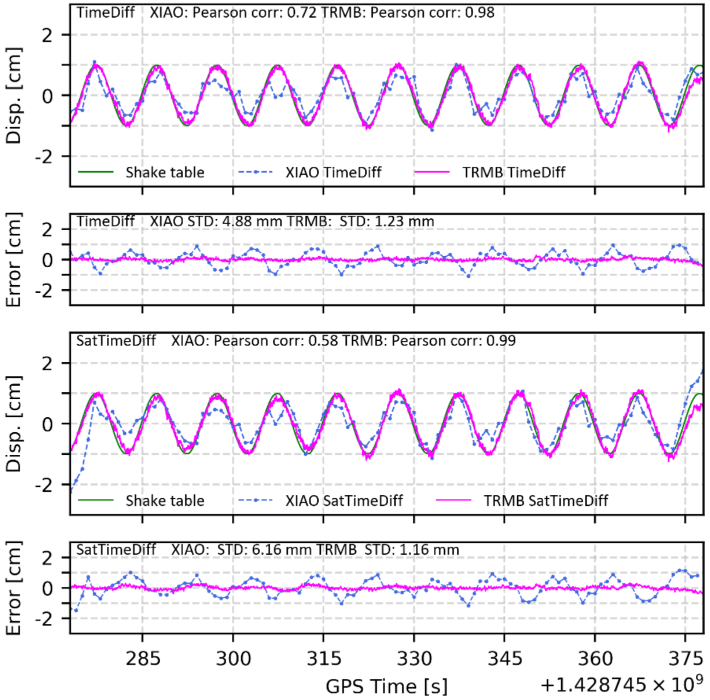


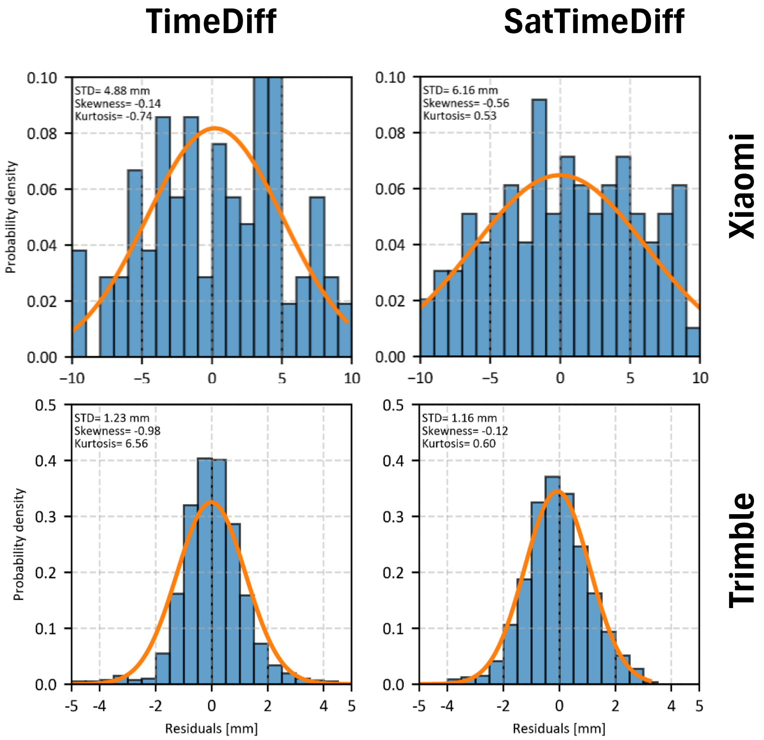
Experiment results: smartphone GNSS-only solution

Sine-wave motion amplitude: 10 mm, frequency: 0.1 Hz

High-rate GNSS-only solution assessment:

- Android smartphone (***Xiaomi***) vs high-grade GNSS receiver (***Trimble Alloy***)
- Inter-epoch differenced GNSS solution (***TimeDiff***) vs Inter-satellite inter-epoch differenced GNSS solution (***SatTimeDiff***)



