# Six-Degree-of-Freedom (6-DOF) Seismogeodesy by Combining High-Rate GNSS, Accelerometers and Gyroscopes

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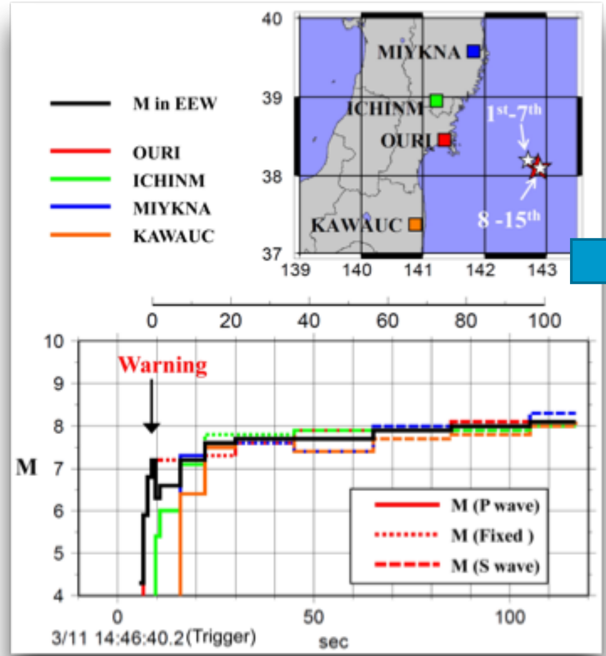
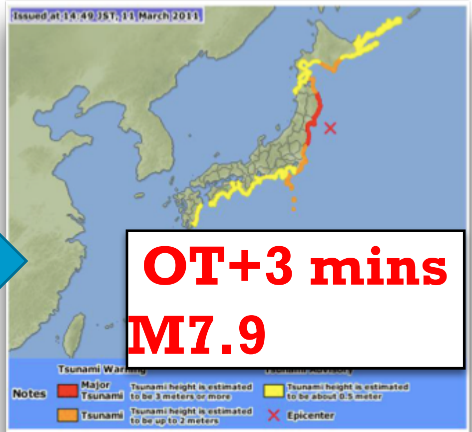
Vienna, Austria

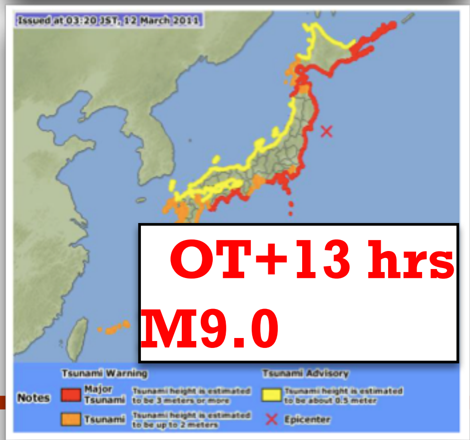
# Prologue: rapid response to 2011 Mw9 Tohoku-oki earthquake

- Rapid accurate determination of mega-earthquake magnitude is far from easy

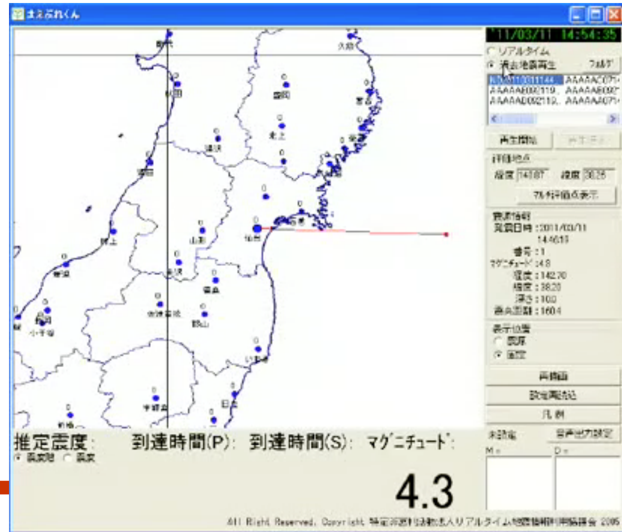



Hoshiba et al. 2011
Ozaki et al. 2011



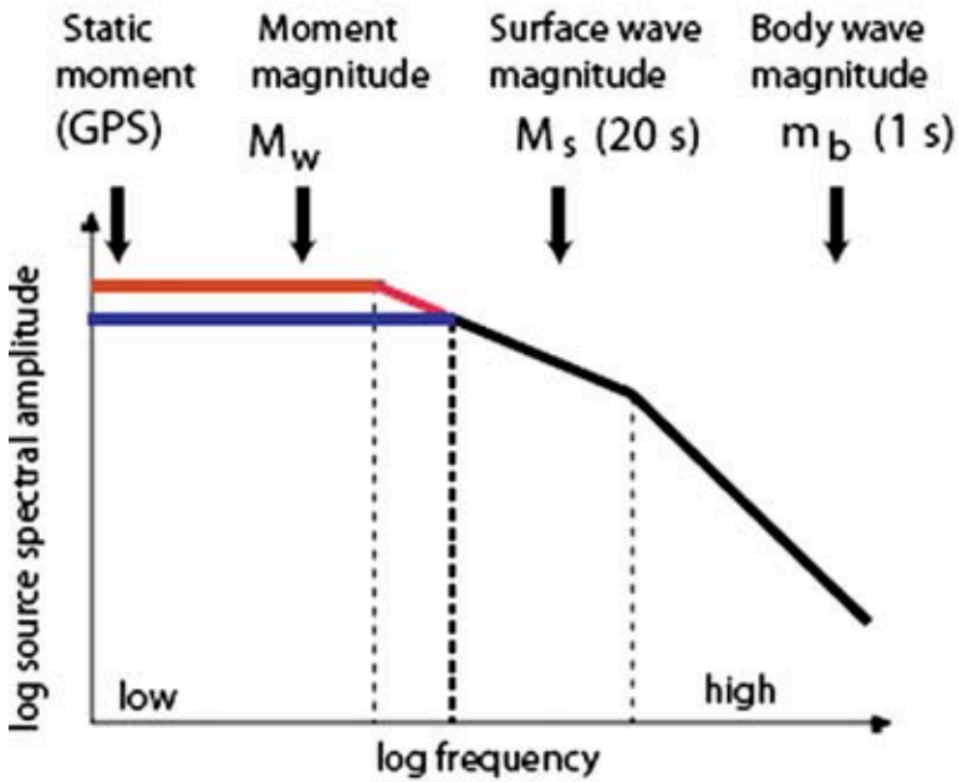







# Motivation: low-frequency seismic signals from large earthquakes

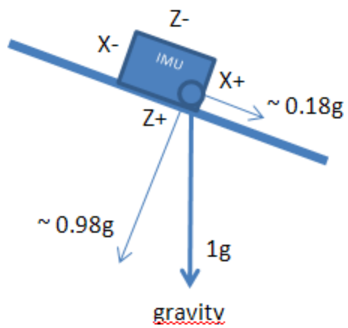
- Near-field seismic observations are keys to inverting for the magnitude and source kinematics of large earthquakes (e.g., M>7)
- Seismic waveforms of large earthquakes are especially dictated by low-frequency signals (e.g., <0.05Hz)
- However, near-source seismometers cannot recover accurately such low-frequency displacements



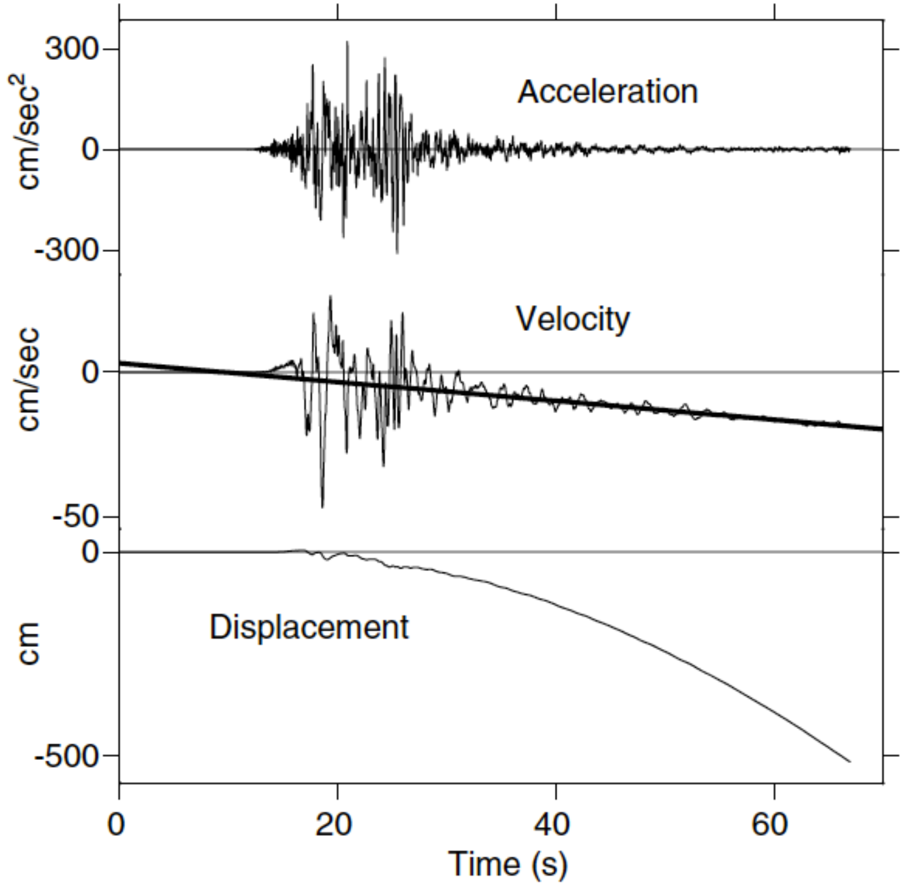

Blewitt et al. 2009

# Strong-motion seismometers: serious drift

- Broadband seismometers clip …
- Accelerometers
  - Doubly-integrated displacements drift drastically


