Resolving dynamic ground motions with high-rate GNSS and implications for data fusion in broadband seismology and Earthquake Early Warning

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Resolving Hazardous Ground Movements with GNSS


Autonomous GNSS station

(Image: P. Limpach)

Geodetic GNSS can resolve ground movements ranging from *Millimeters per Year* to *Millimeters per Second*

Long-term monitoring (mm level)
Commonly based on static GNSS with daily resolution
Tectonics, post-glacial rebound, slope monitoring, …

Short-term monitoring (cm to mm level)
Real-time kinematic methods (RTK, PPP, velocity estimation), up to 100 Hz resolution
Seismic monitoring, structural health monitoring, landslide monitoring …

How small can dynamic movements be in order to be detected?

Detection of Significant Displacements

- **Basis: epoch-wise estimation of displacement parameters** $\hat{\mathbf{x}}$
  Under a null hypothesis $H_0: \quad E(\hat{\mathbf{x}}) = 0$ (no movement) the test quantities are

  … in case the variance of the parameters is known:

$$\hat{\mathbf{x}}^T \mathbf{\Sigma}_{\hat{\mathbf{x}}\hat{\mathbf{x}}}^{-1} \hat{\mathbf{x}} \quad \sim \quad \chi^2(f, 0)$$

  … in case the variance of the parameters is estimated

$$\hat{\mathbf{x}}^T \mathbf{S}_{\hat{\mathbf{x}}\hat{\mathbf{x}}}^{-1} \hat{\mathbf{x}} \quad \sim \quad F(f, r, 0)$$

- Given the variance and non-centrality parameters, *minimum detectable displacements* can be computed

Seismic Monitoring with GNSS Instantaneous Velocity Estimates

Instantaneous Velocity Estimates:

- Based on time-differenced carrier phase
- Real-time, high-rate (≥ 1 Hz), stand-alone
- Detection down to sub-mm/s possible

Hohensinn R. et al, «*Movement Detection Based on High-Precision Estimates of Instantaneous GNSS Station Velocity.*», Surveying Engineering, 2019

Example:

- Italian „RING“ GNSS network (RHS)
- M_w 6.5 earthquake in 2016 „Norcia“
- <u>Station distance from epicenter:</u>
  Few km up to ~180 km