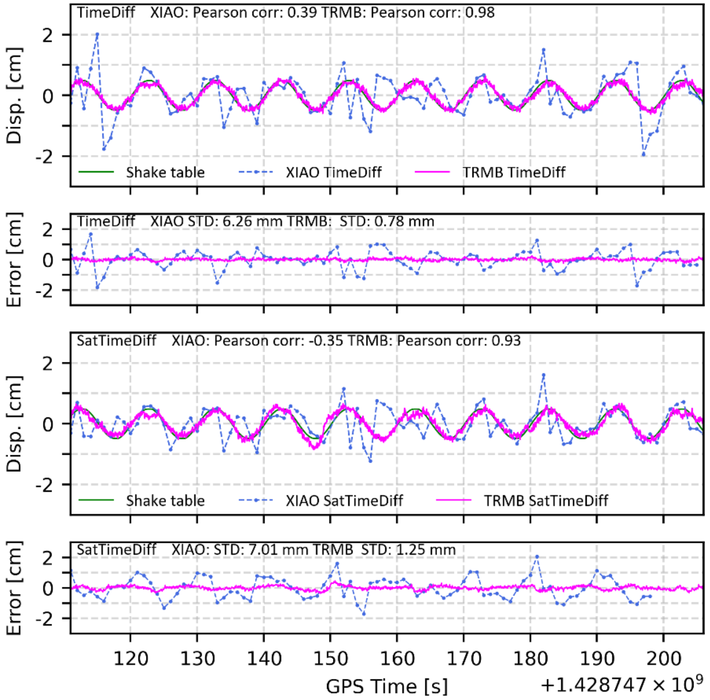


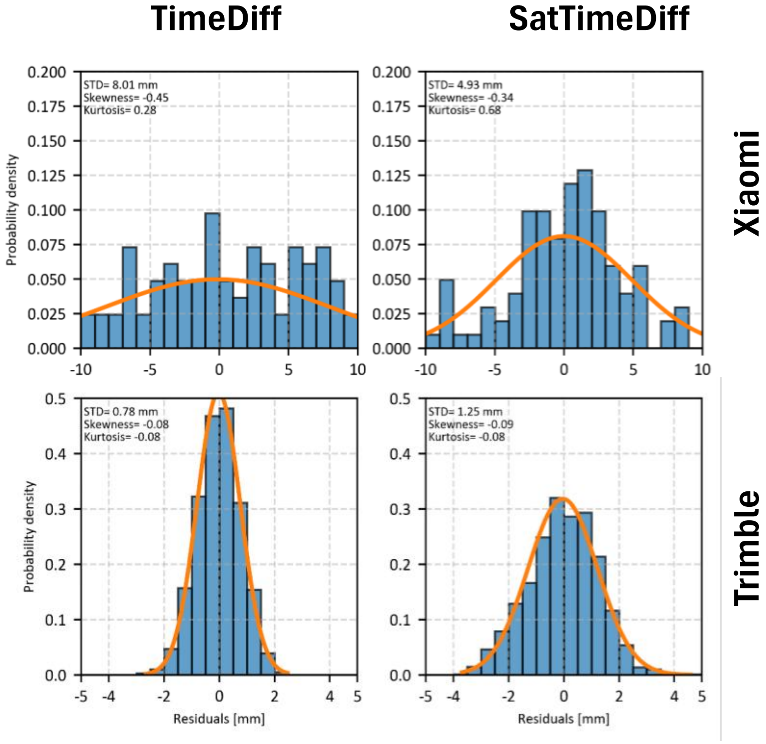
Experiment results: smartphone GNSS-only solution

Sine-wave motion amplitude: 5 mm, frequency: 0.1 Hz

High-rate GNSS-only solution assessment:

- Android smartphone (***Xiaomi***) vs high-grade GNSS receiver (***Trimble Alloy***)
- Inter-epoch differenced GNSS solution (***TimeDiff***) vs Inter-satellite inter-epoch differenced GNSS solution (***SatTimeDiff***)





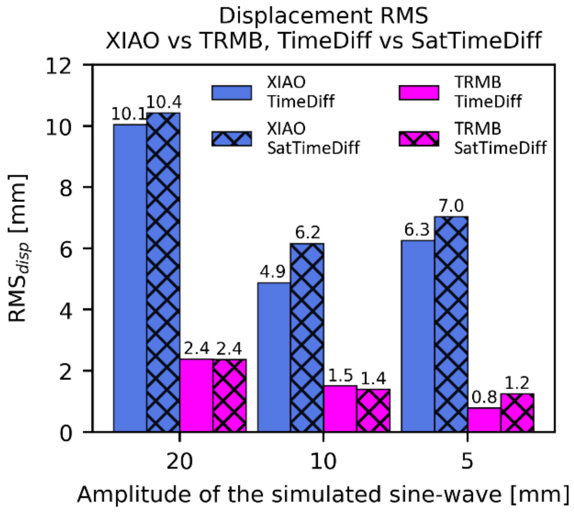
Experiment results: smartphone GNSS-only solution