$$\frac{1}{2}at^2$$



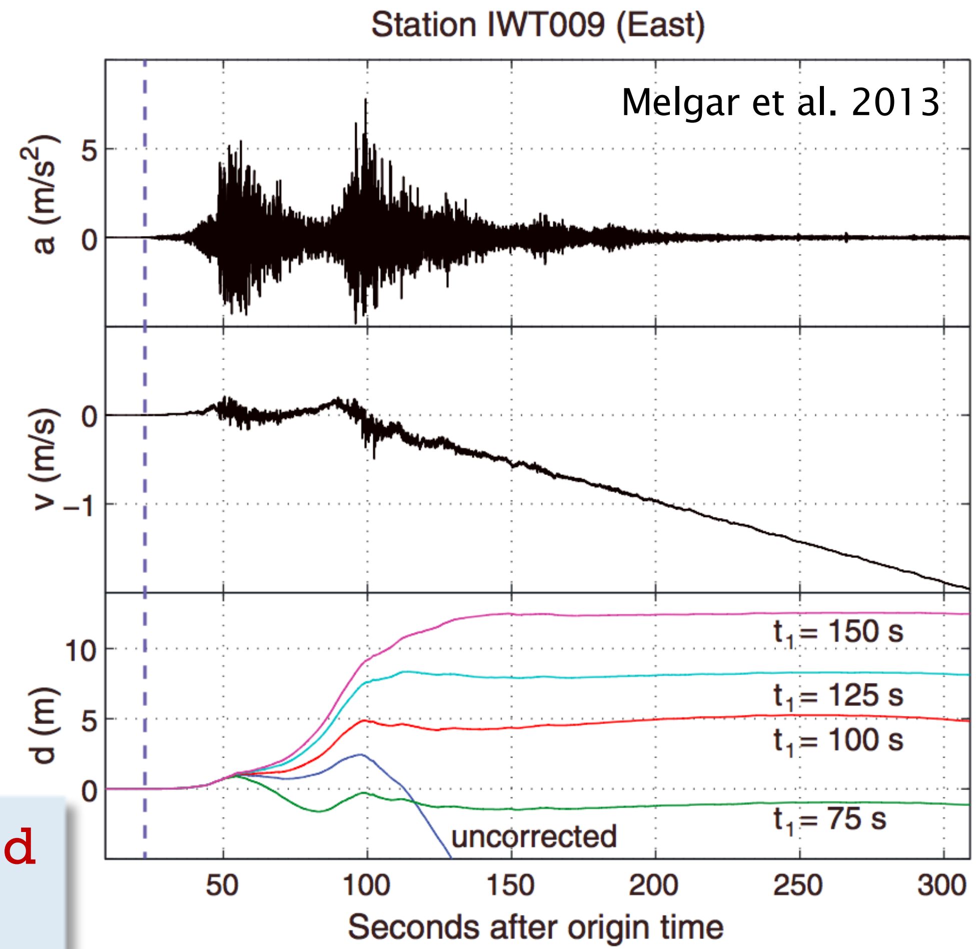
# Strong-motion seismometers: baseline correction?

- Two ambiguities in baseline correction
  - Time of acceleration shift

$$v_f(t) = v_0 + a_f(t); t \in (t_1, t_f).$$

  - Initial time of acceleration baseline

$$a_m = \frac{v_f(t_1)}{t_1 - t_i}$$




**Subjective and unsuitable for complicated situations**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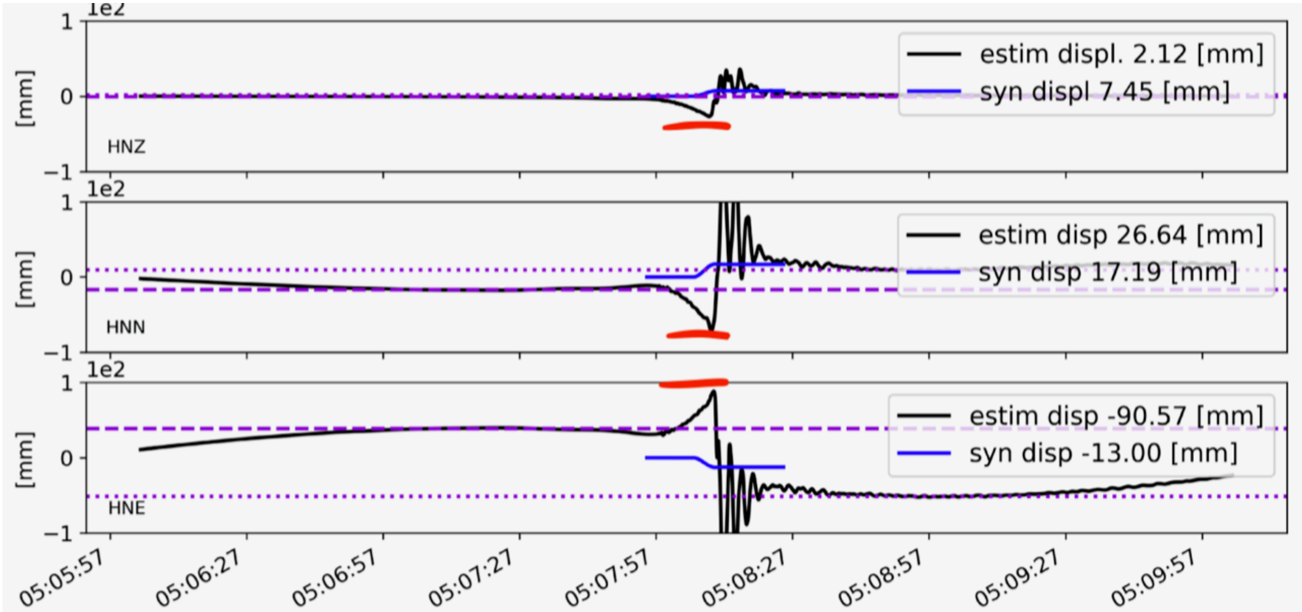
# 6DOF seismometers: will rotational seismometer work?

- Combining accelerometers and gyroscopes to mitigate instrument rotations

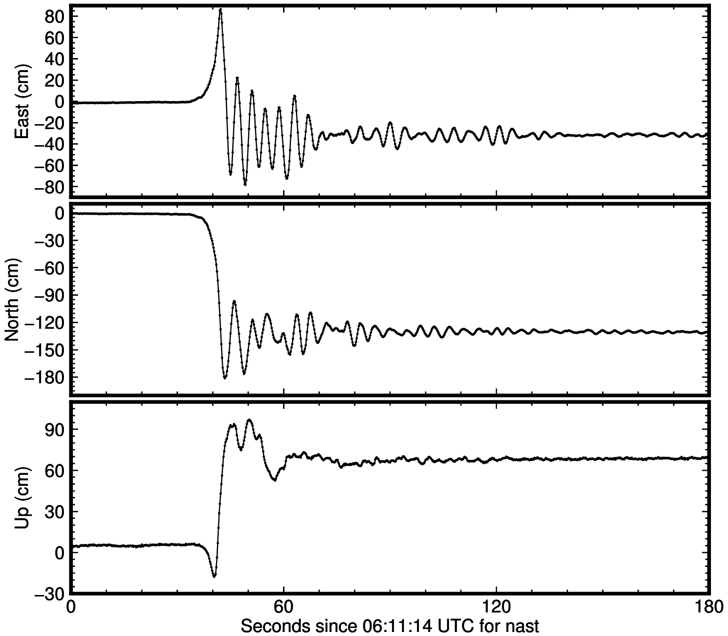

BLACK: displacements by tilt-corrected accelerations

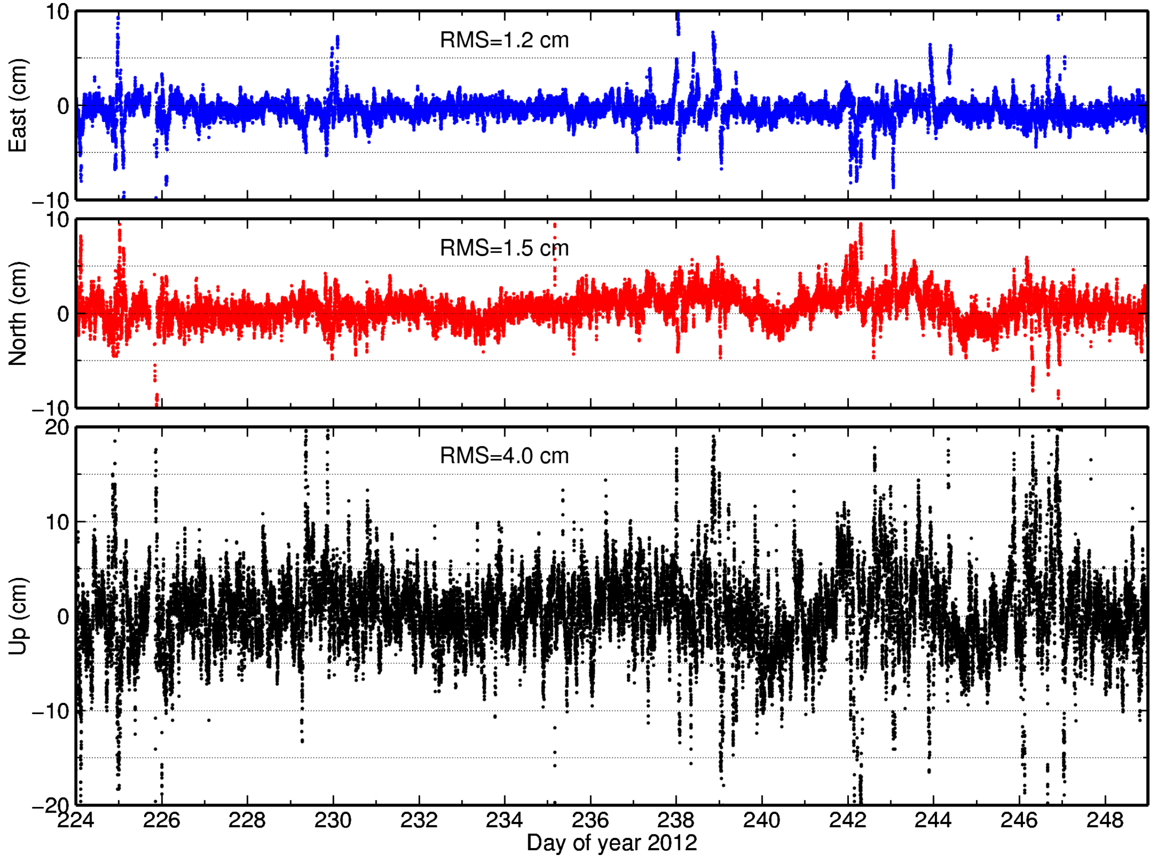
BLUE: displacements by point source synthetics



# High-rate GNSS: noisy displacements

- GPS/BeiDou/GLONASS/Galileo
  - Errors mix with seismic signals
  - Centimeter-level noise