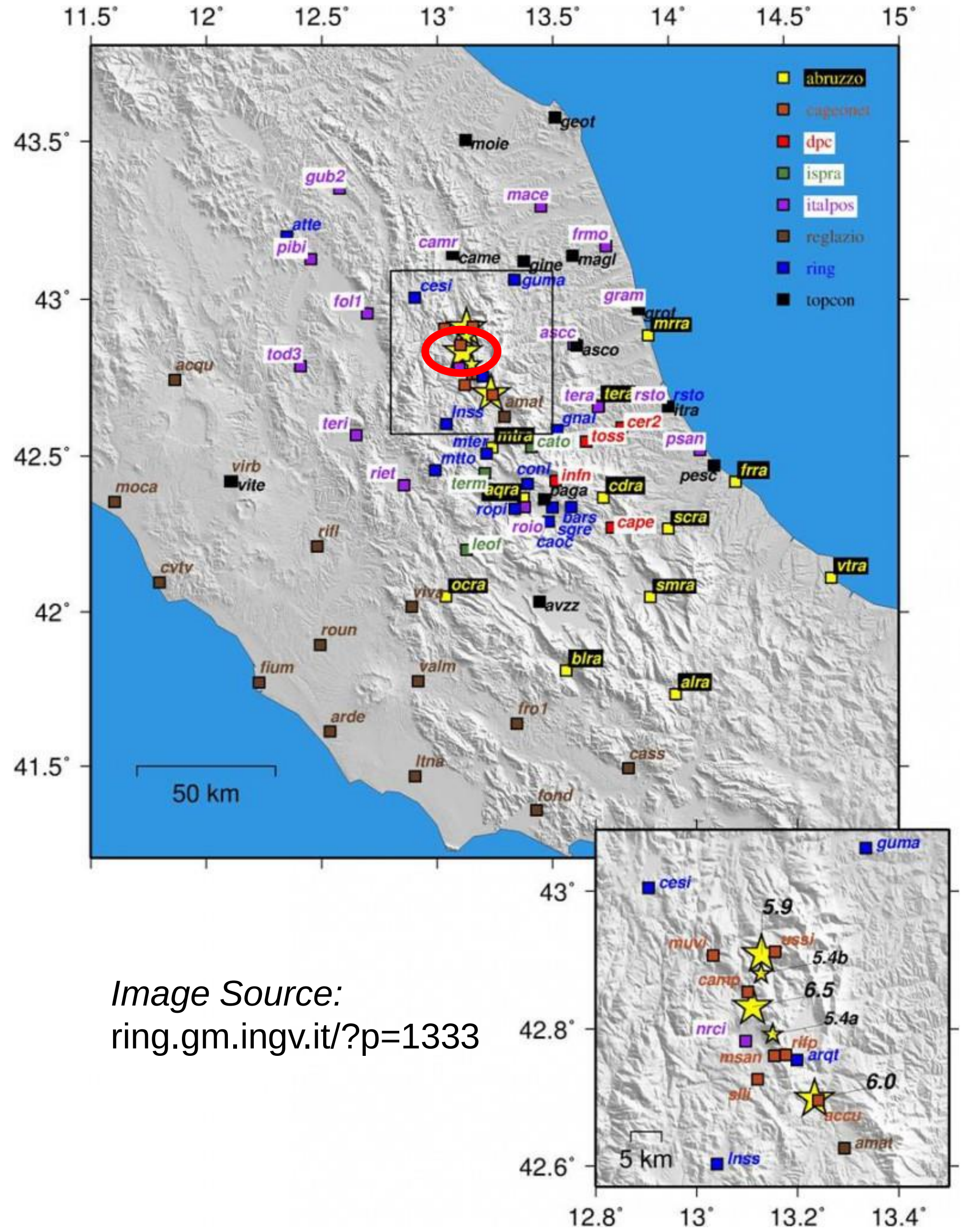


Image Source:
ring.gm.ingv.it/?p=1333

Norcia Earthquake: Results

