Rapid Determination of Earthquake Magnitude using GPS for Tsunami Warning Systems

**Geoffrey Blewitt, Corné Kreemer,
Bill Hammond, and Hans-Peter Plag**

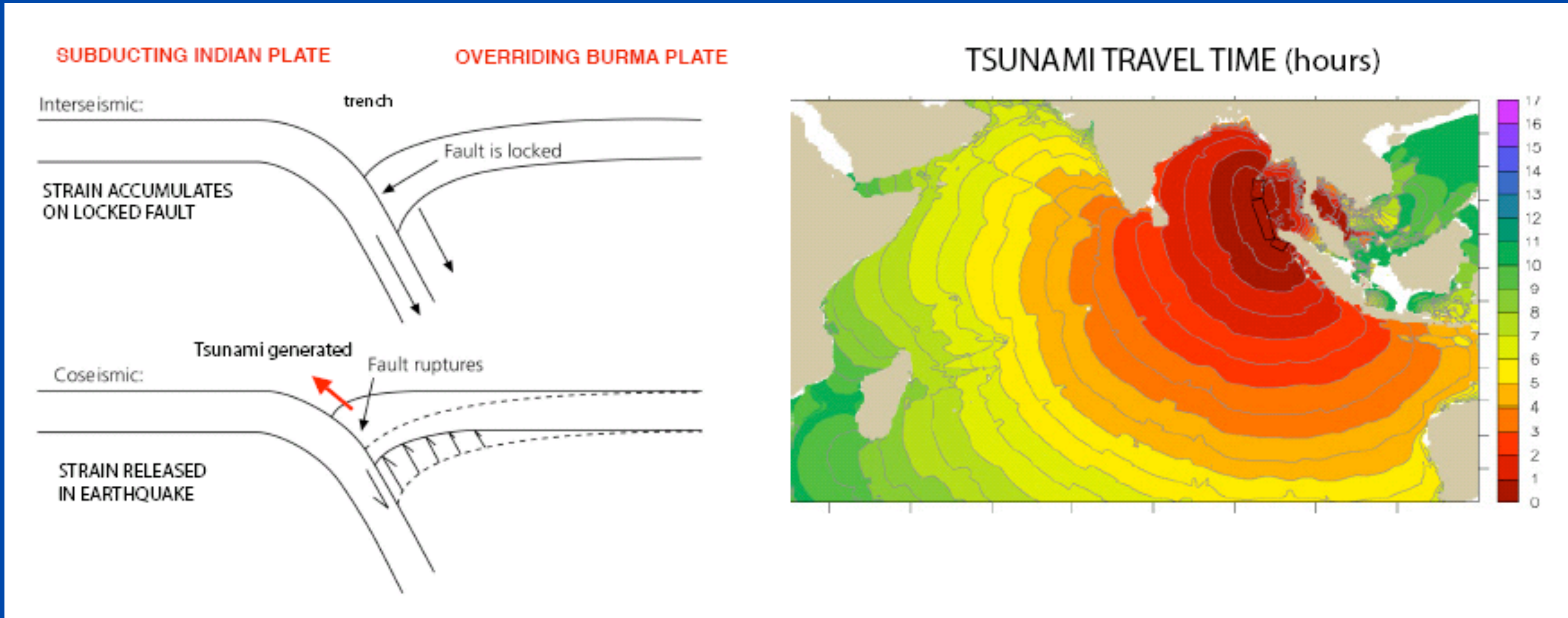
Nevada Geodetic Laboratory

Nevada Bureau of Mines and Geology, and Seismological Laboratory,
University of Nevada, Reno, NV 89557, USA
email: gblewitt@unr.edu

Seth Stein and Emile Okal

Department of Geological Sciences, Northwestern University,
Evanston, IL 60208, USA