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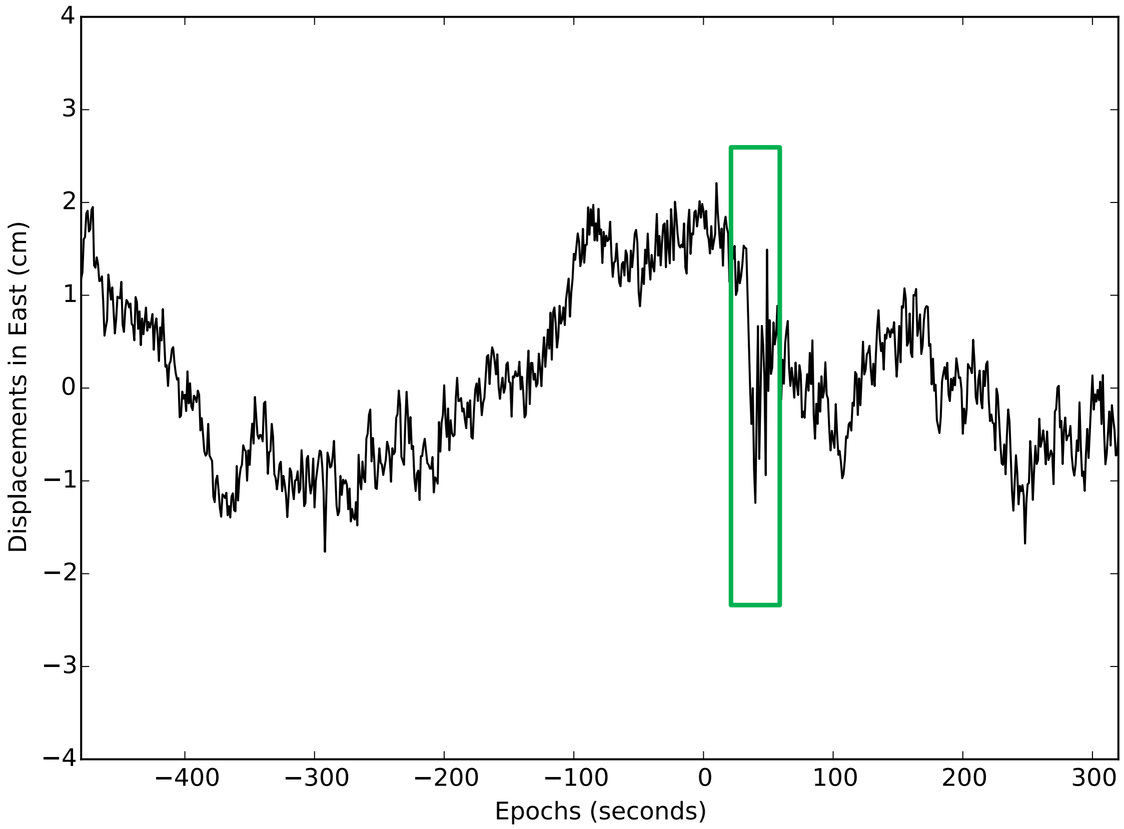
# High-rate GNSS: low-frequency errors dominate

- Orbit, atmosphere, and multipath cause mainly low-frequency errors
  - e.g., <0.05 Hz
- Seismic signals are easily overwhelmed by GNSS errors




**How to enhance GNSS precisions at low-frequency bands?**





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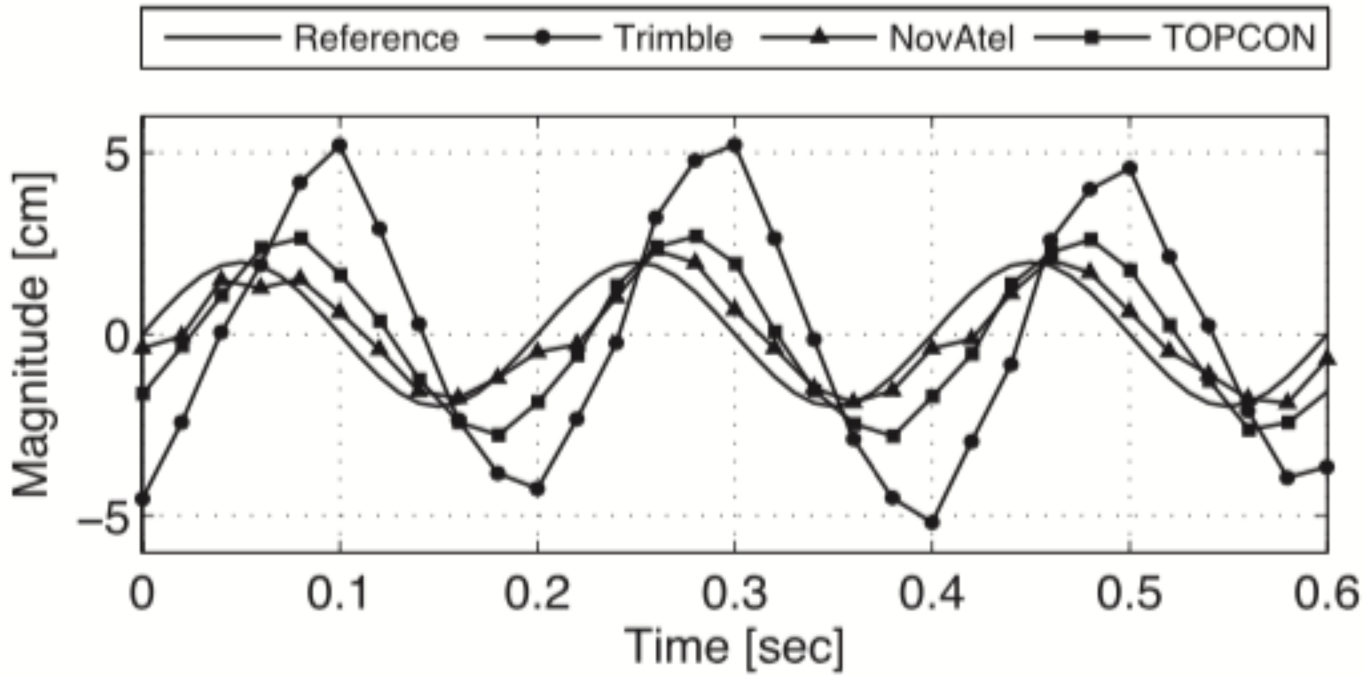
# High-rate GNSS: biased under fierce earthquake strike

- Biased GNSS displacements in case of strong ground motions
  - 125% amplitude error
  - 40ms phase lag

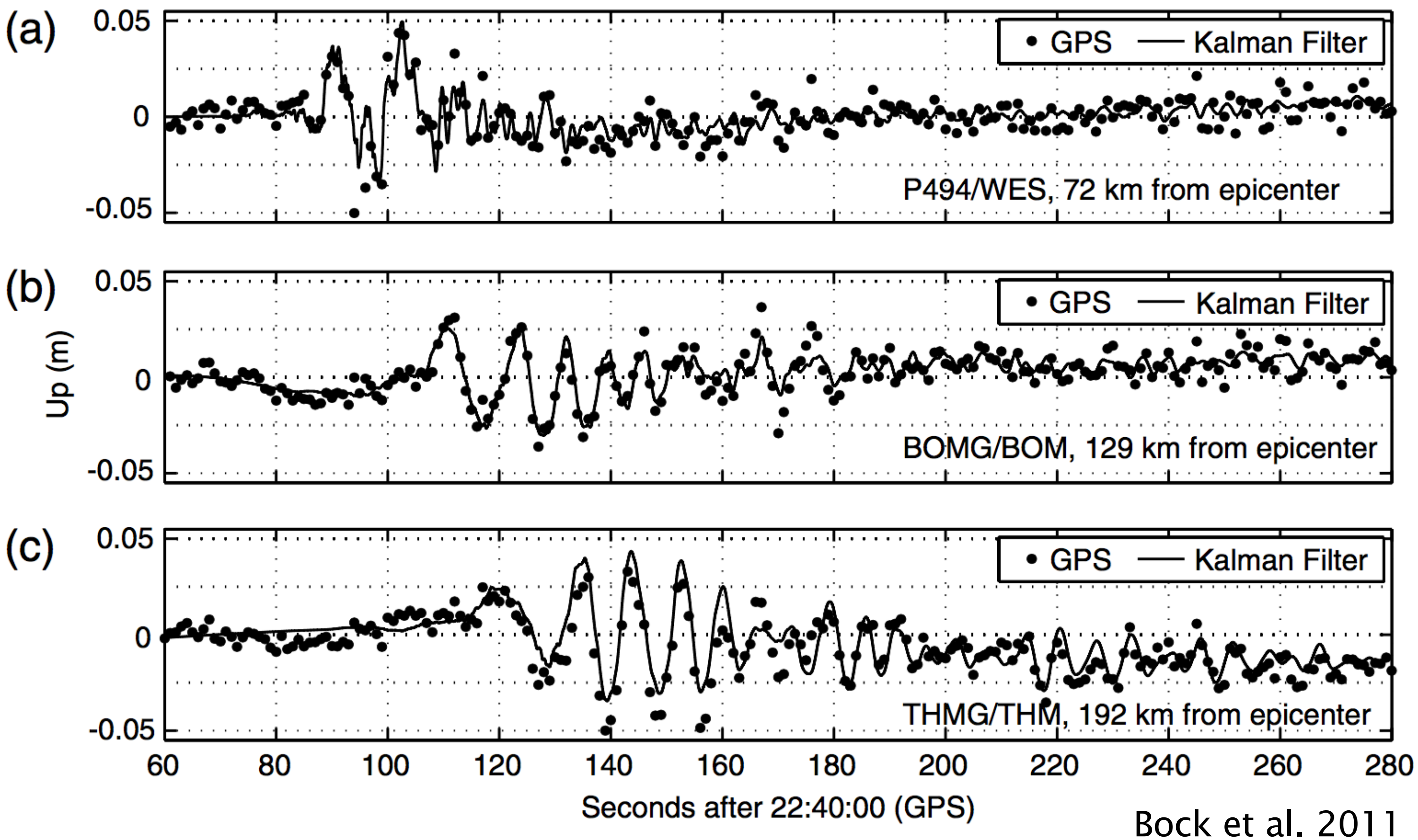



Ebinuma and Kato 2012

# Collocated accelerometer and GNSS

- Exploit the complementariness between accelerometer and high-rate GNSS
- Performance
  - Improve displacement and bandwidth
  - Keep permanent displacements
  - The high-frequency displacements depend on accelerometers while the low-frequency portions are governed by GNSS