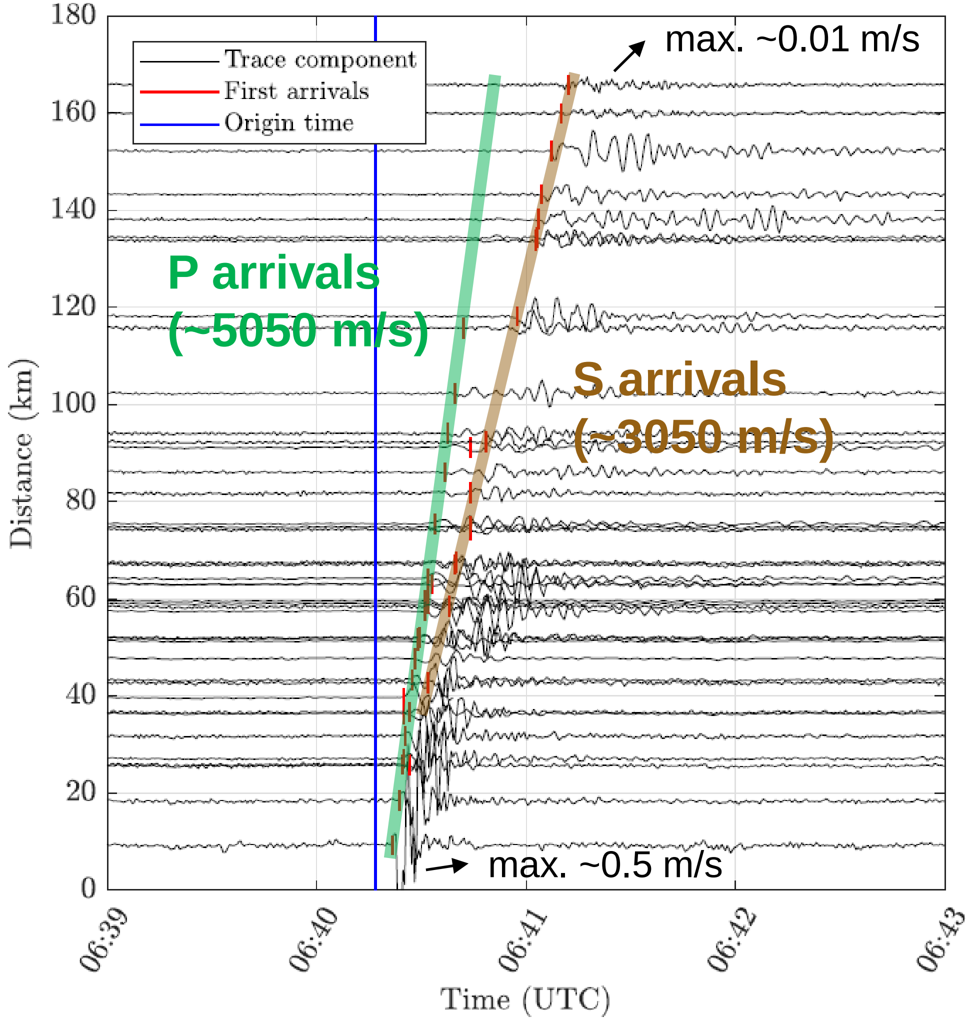
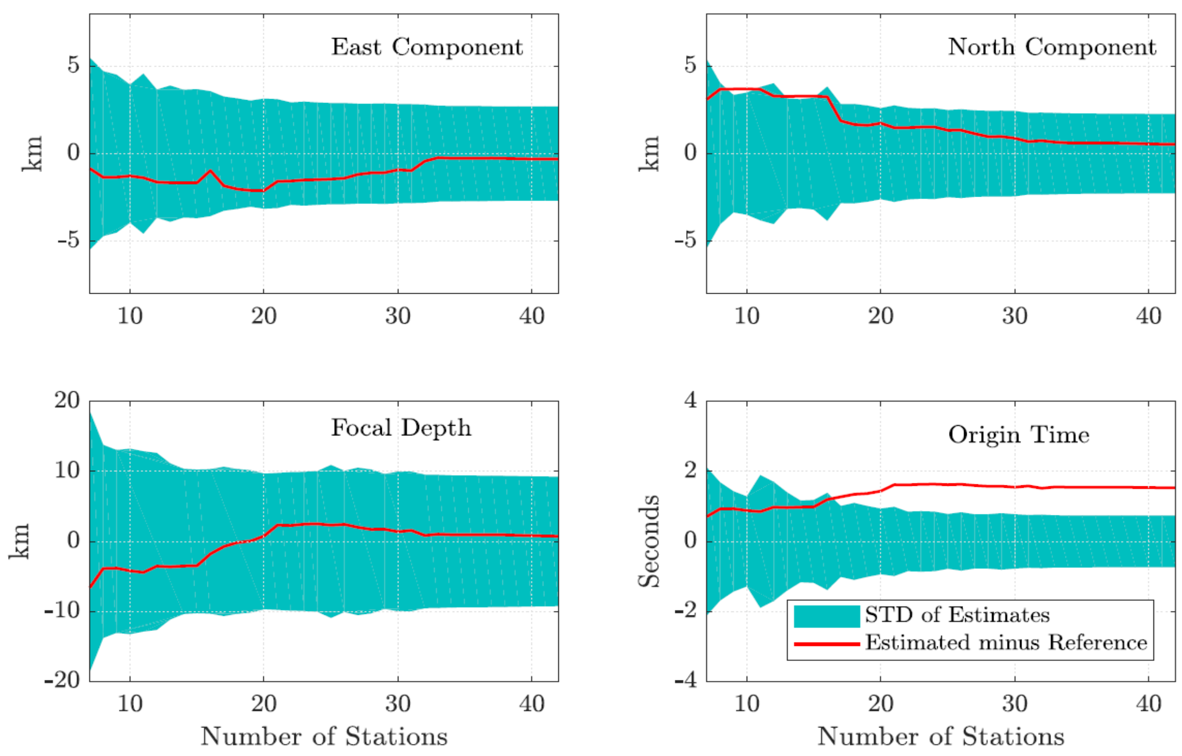