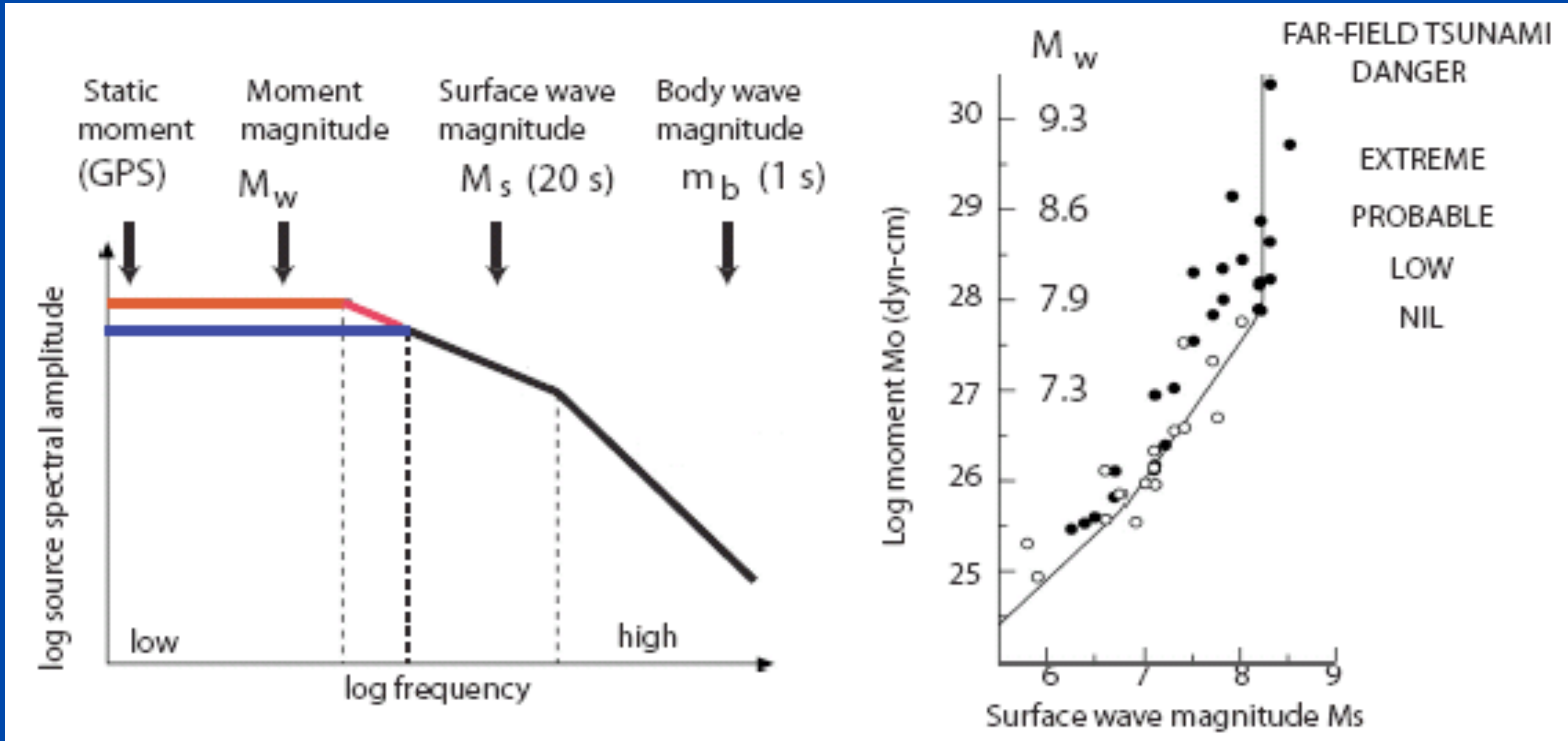
Oceanwide Tsunami Warning: The Challenge



- First hour is important for early warning of oceanwide tsunamis
- Tsunamigenic potential directly relates to seismic moment

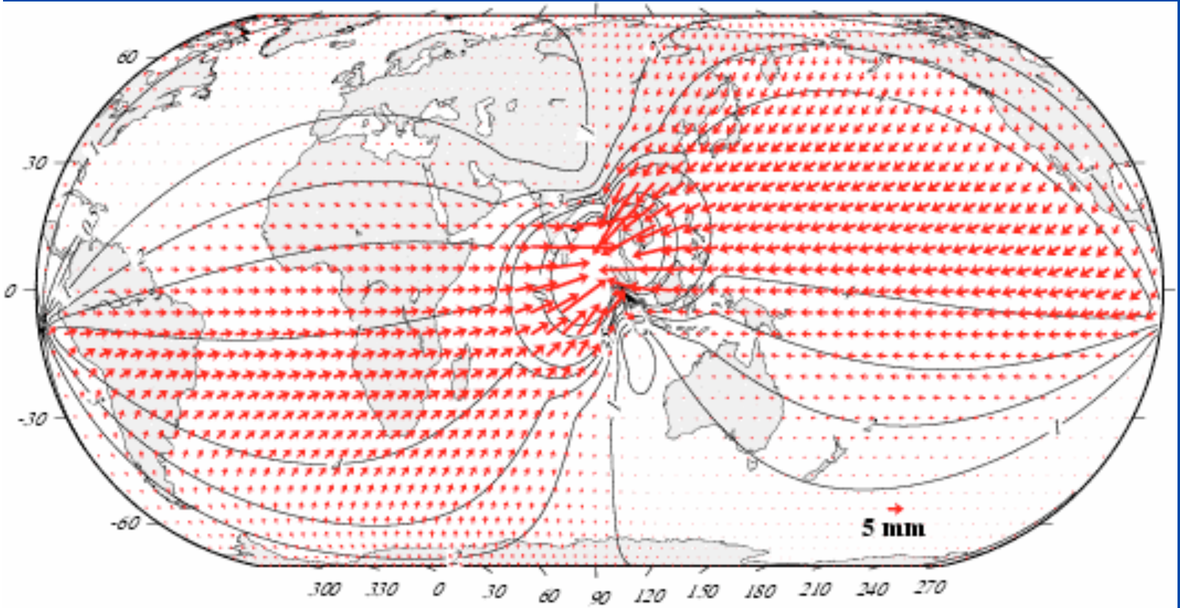
  ~ (fault slip) x (rupture length) x (rupture width)
- Underestimation of seismic moment for great earthquakes compromises early warning (Kerr, 2005; Menke and Levin, 2005)