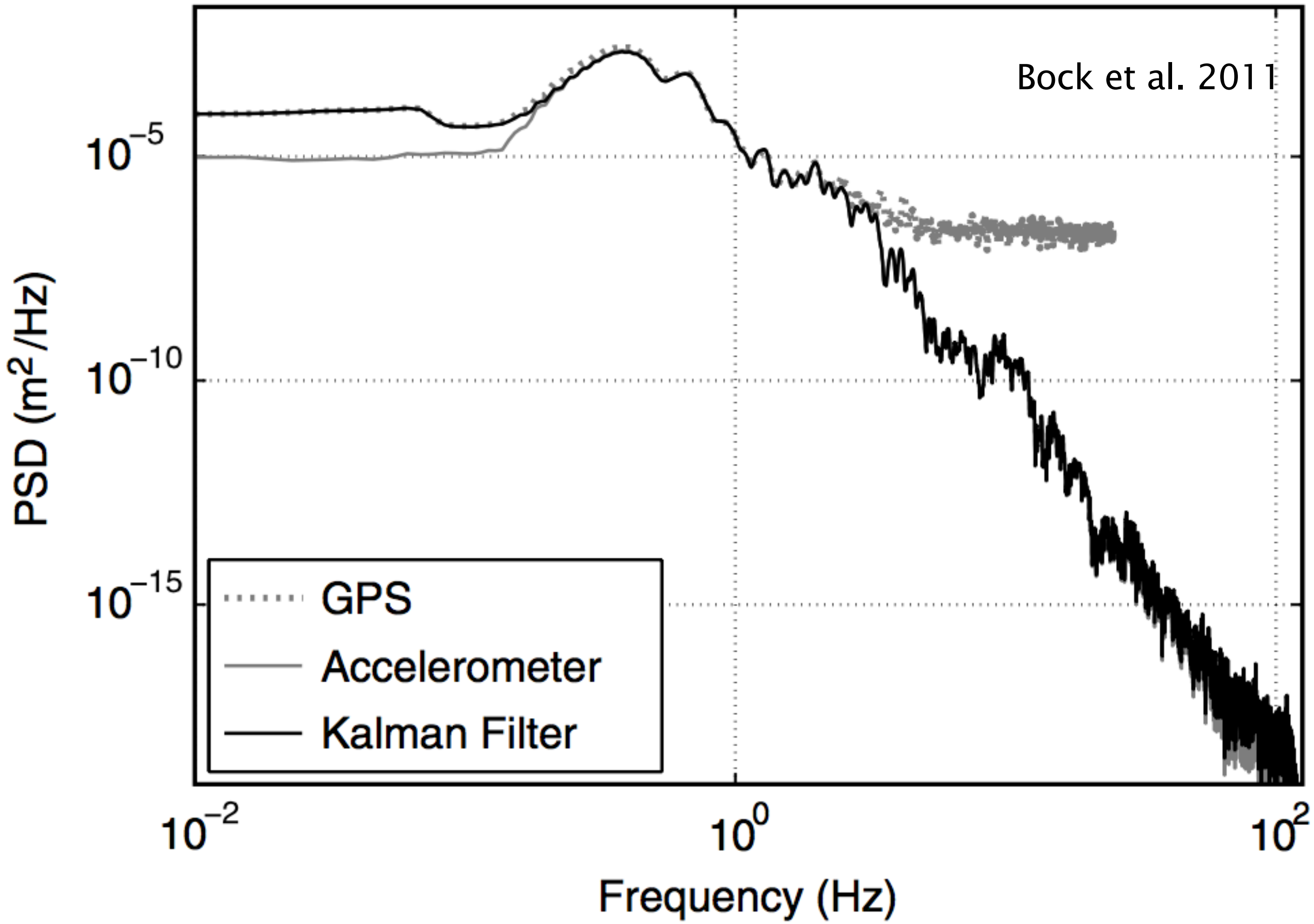
# Demonstration using a shake table




Bock et al. 2011

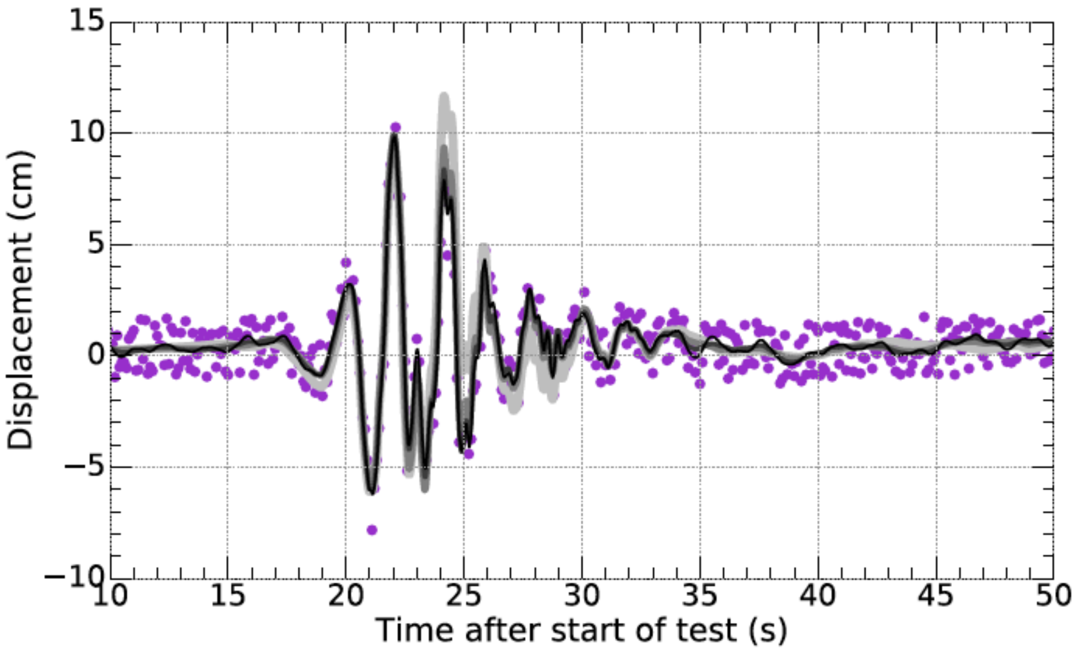
# Demonstration using a shake table

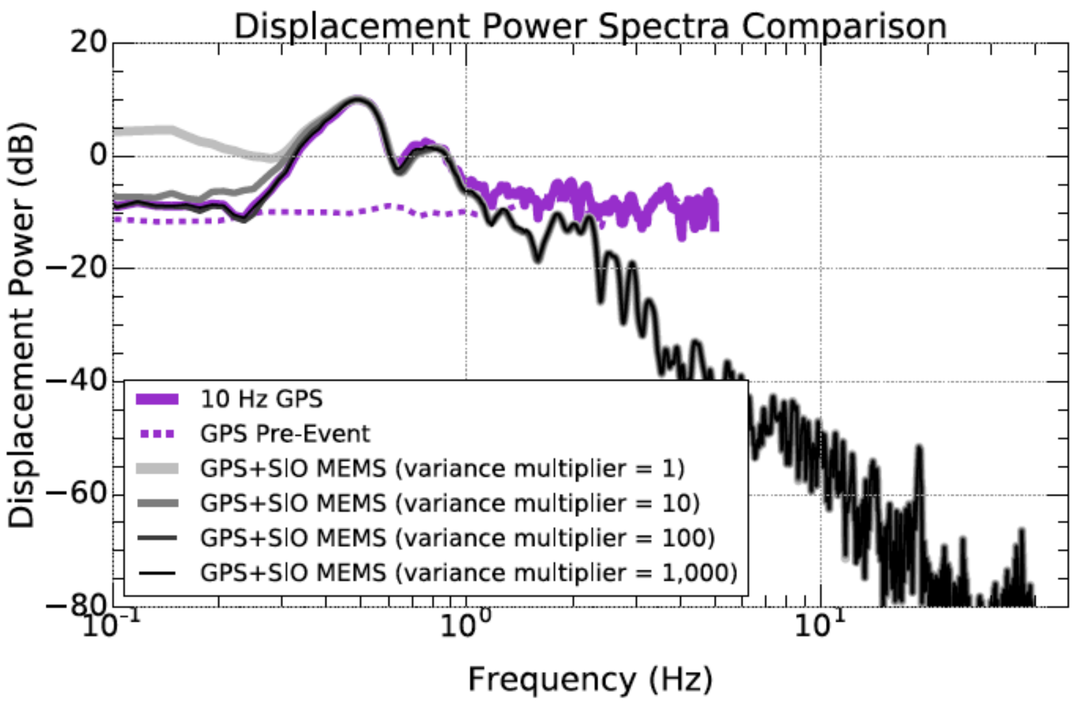
- Frequency domain



# Collocated accelerometer and GNSS: data fusion weighting

- In general, accelerometer data are downweighted by 100+ times in the data fusion

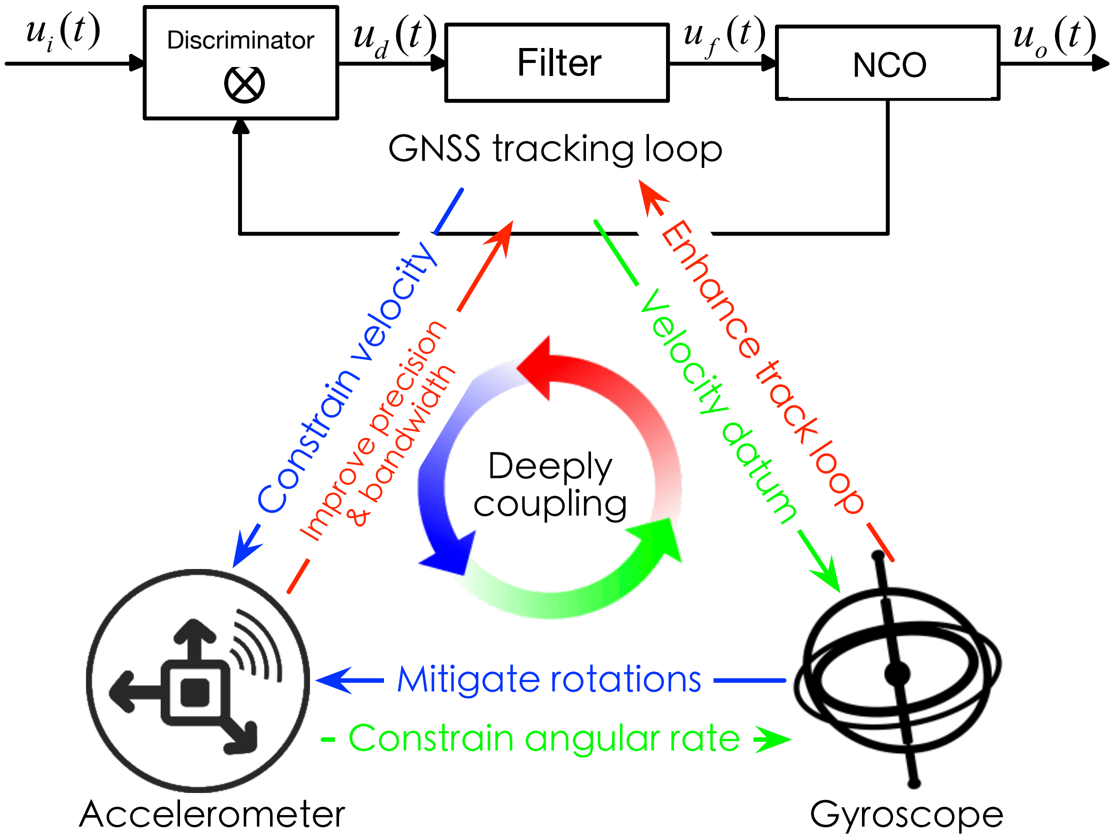



Accelerometer contribution to low-freq. displacements is not exploited

# 6-DOF seismogeodesy

- Deeply integrating high-rate GNSS, accelerometers and gyroscopes
  - Rotational seismometer can calibrate baseline errors of accelerometers
  - Introduce Euler angle to model instrument rotations
  - GNSS provide displacements to constrain inertial sensors