Figure (left): GNSS Velocity north component and detected first arrivals

Figure (bottom): Results from GNSS-only hypocenter localization



… as close as 1 km to reference solution

Figures: Hohensinn R., Geiger A., *«Stand-Alone GNSS Sensors as Velocity Seismometers: Real-Time Monitoring and Earthquake Detection»,* Sensors, 2018

Optimal Combination of GNSS and Seismometer Observations

▪ Example: 7.0 M_w earthquake Kumamoto, Japan, 2016

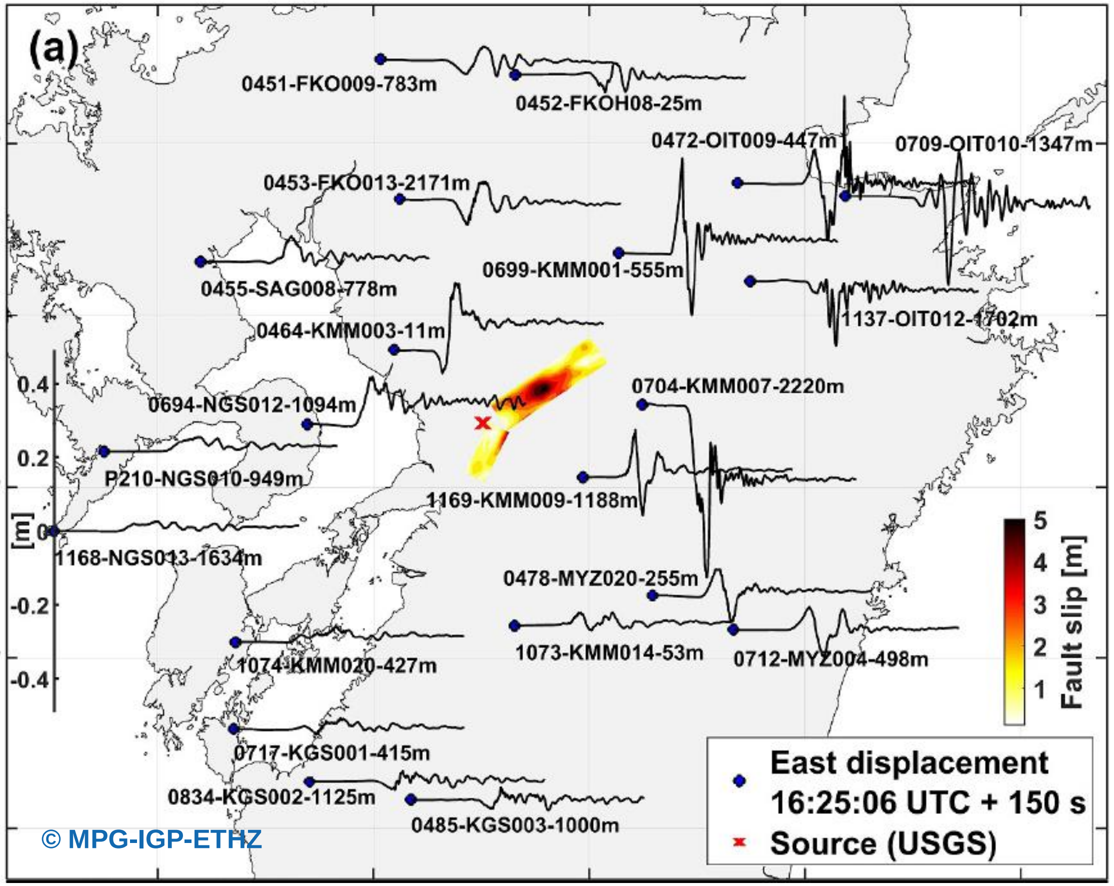


Figure: Broadband displacement waveforms (GNSS combined with strong-motion seismometer)

- Short-term precision of real-time GNSS displacements can reach level of millimeters
- Combination with strong-motion accelerometer observations: real-time (Kalman filter), near real-time (smoother)
- The result is a seismic broadband displacement and velocity waveform
- Fosters a fast and reliable earthquake response (e.g., finite fault inversion, early warning)