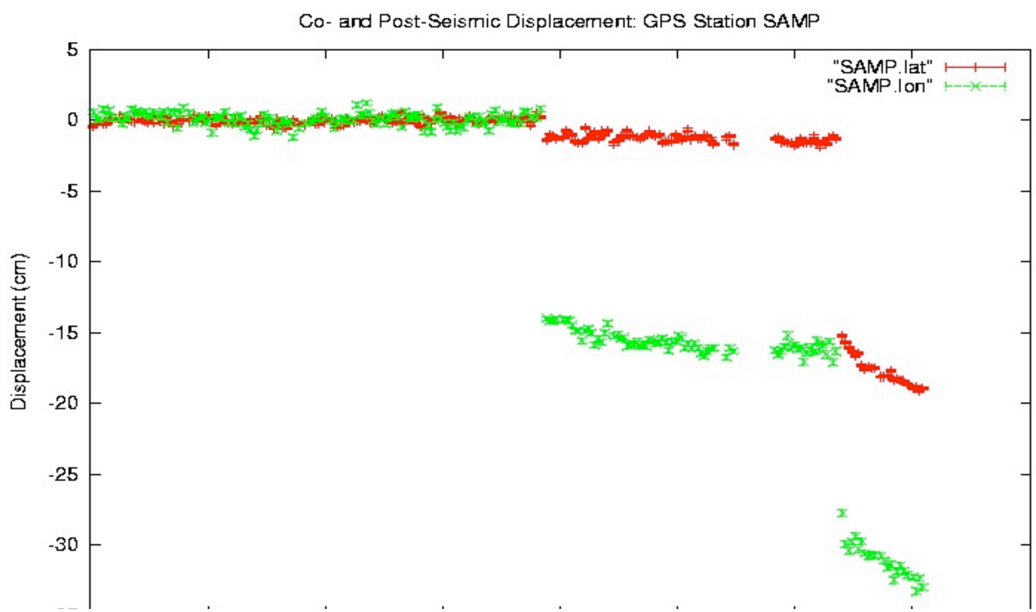
Seismic Magnitude Saturation: A Major Obstacle to Early Warnings



- Early seismic magnitudes saturate at 8–8.3 (Geller, 1976)
  - but oceanwide tsunamis typically require $M_w > 8.5$
- Can the static moment be estimated early using GPS?

2004 Sumatra Earthquake Static Displacements





- Post-event estimation of displacement field
  - – global deformation!
  - > 10 mm as far as India
- Provides ground truth
  - – compare displacements with rapid estimates
  - – 1-mm precision
  - – constrains magnitude and slip distribution
- Provides lessons
  - – use far-field to stablize the reference frame and prevent saturation

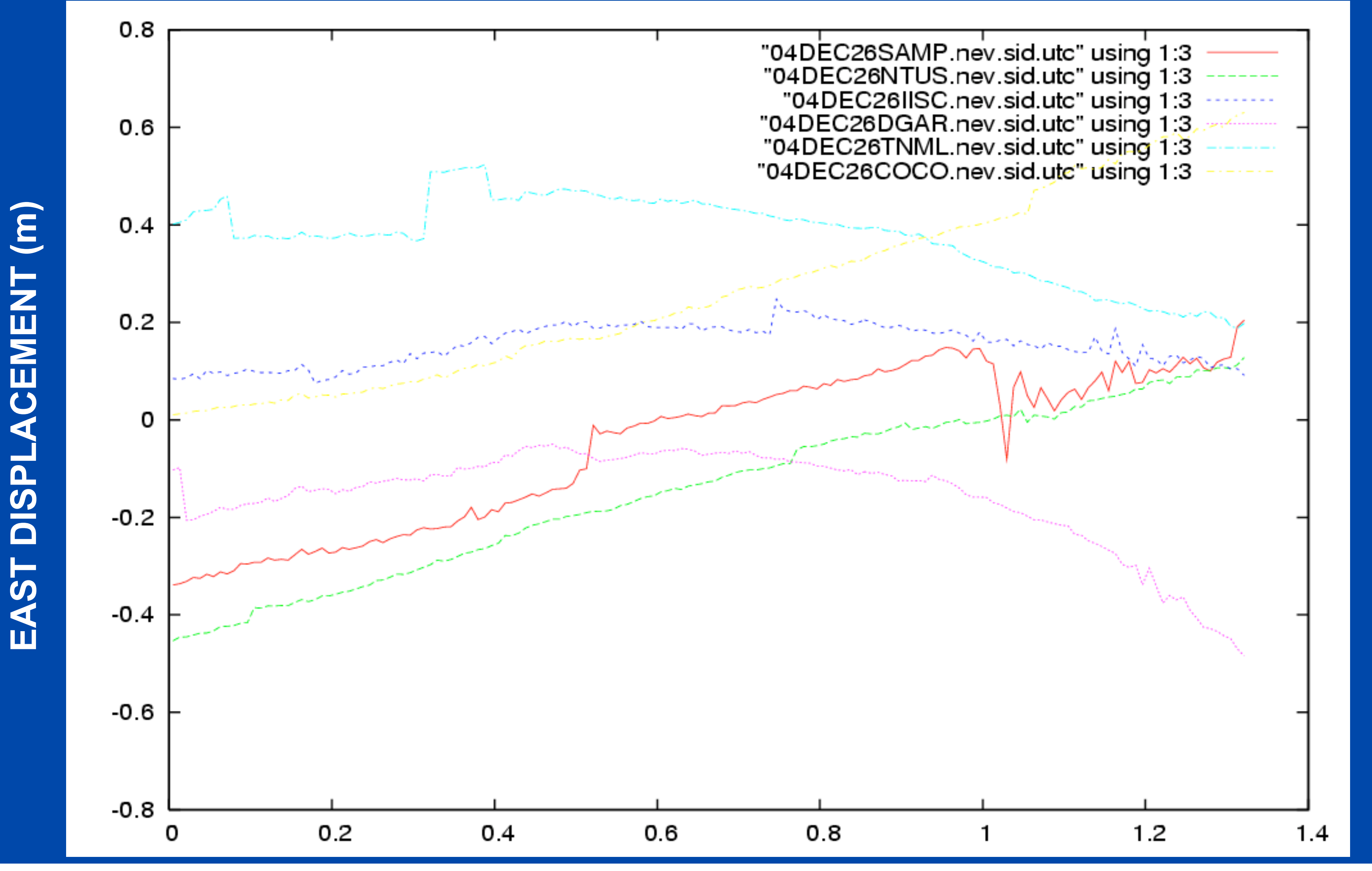
Research Questions

- Can the static moment be estimated early using GPS ?
- How well can we invert for the earthquake model ?
- Which GPS data processing strategies work ?
- How important are accurate real-time orbits ?
- How important are nearby stations ?
- What is required to do all this in real time ?
- How can this be used for tsunami warning?