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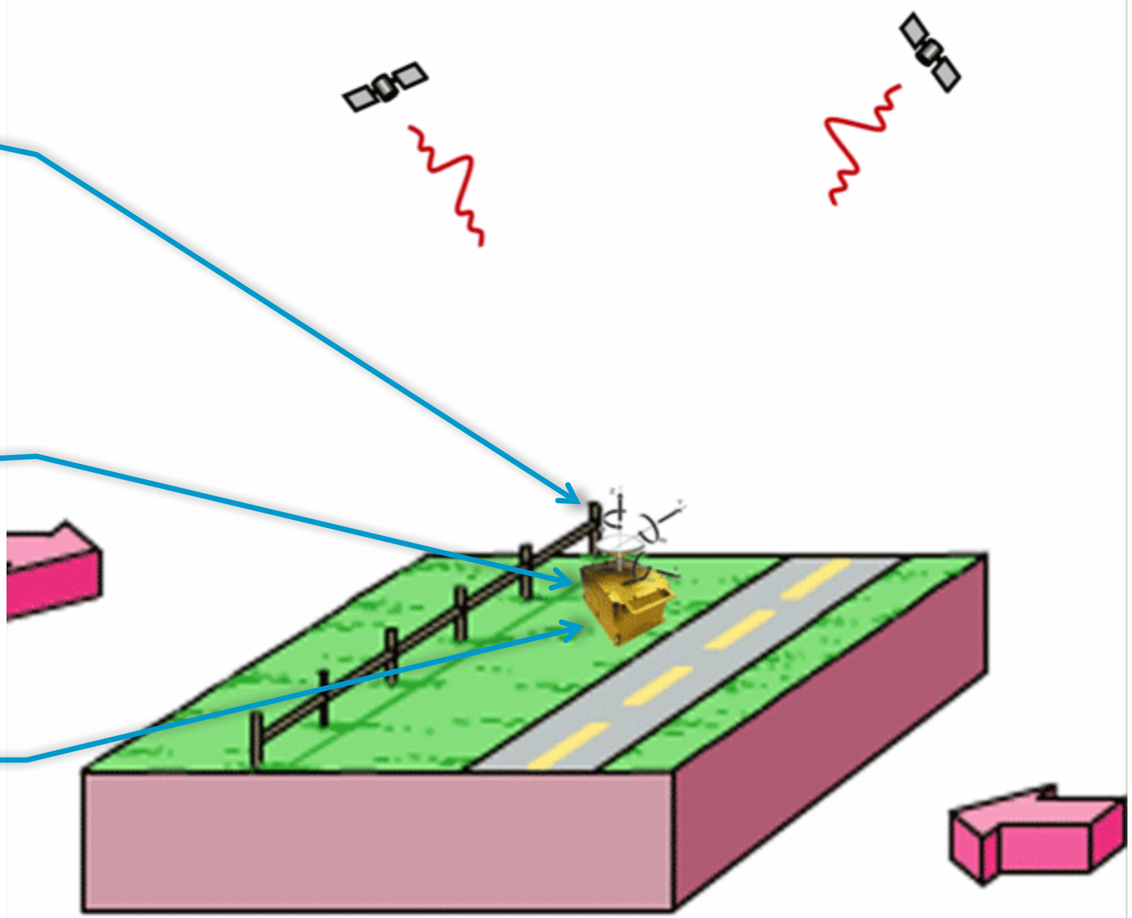
# 6-DOF GNSS seismometer for strong motions

Resilient to strong motion (2g) to be close to faults

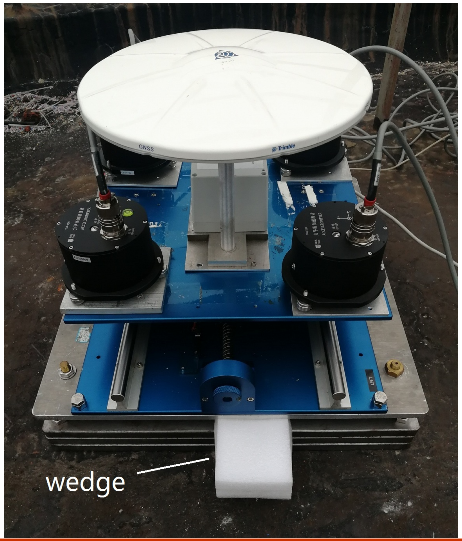
GNSS phase error smaller than 2 mm in case of 2g acc.

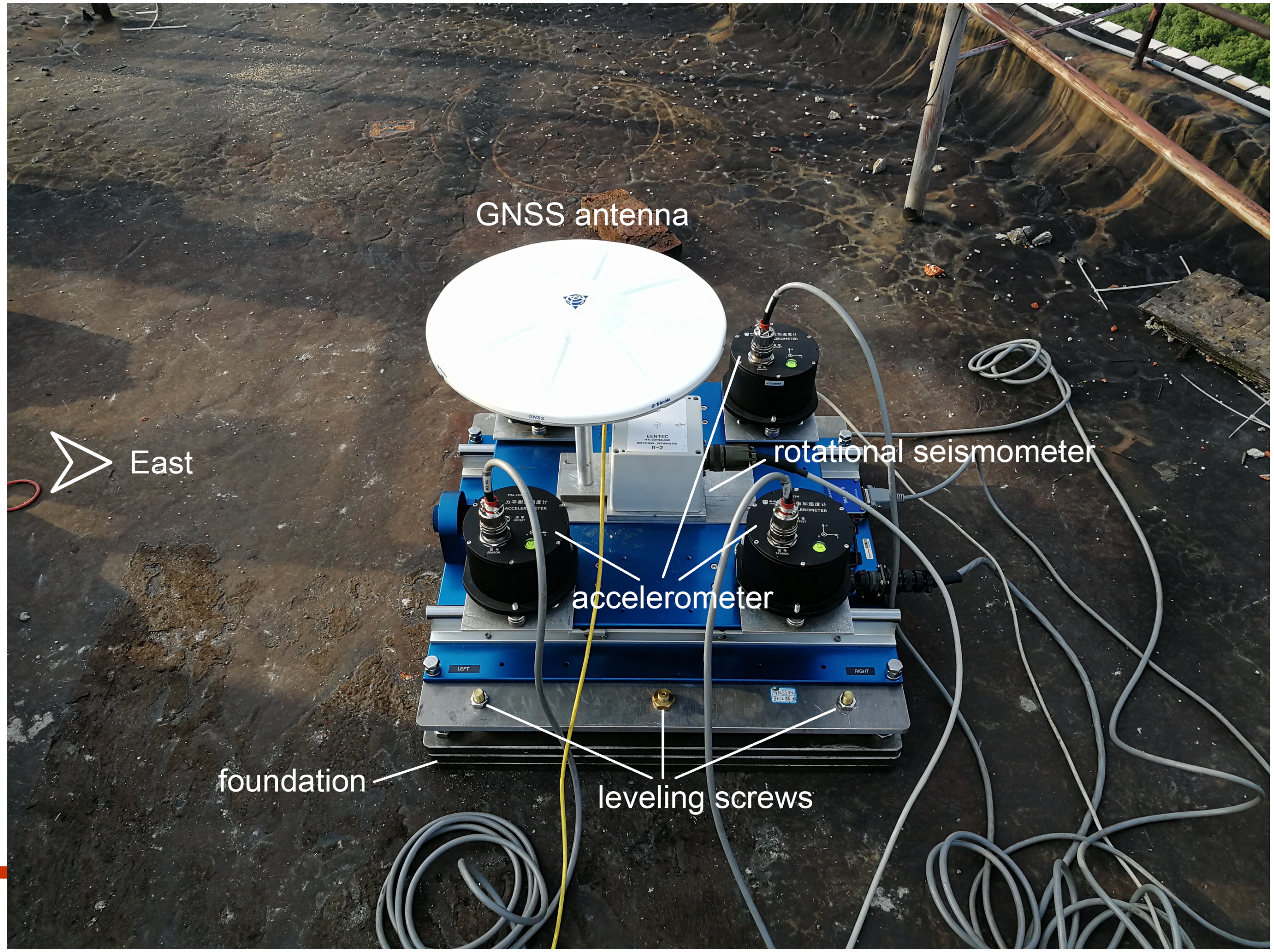
Broadband (0-50Hz), mm displacements and mrad rotations



# Experimental verification

- Shake table test
  - Four accelerometers
  - An R2 gyroscope
  - A GNSS receiver and antenna
  - A wedge to create tilt



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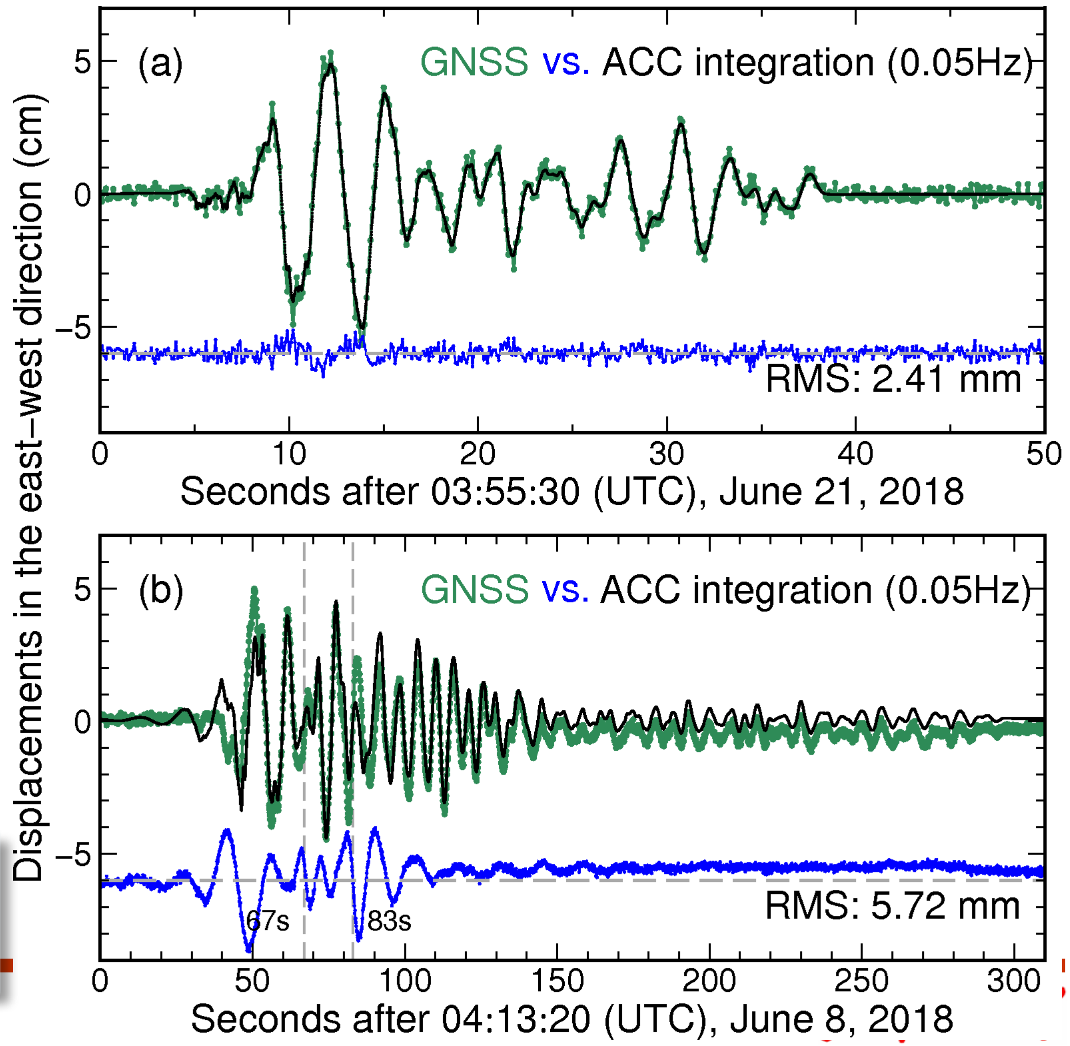
# Acceleration integration to recover coseismic displacements