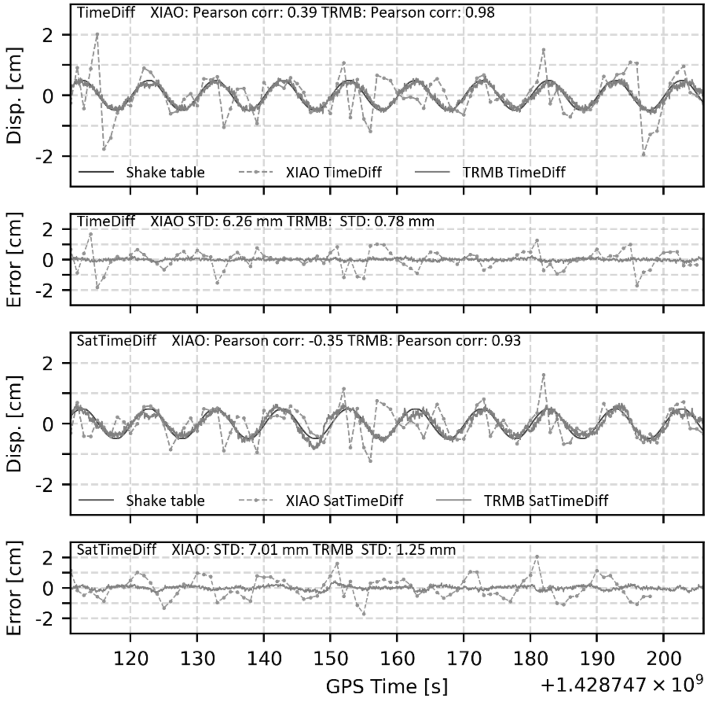
Sine-wave motion amplitude: **5 mm**, frequency: 0.1 Hz

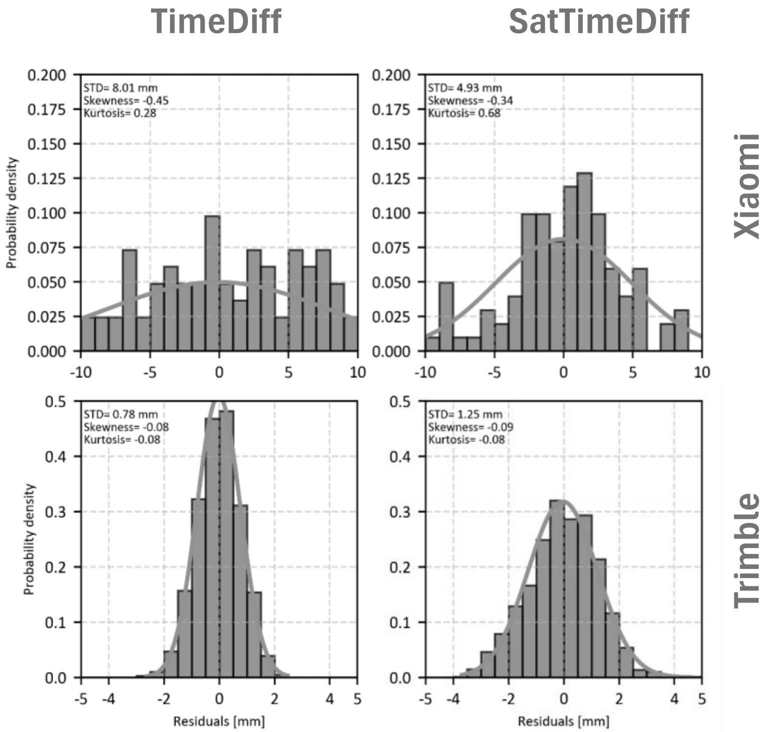
High-rate GNSS-only solution assessment:

- Android smartphone (***Xiaomi***) vs high-grade GNSS receiver (***Trimble Alloy***)
- Inter-epoch differenced GNSS solution (***TimeDiff***) vs Inter-satellite inter-epoch differenced GNSS solution (***SatTimeDiff***)

Summary of GNSS-only solution performance

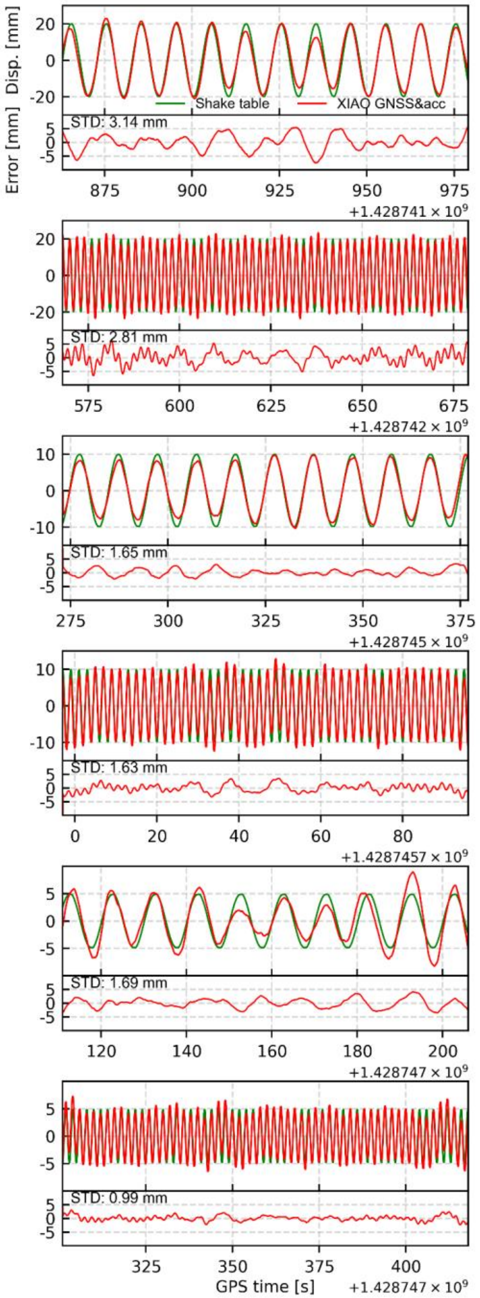




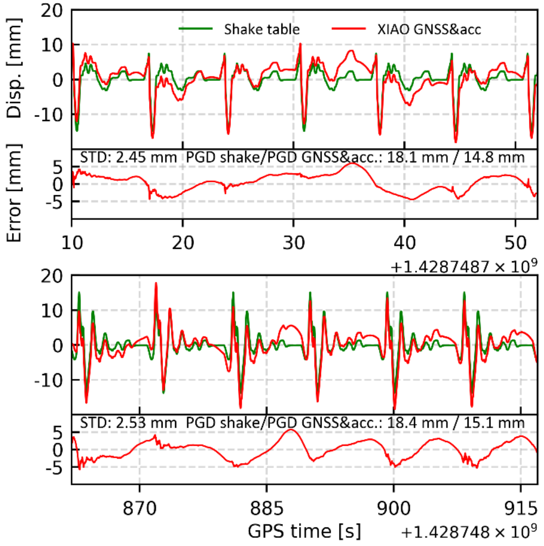


Experiment results: smartphone GNSS & accelerometer coupled solution

Sine-wave motions



Earthquakes



- Displacement time series of smartphone-embedded GNSS & accelerometer coupled solution
- Benchmark displacement time series