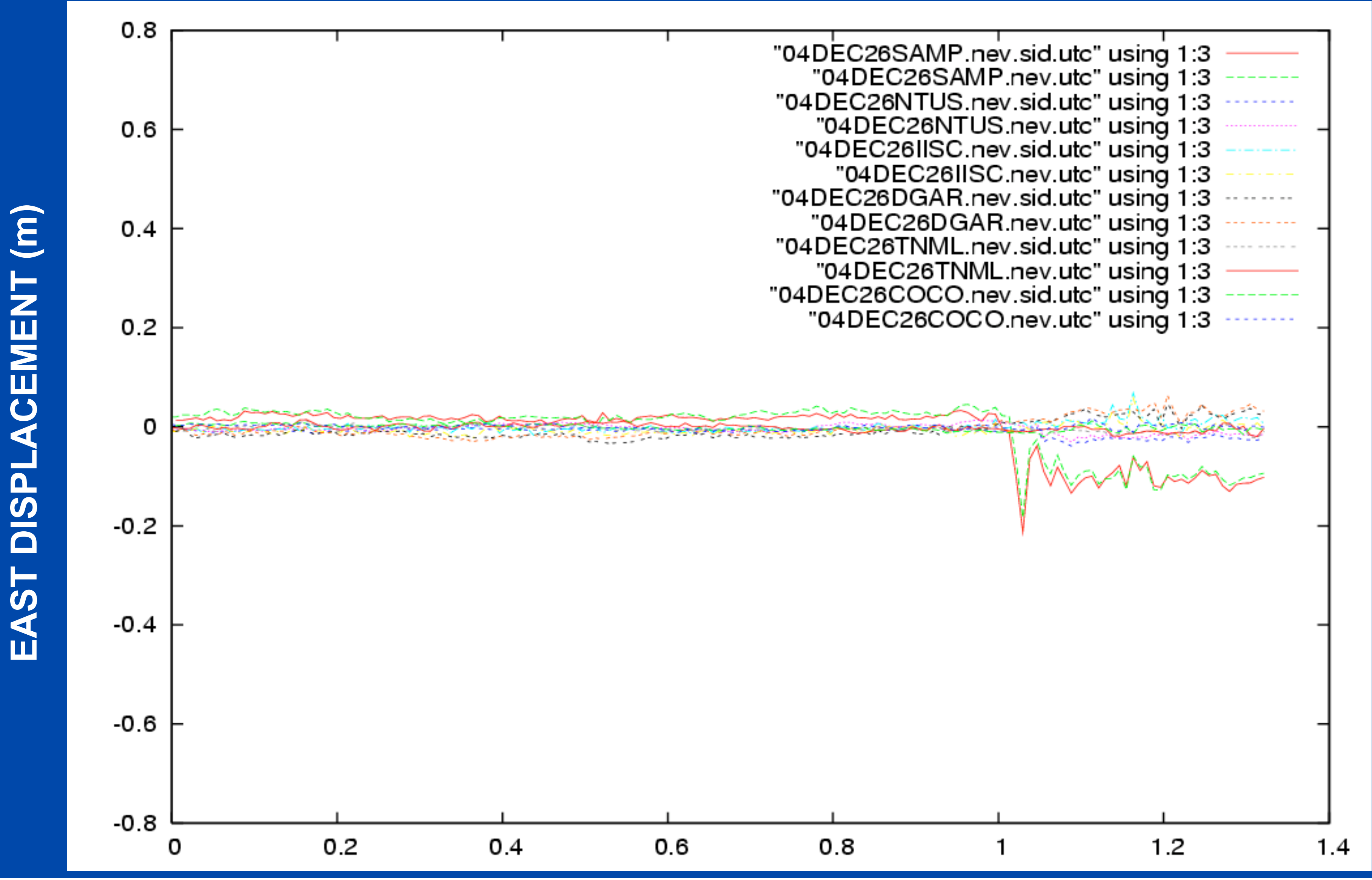
GPS Analysis

- Analysis simulates a real-time situation
  - only use information that can be available in real time
- Data
  - 24 hours of data up until 20 minutes after origin time
- Estimated Parameters
  - GPS satellite orbits and clocks
  - Station clocks
  - Station positions (as white noise if < 3,500 km from source)
  - Earth's pole position and rate of rotation
  - Tropospheric zenith delay and gradients (random walk)
  - Multipath mitigated using position-based sidereal filter