Optimal Combination of GNSS and Seismometer Observations

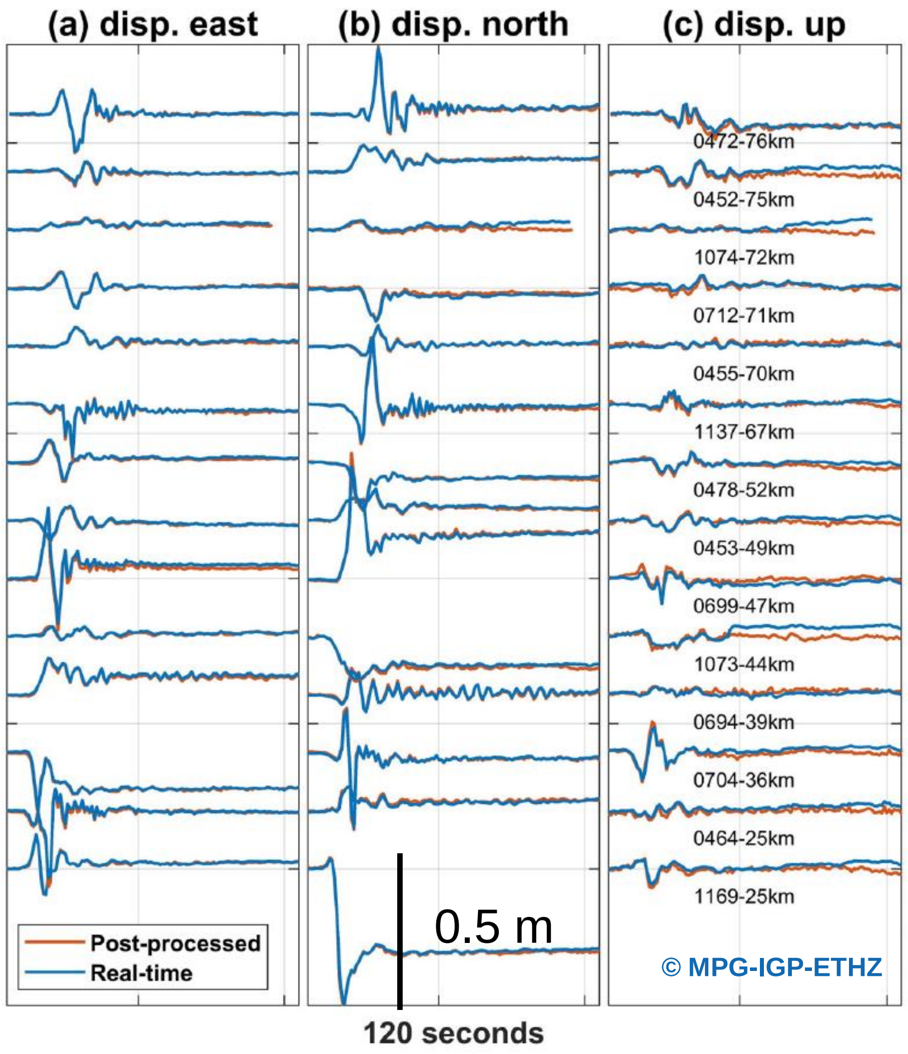
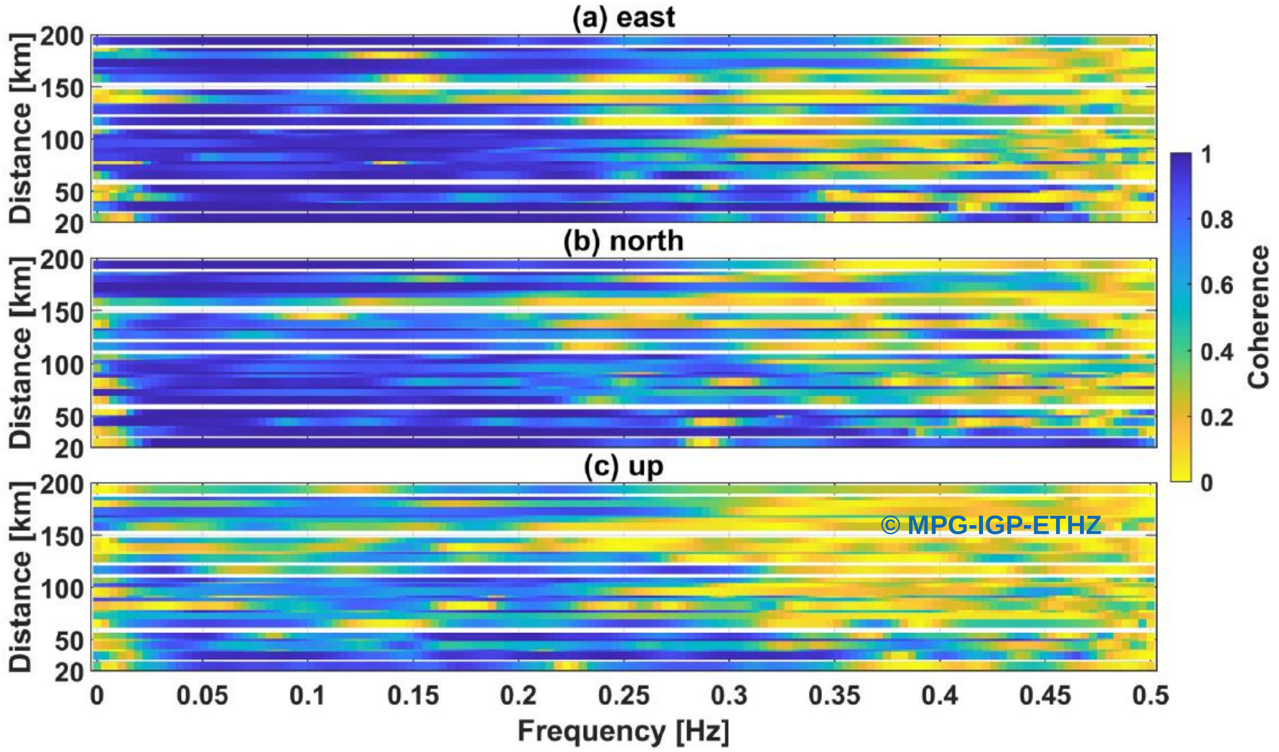