- April 4, 2010, El Mayor Mw 7.2 event, displacements in N-S direction
  - a) without tilting the table
  - b) tilting the table
- Fourth-order Chebyshev filter with a cut-off frequency 0.05 Hz
- An ultra-short baseline GNSS solution as benchmark (mm precision)

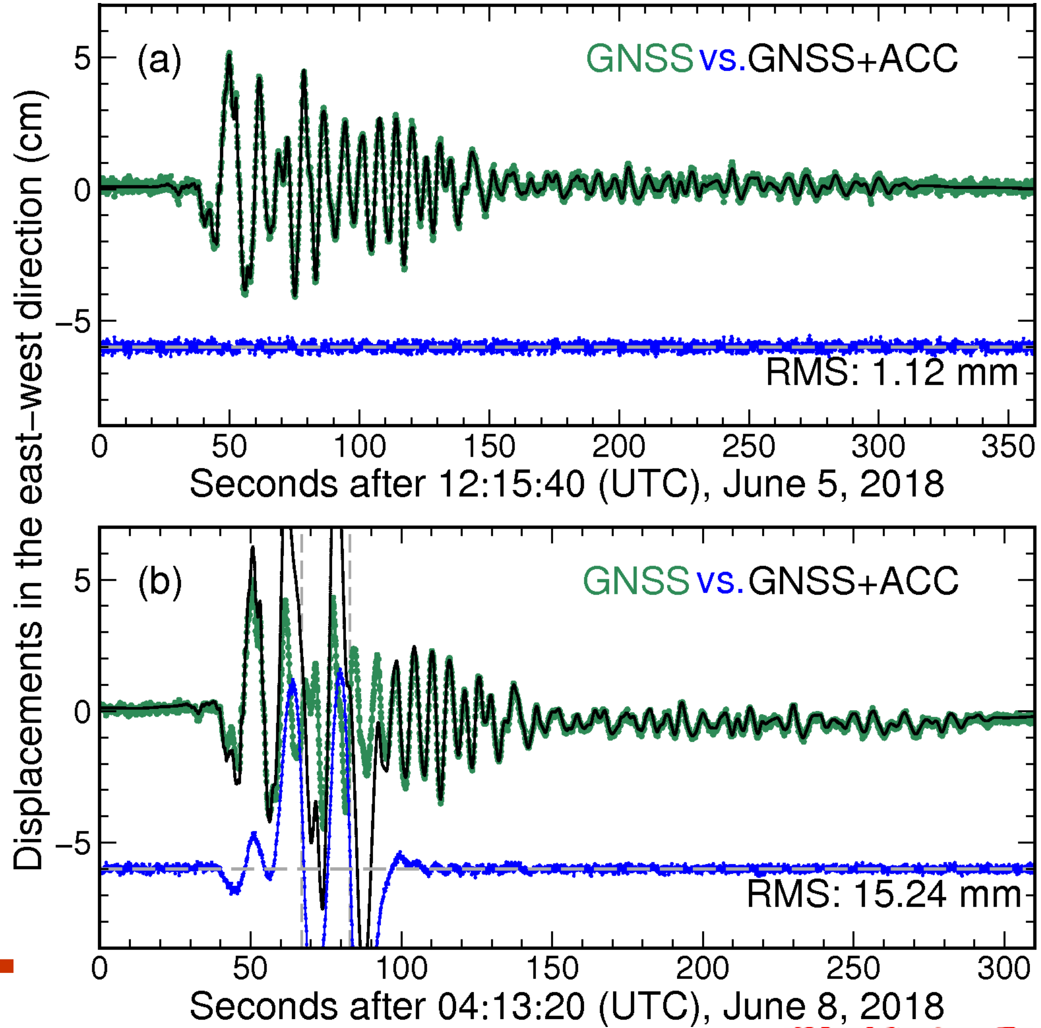
Acceleration integration is invalidated by rotation errors



# Combine collocated accelerometer and high-rate GNSS

- April 4, 2010, El Mayor Mw 7.2 event, displacements in N-S direction
  - a) without tilting the table
  - b) tilting the table
- Accelerometer data were weighted according to their formal precision

**Instruments tilts damage the integration of accelerometer and GNSS data**



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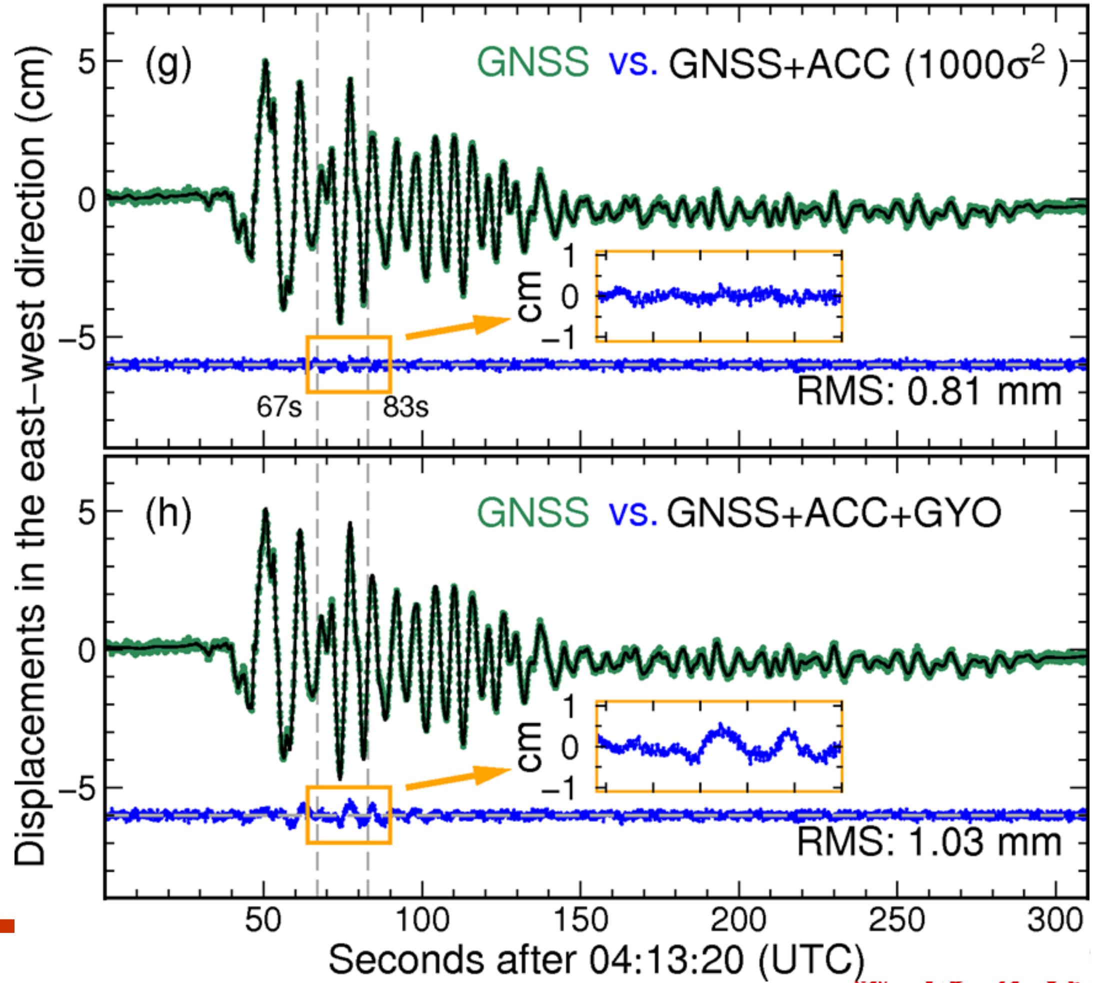
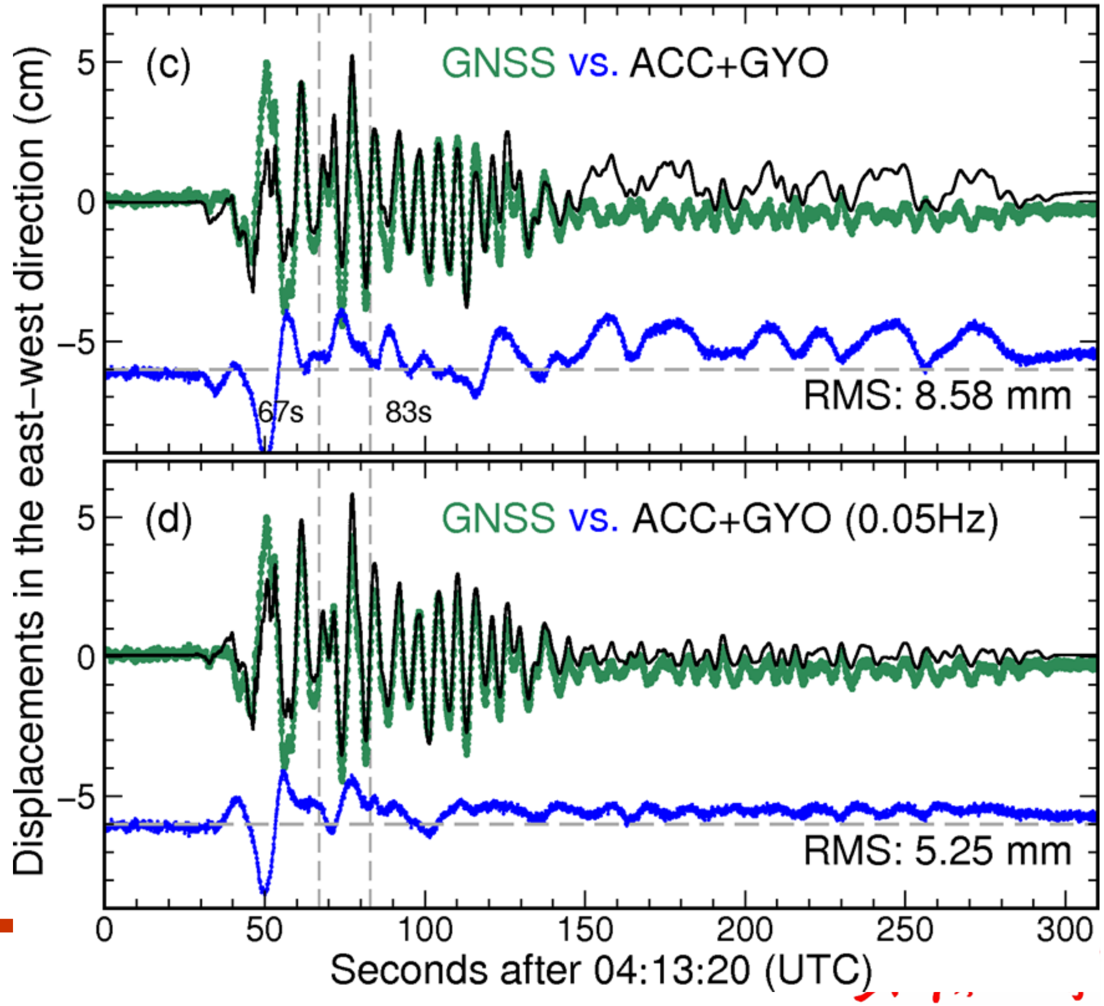
# Introducing rotational data into this combination