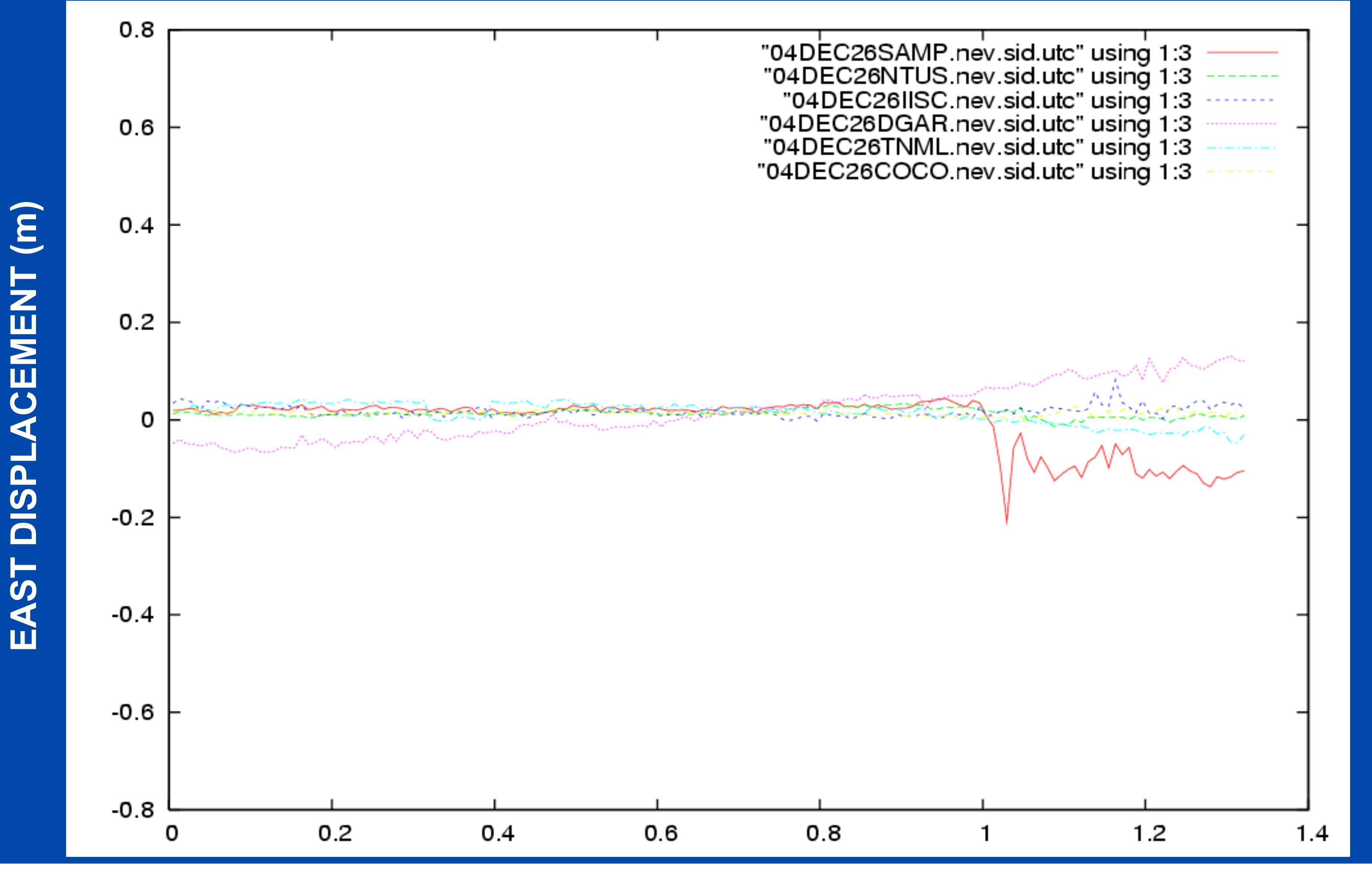
The Need for Accurate Orbits:
30-sec Time Series using Broadcast Orbits