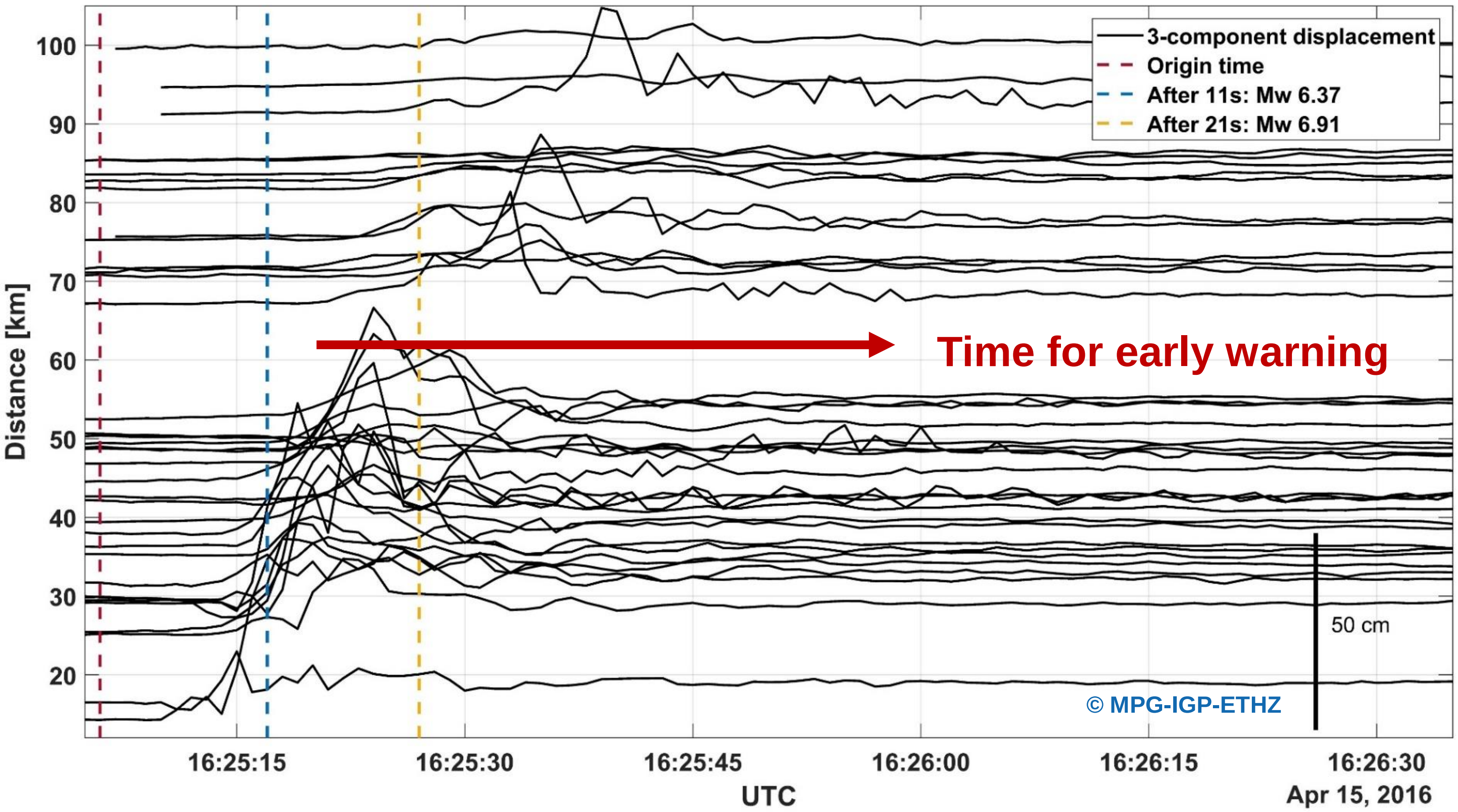
Figure (left) Kumamoto: comparison of postprocessed and realtime standalone GNSS for co-located stations up to 80 km

Figure (bottom) Kumamoto: coherence analysis of GNSS and seismometer displacements for co-located stations up to 200 km



GNSS and Earthquake Early Warning

- **GNSS fosters a reliable magnitude estimation by PGD** (Peak Ground Displacements)



Melgar, Diego, et al. *"Earthquake magnitude calculation without saturation from the scaling of peak ground displacement."* Geophysical Research Letters 42.13 (2015)

Figure: Dahmen, N., Hohensinn R., Clinton J.F., *«Comparison and Optimal Combination of GNSS and Seismometer Observations: a case study for the 2016 Kumamoto Earthquake»,* Bulletin of the Seismological Society of America (submitted)