- Permanent tilts experiment
  - Two permanent tilt events at 67s and 83s
  - 4 mm permanent displacement
- 6-DOF seismogeodesy does not require downweighting the accelerometer data, but achieve a good consistency with the GNSS benchmark



# Classic 6-DOF seismometers: Accelerometer+Gyroscope

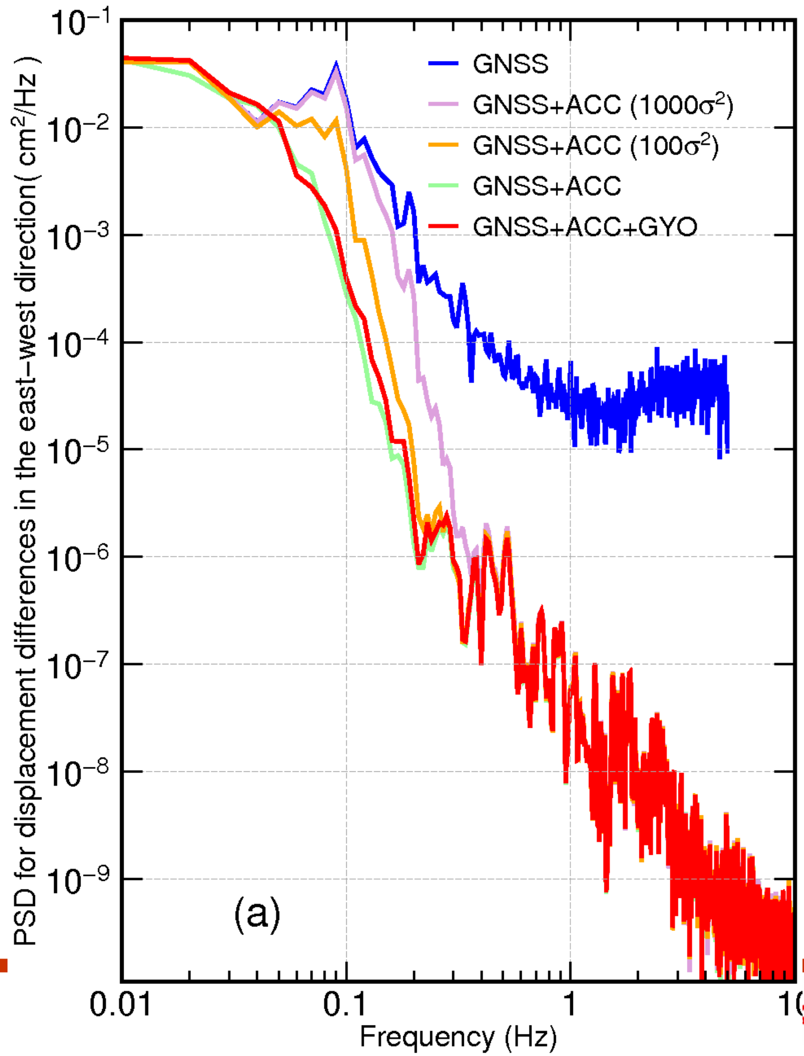
- Still drift, albeit on short periods
  - Gyroscope is an inertial sensor as well and has accumulative errors of course
- We can hardly trust the acc+gyro recovered displacements



# Accelerometer data contribution to low-frequency displacements

- PSD of different solutions
  - The green curve is the benchmark PSD
- Downweighting accelerometer data will underestimate their value in recovering low-frequency displacements

**Accelerometer contribution to low-frequency displacements is recognized in 6-DOF seismogeodesy**



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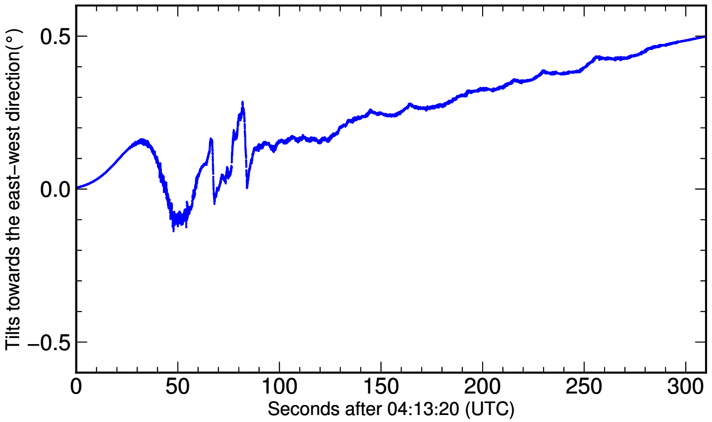
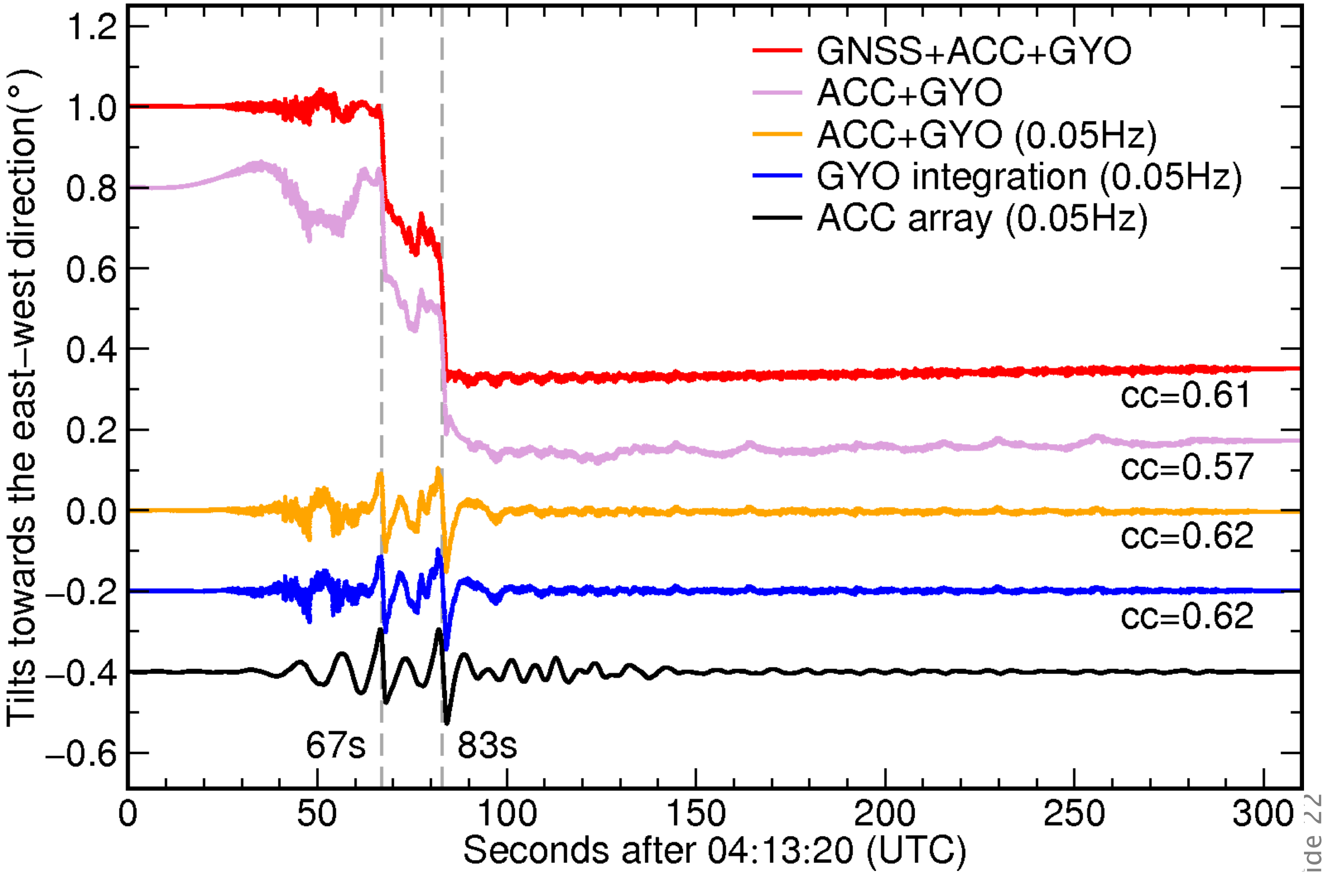
# Coseismic rotations from 6-DOF seismogeodesy

- 6-DOF seismogeodesy recovers permanent tilts
  - No drift errors
  - High correlation with accelerometer-array results





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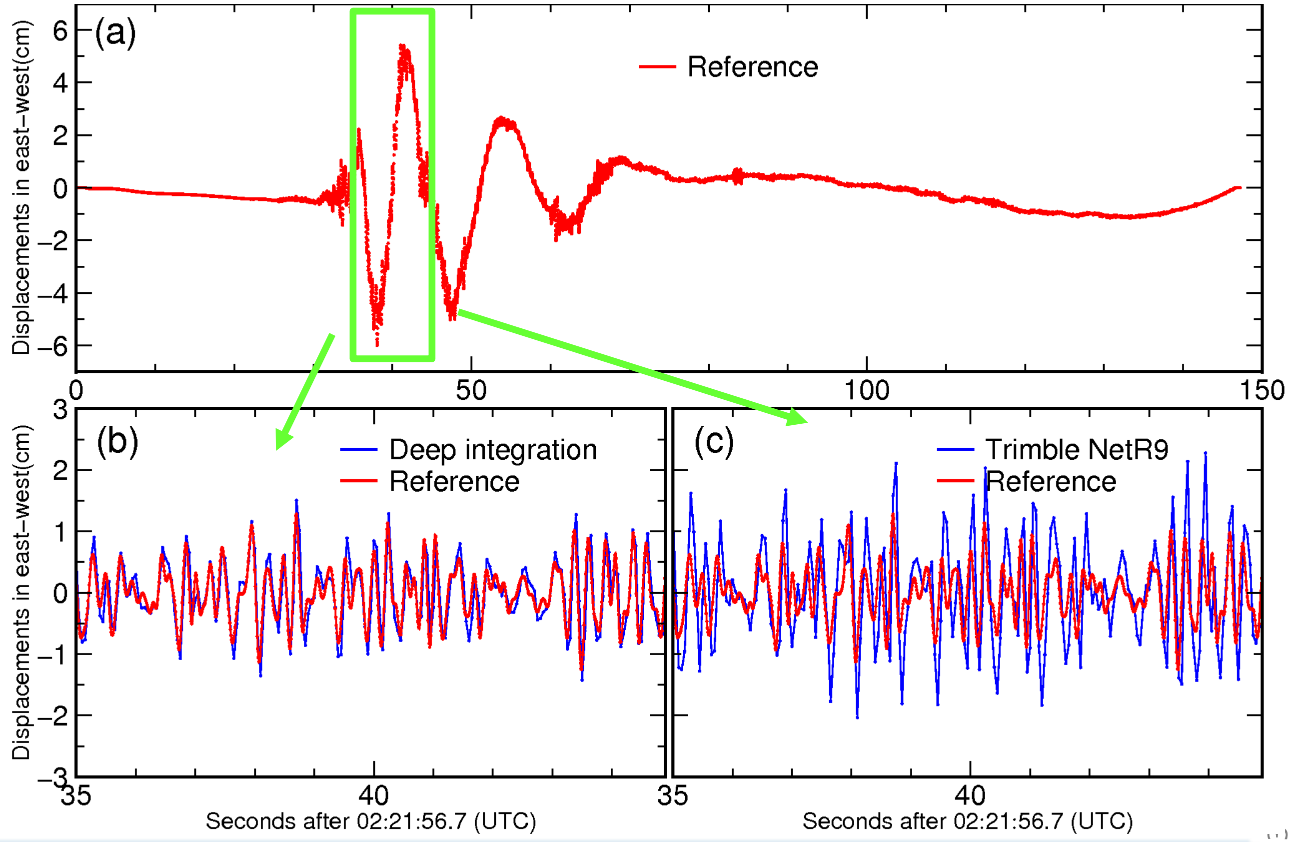
# Suppress high-dynamic errors in case of fierce motions