The Need for Accurate Orbits:
30-Sec Time Series using Estimated Orbits

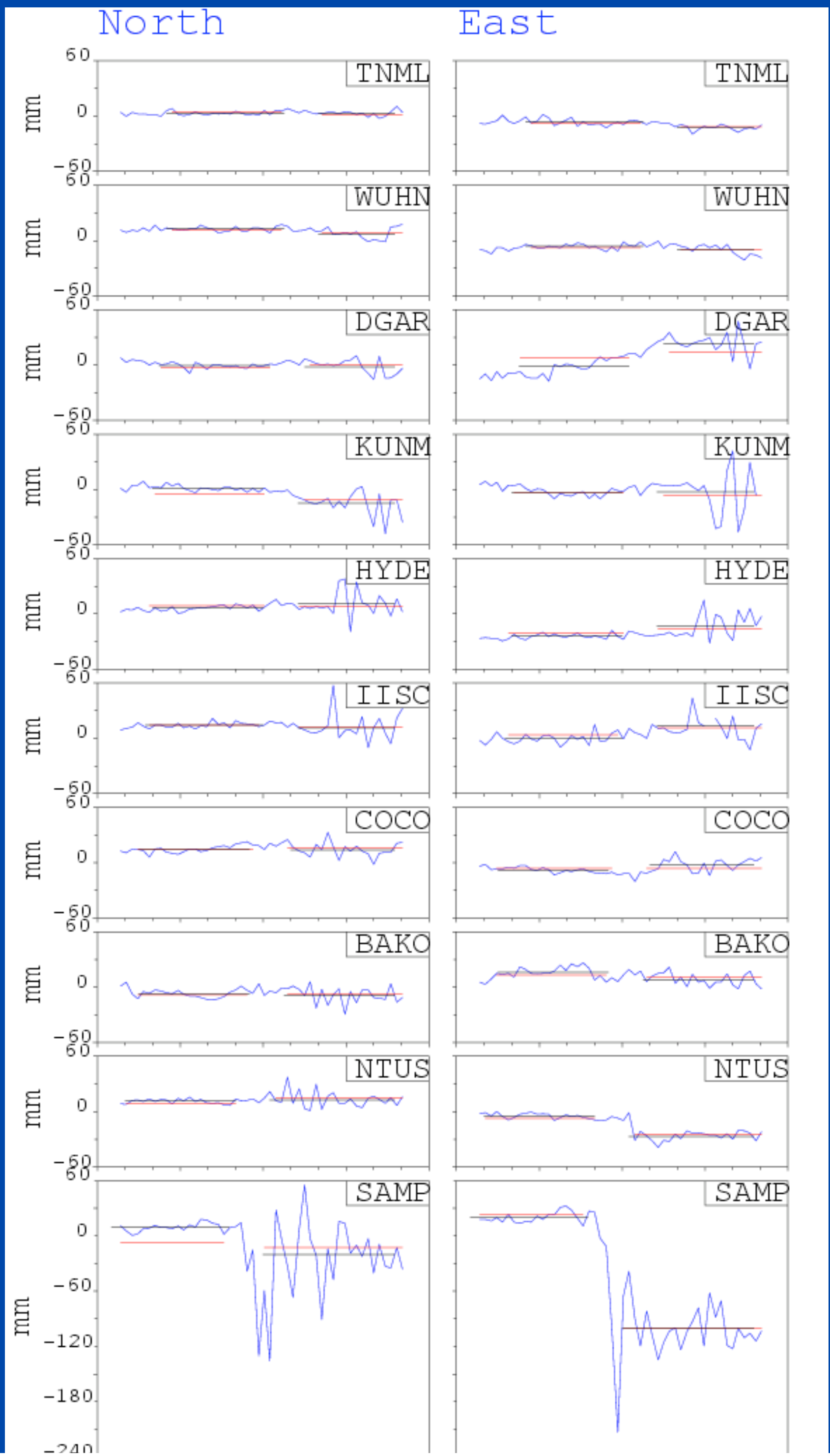


The Need for Accurate Orbits:
30-sec Time Series using IGS Ultra-Rapids

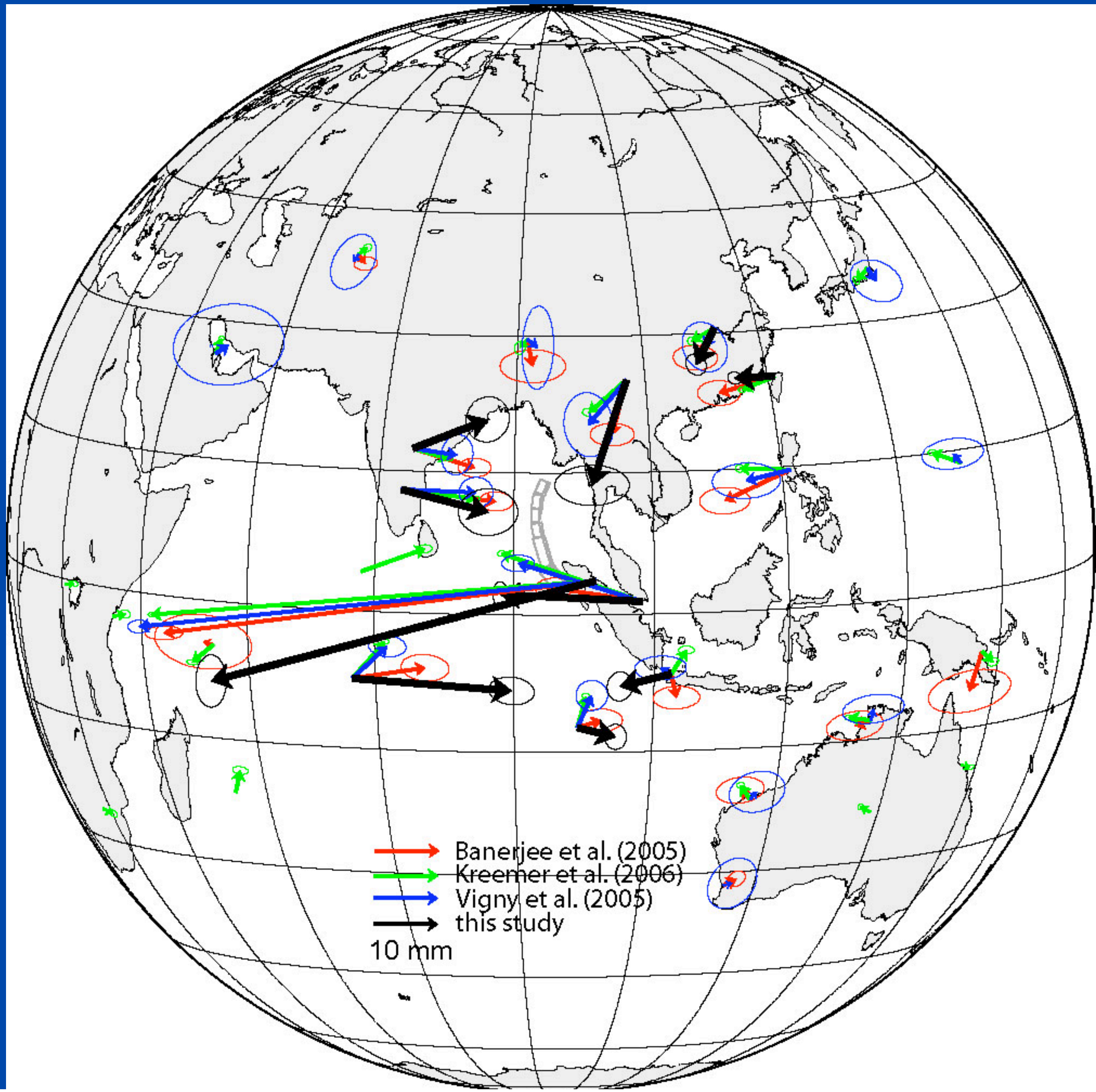


GPS 30-sec Series

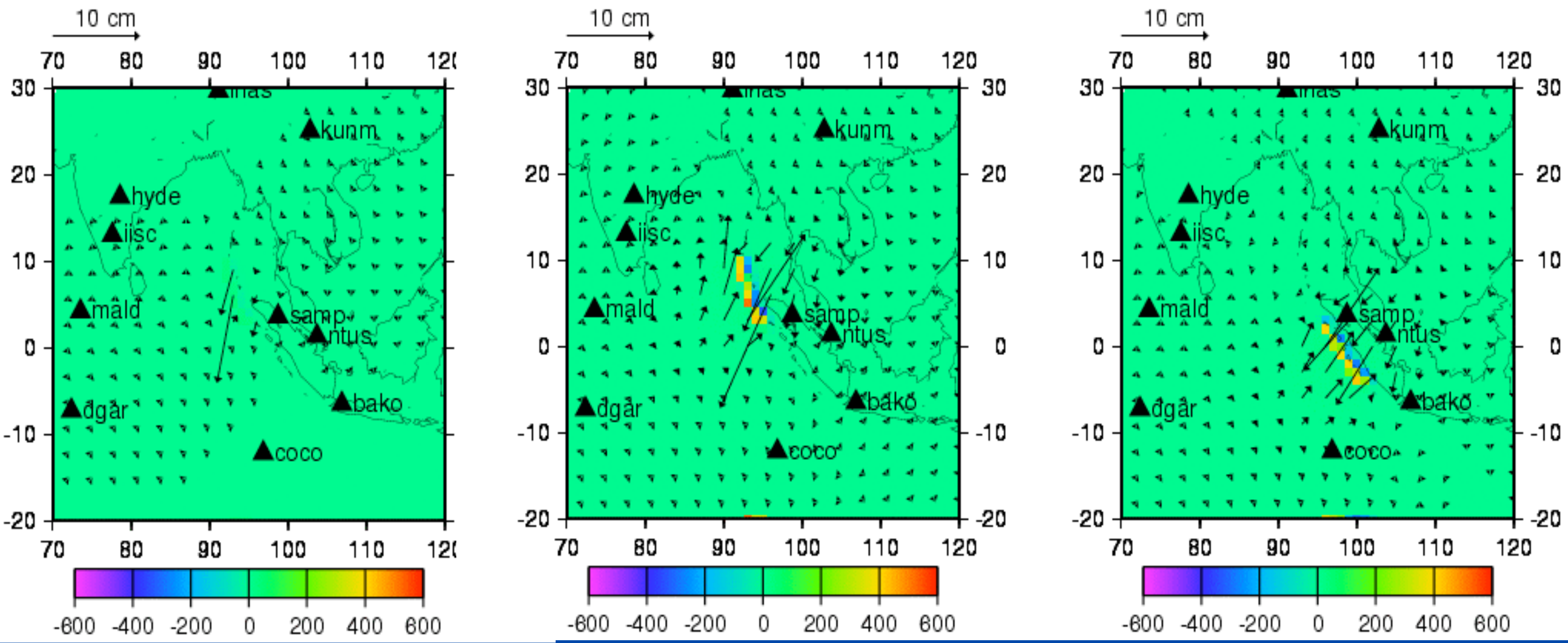
- Rapid static displacement
  - Data confirm that it arrives mostly with body waves
  - Estimated within minutes
  - Time windows:
    - origin time from seismology
    - 10 minutes before first arrival
    - 3 minutes “dead time”
    - 15 minutes after origin time
  - Accuracy ~ 7 mm
- Can be used to estimate earthquake slip model
  - Model displacements ~ 3 mm