GNSS and Earthquake Early Warning

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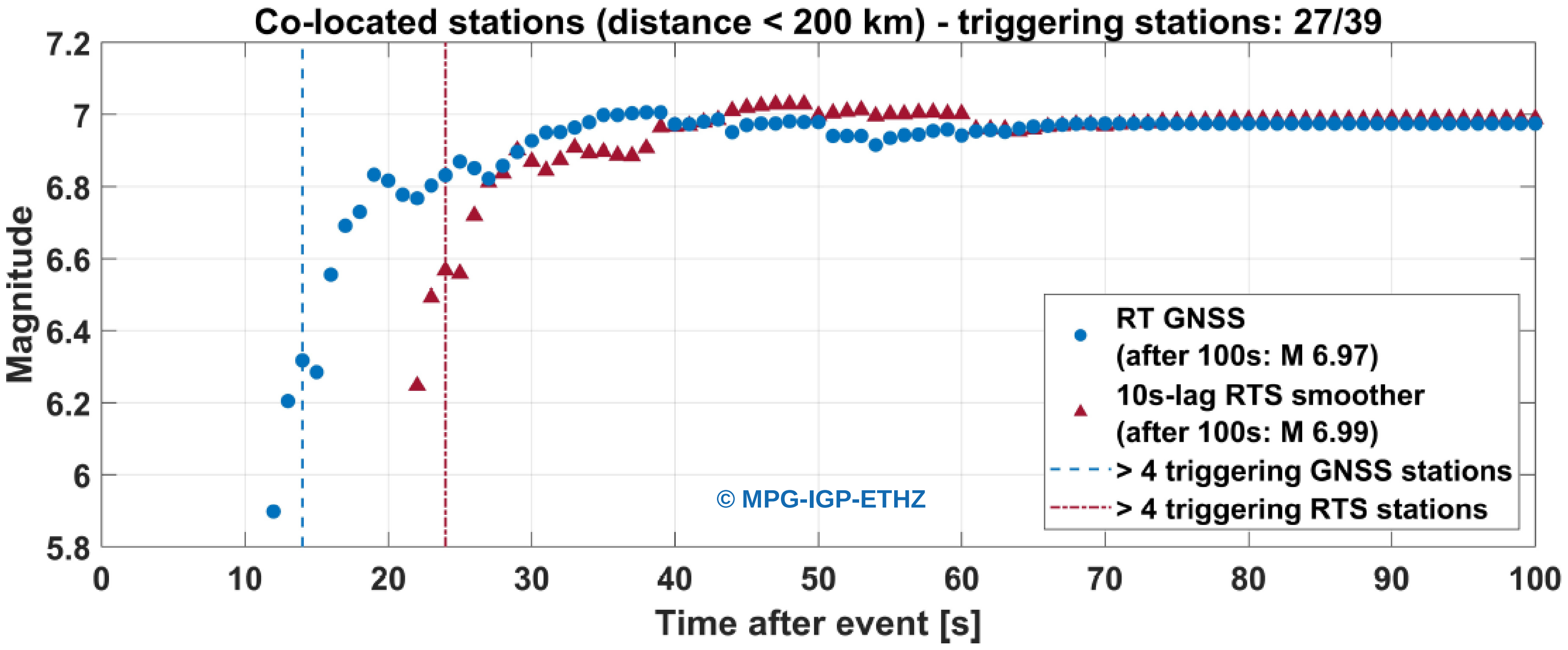


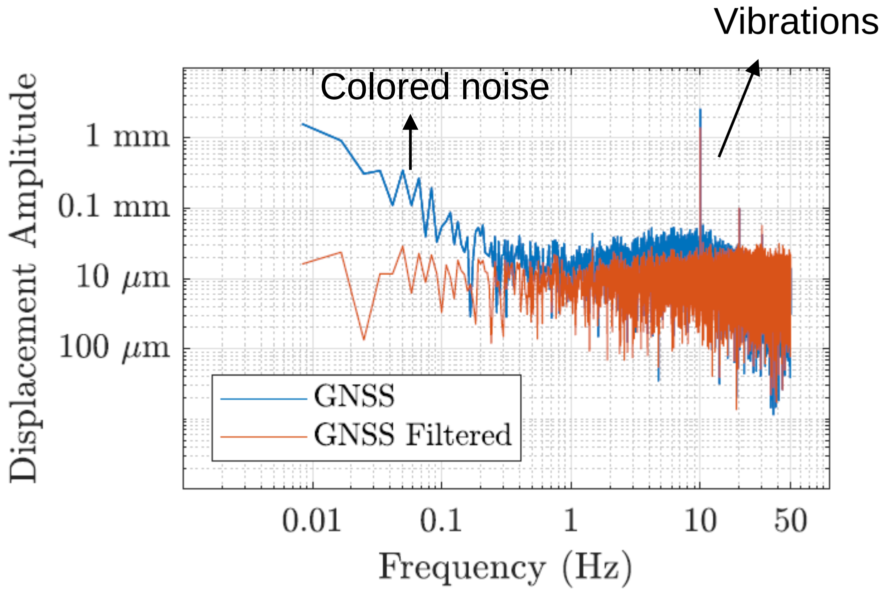
Figure: Magnitude computation by PGD with real-time (RT) GNSS and near-RT optimally combined displacements

- Optimal choice of GNSS stations by statistical testing for significant displacements

Figure: Dahmen, N., Hohensinn R., Clinton J.F., *«Comparison and Optimal Combination of GNSS and Seismometer Observations: a case study for the 2016 Kumamoto Earthquake»*, Bulletin of the Seismological Society of America (submitted)