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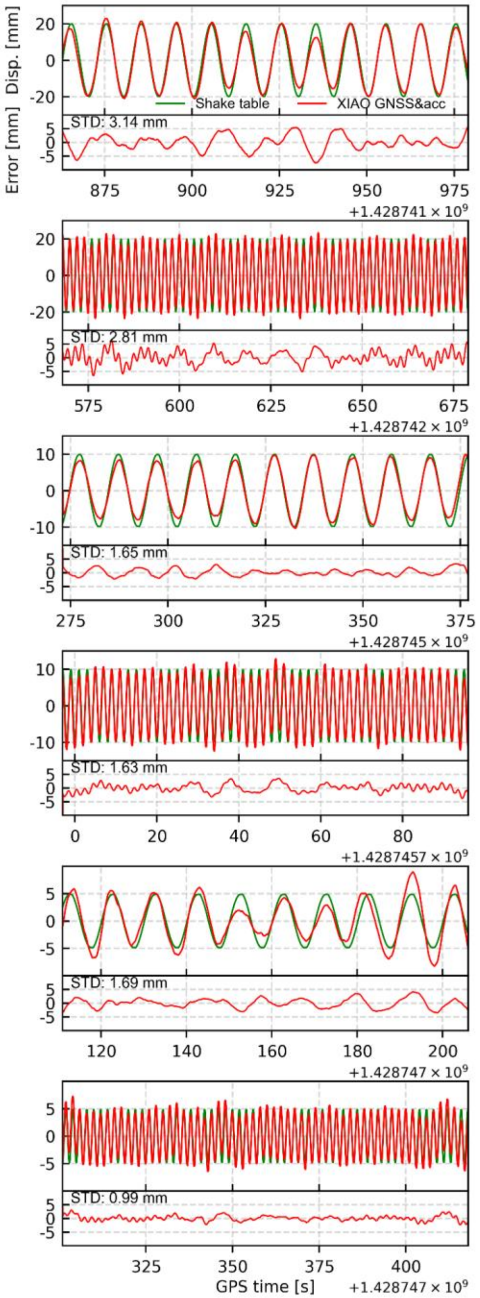
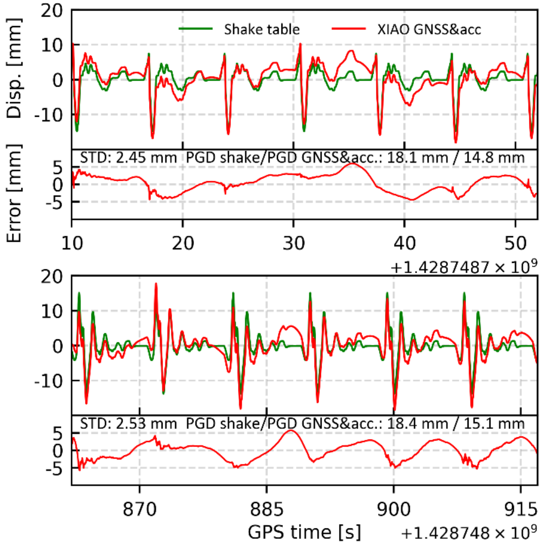
Experiment results: smartphone GNSS & accelerometer coupled solution