- Wenchuan Mw8.0 earthquake waveforms
  - a) RED: simulated benchmark waveforms
  - b) 35~45s waveform after 1 Hz high-pass filtering for 6DOF GNSS receiver
  - c) 35~45s waveform after 1 Hz high-pass filtering for Trimble NetR9 receiver




**Deep integration suppresses strong-motion errors of GNSS tracking loops**



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# Conclusions and outlook

- 6-DOF seismogeodesy
  - Integrate high-rate GNSS, accelerometer and gyroscope to achieve accurate broadband translational and rotational motions
  - Displacements and rotations are derived without any high-pass filtering or baseline correction schemes
  - Accelerometer data contribution to low-frequency displacements is recognized
- Direct inertial data into the tracking loop of GNSS receiver will enhance its resilience to strong motions up to 2g or more
- The collocation or integration of geodetic and seismic sensors is advantageous and should be encouraged and required

CENTER NSS 武汉大学卫星导航定位技术研究中心
国家卫星定位系统工程技术研究中心

# Thank you!

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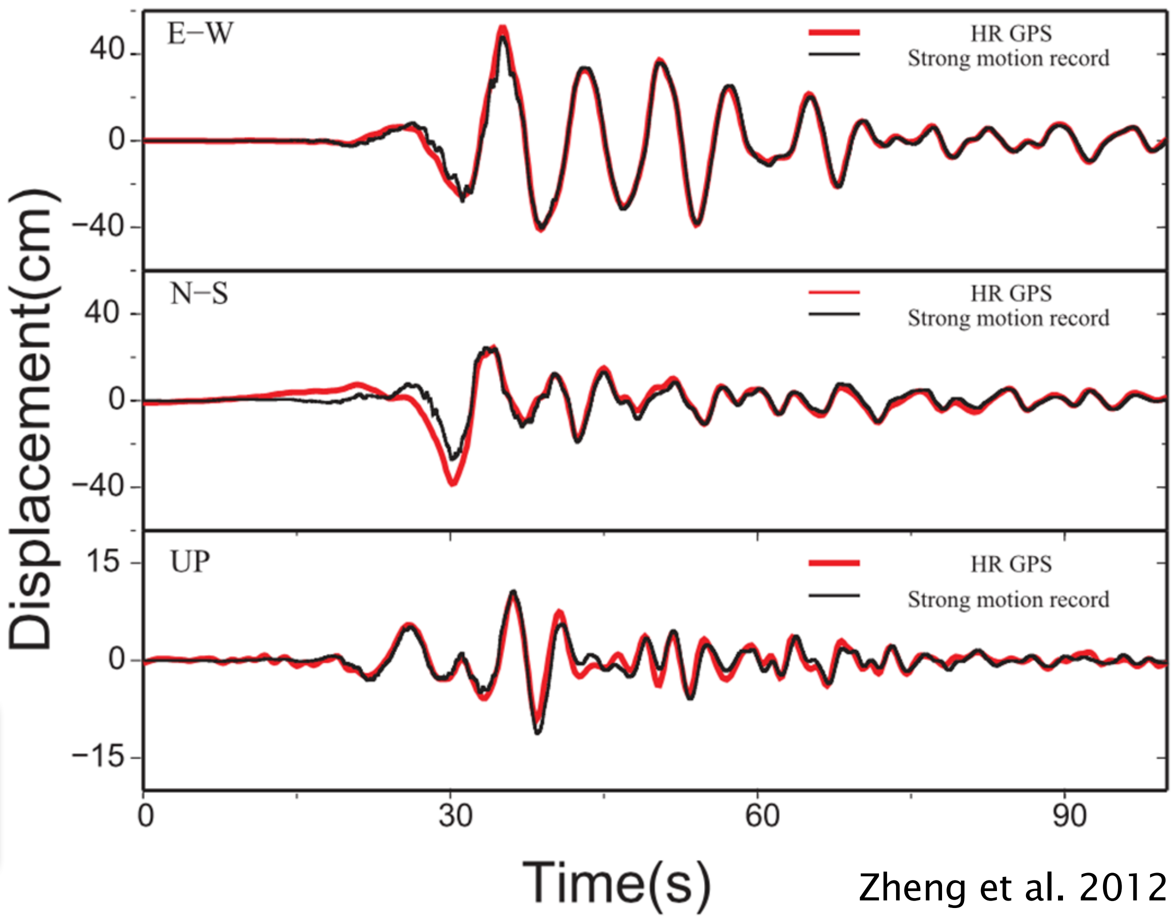
Two papers: 10.1029/2020GL087161, 10.1029/2018GL081398

# Strong-motion seismometers: high-pass filtering?

- In contrast, high-pass filtering
  - Signals below the cut-off frequency are lost definitely
  - Can signals above the cut-off frequency be recovered accurately?

**High-pass filters may cause signal distortions**



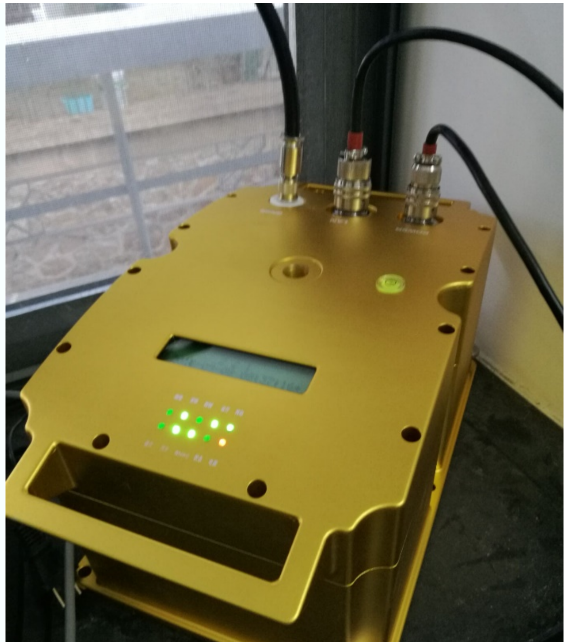

Zheng et al. 2012

# Combine collocated accelerometer with high-rate GNSS

- Industrial and scientific instruments


Geodetic module of UCSD


SG-160 of Trimble



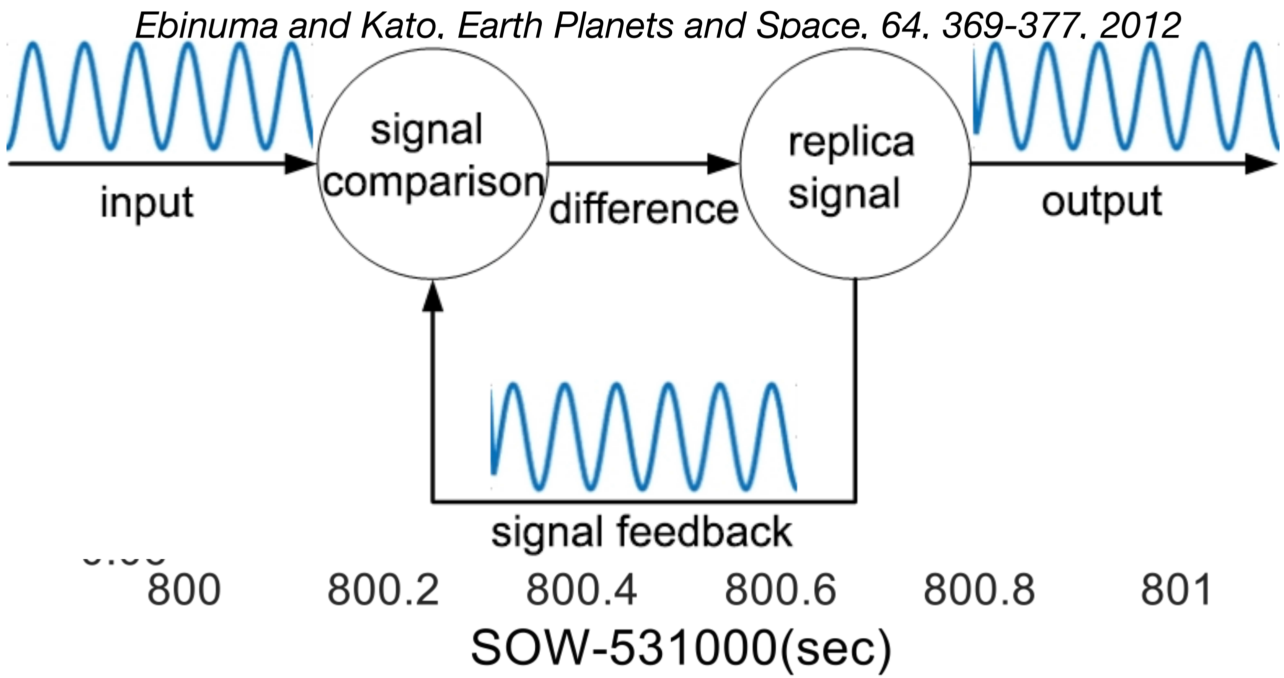
Integrated seismograph of WHU/HBEA

# Instrumental specification

| Item | TDA-33M | eentec R2 |
|---|---|---|
| Full scale | ±2g | ±0.4 rad/s |
| Noise | $< 1 \times 10^{-6}$g | $0.6 \times 10^{-7}$rad/s @ 1 Hz |
| Dynamic range | ≥145 dB | ≥117 dB |
| Frequency range | DC–80 Hz | 0.033–50 Hz |
| Sensitivity | ±2.5 v/g | 5.0 v/rad/s |
| Linearity | ≤0.1% | 3 dB |
| Translational sensitivity | <1% | None |
| Operating temperature | -40°C~65°C | -15°C~55°C |
| Zero drift | $<3\times10^{-4}$g/°C | None |
| Power supply | 9~18 VDC | 9~18 VDC |
| Dimensions | Diameter=12 cm, height=8 cm | 15.8 cm×15.8 cm×10.0 cm |
| Weight | 1.8 kg | 1.5 kg |

# High-rate GNSS: strong motion distortions

- GNSS tracking loop
  bandwidth: ~20 Hz
  - Missing high-frequency signals
- GNSS tracking loop suffer
  from strong dynamic stress
  from strong motions
  - Amplitude distortions
  - Phase delay error




**Do we trust high-rate GNSS to record strong motions?**