Vibration Detection with GNSS

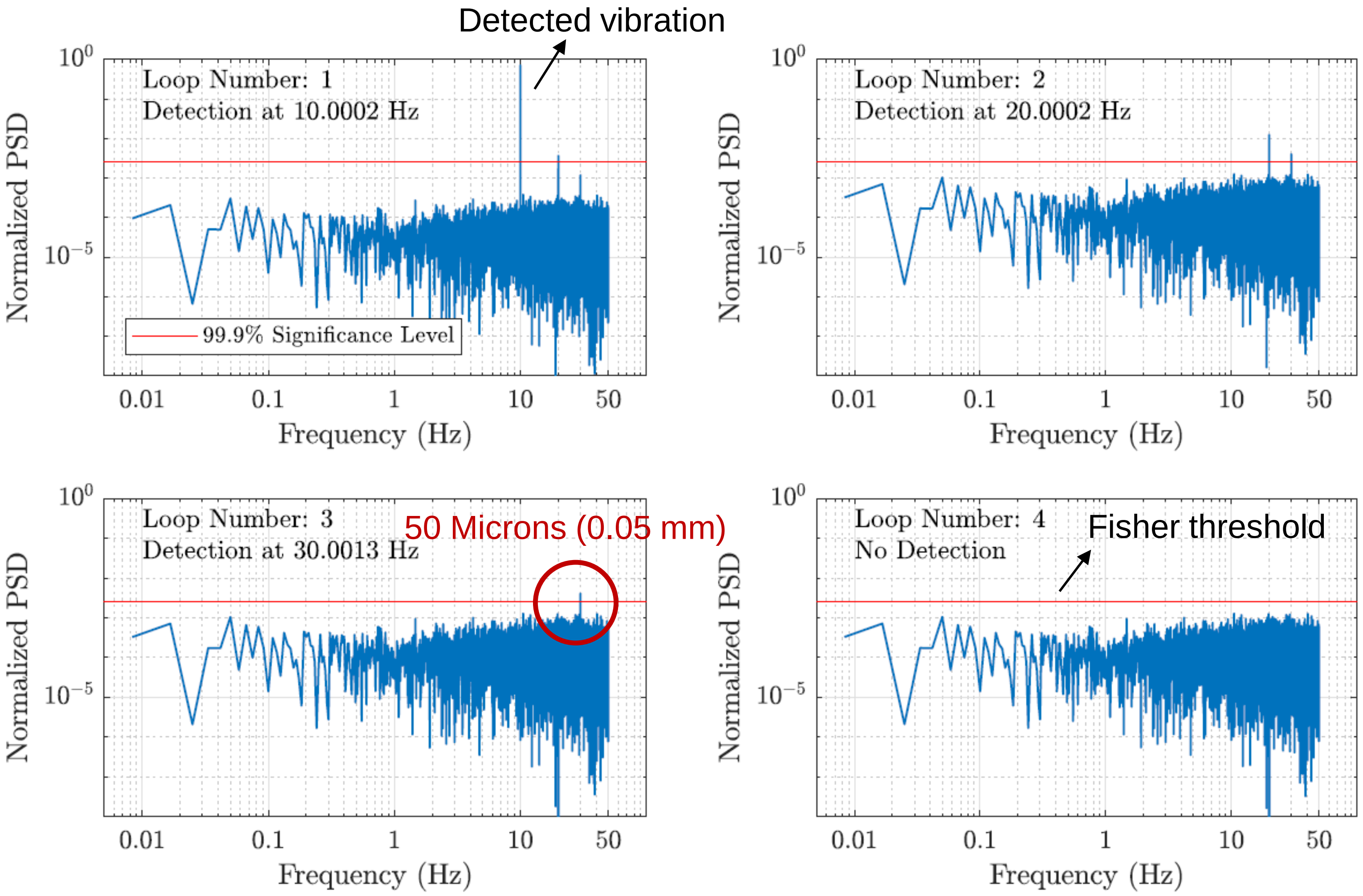
- **Basis: High-rate (100 Hz) displacement time series (short baseline)**



For the detection of the smallest signals, error models have to be calibrated

Figure: Shake table setup, Häberling S., *«Theoretical and practical aspects of high-rate GNSS Geodetic Observations»,* PhD thesis, 2017

Vibration Detection with GNSS



Workflow

1. Error model calibration (ARMA/ARIMA models)
2. Prewhitening
3. Vibration Detection (Fisher Test)
4. Optionally repeat procedure

Hohensinn R. et al, *«Dynamic Displacements from High-rate GNSS: Error Modeling and Vibration Detection», Measurement* (2020)

Conclusions

- GNSS can resolve ground motions down to millimeters in real-time
- Effects of colored GNSS noise should be accounted for
- Dense GNSS networks (spacing of few tens of kilometers, like GEONET in Japan) foster reliable Earthquake Early Warning
- Broadband seismogeodesy (including rotational sensors) further pushes rapid and reliable response to earthquakes