Sine-wave motions



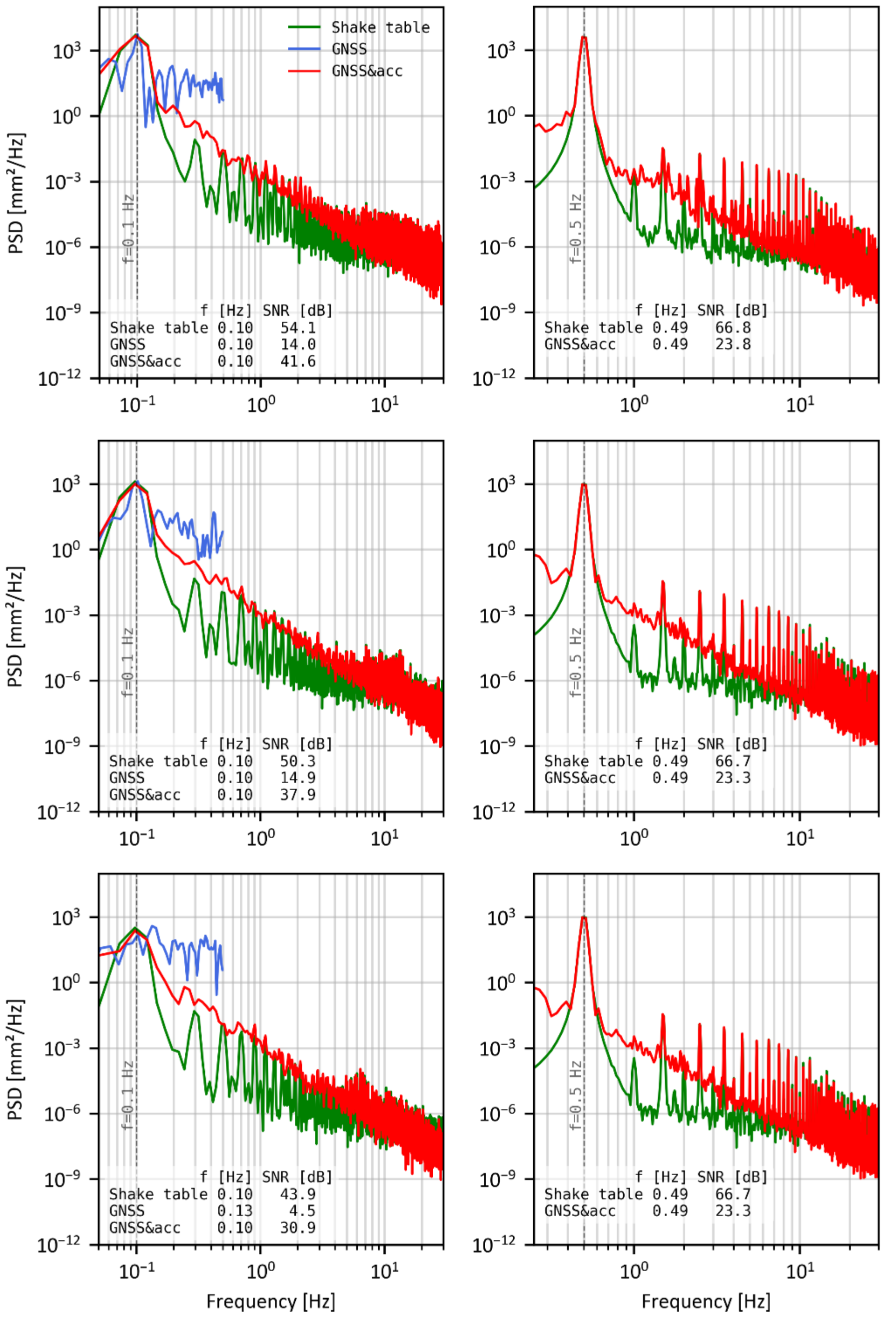
Earthquakes



- Coupling smartphone acceleration and GNSS typically enhances precision by about threefold with respect to the smartphone GNSS-only solution
- Even vibrations with a 5 mm amplitude are precisely captured, as the smartphone-coupled solution reconstructed 5 mm/0.5 Hz vibration with an RMS ~1 mm.

Motion	RMS [mm]
Sine wave #1 (20 mm/0.1 Hz)	3.1
Sine wave #2 (20 mm/0.5 Hz)	2.8
Sine wave #3 (10 mm/0.1 Hz)	1.7
Sine wave #4 (10 mm/0.5 Hz)	1.6
Sine wave #5 (5 mm/0.1 Hz)	1.7
Sine wave #6 (5 mm/0.5 Hz)	1.0
el Centro seismic waveform	2.5
Cape Mendocino seismic waveform	2.5

Experiment results: smartphone GNSS & accelerometer coupled solution



- ✓ Coupling smartphone acceleration and GNSS reduces the solution noise.

Conclusions

- **Smartphone GNSS-only solution** correctly detects dynamic displacement; however, its usefulness is limited by its sampling rate, which misses higher-frequency oscillations, and the accuracy, reflected in **RMSs ~5–10 mm** range, excluding very small vibrations at the millimeter scale.
- Considering two analyzed GNSS-only processing schemes (**TimeDiff** vs. **SatTimeDiff**), we found that while the differences in displacement accuracy were negligible with **high-grade receiver** data (**up to 0.4 mm**), they were slightly more pronounced **with smartphone data** (**up to 1.3 mm**).
- For all **sine-wave motions**, the **smartphone GNSS & accelerometer coupled solution** accurately reproduced the simulated vibrations, with **RMS errors of 1–3 mm**.
- Analysis of **earthquake-related displacements** generally showed that displacement accuracy was comparable to that in vibration cases, exhibiting **displacement errors** of approximately **2.5 mm**.
- Time-frequency analysis with PSDs indicated that **coupling** in **smartphone sensors reduces solution noise**, making the dominant frequency more pronounced relative to the background noise.
- We confirmed the hypothesis that Android smartphones can serve as a low-cost source of information on high-frequency displacement, potentially aiding early warning systems in seismology, SHM, and geohazards.

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