Rapid Displacement Field



Fingerprint Approach to Inversion

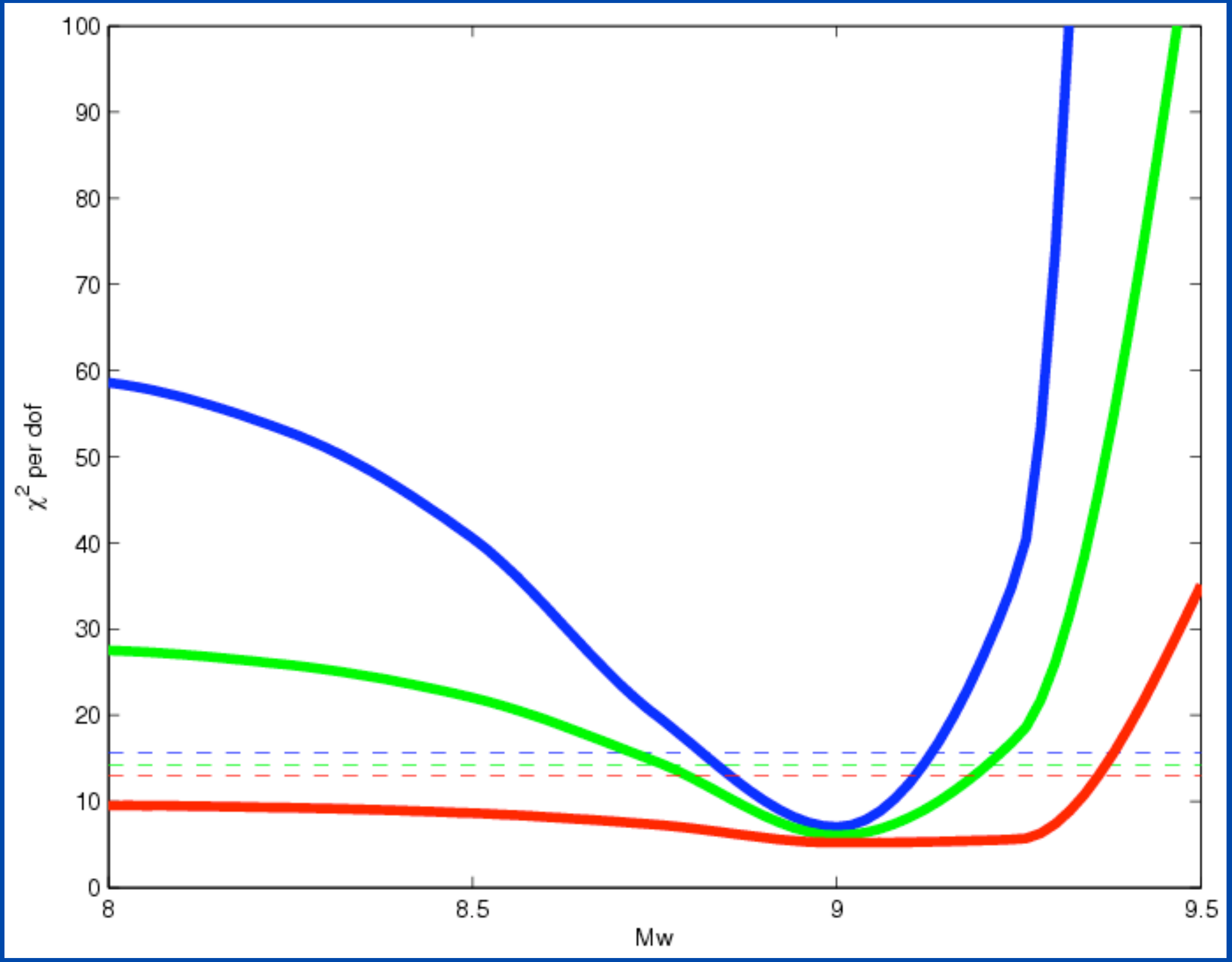


Rupture length: 1000 km
Magnitude: 8.50
(northward rupture)

Rupture length: 1000 km
Magnitude: 9.25
(northward rupture)

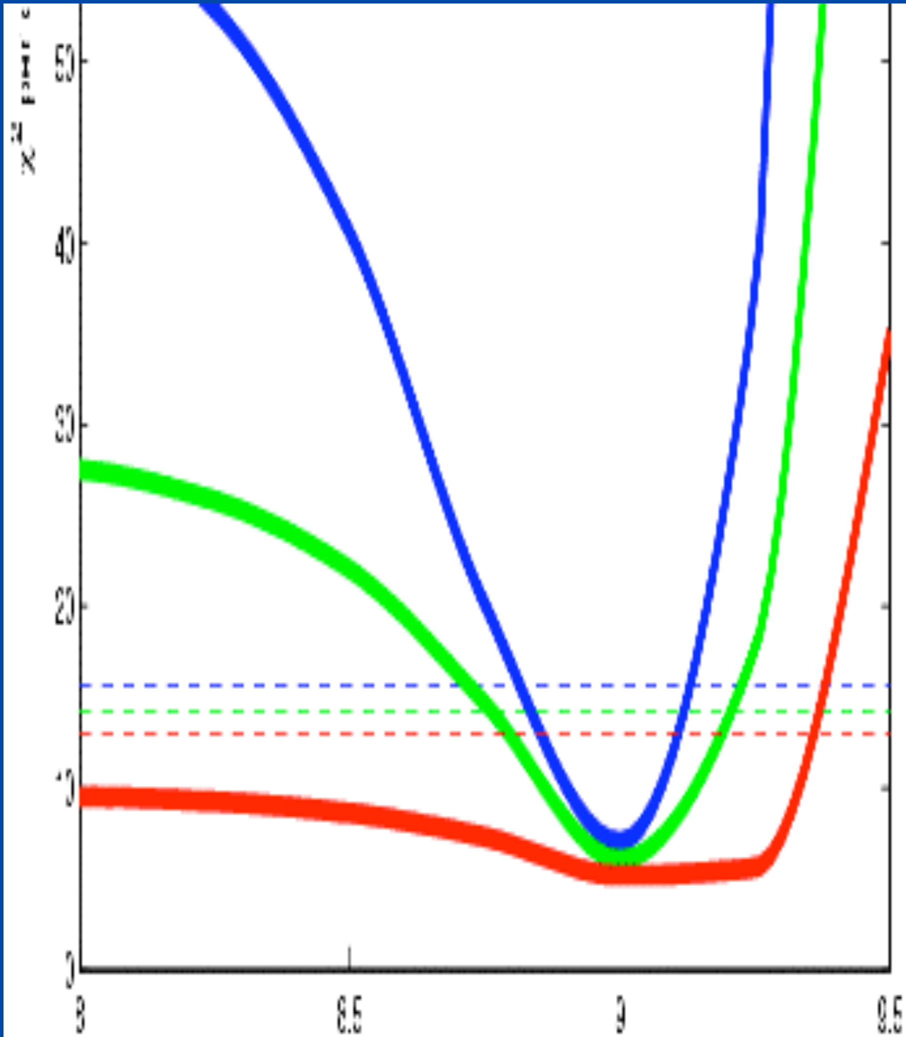
Rupture length: 1000 km
Magnitude: 9.25
(southward rupture)

Rapid Moment Magnitude Estimation

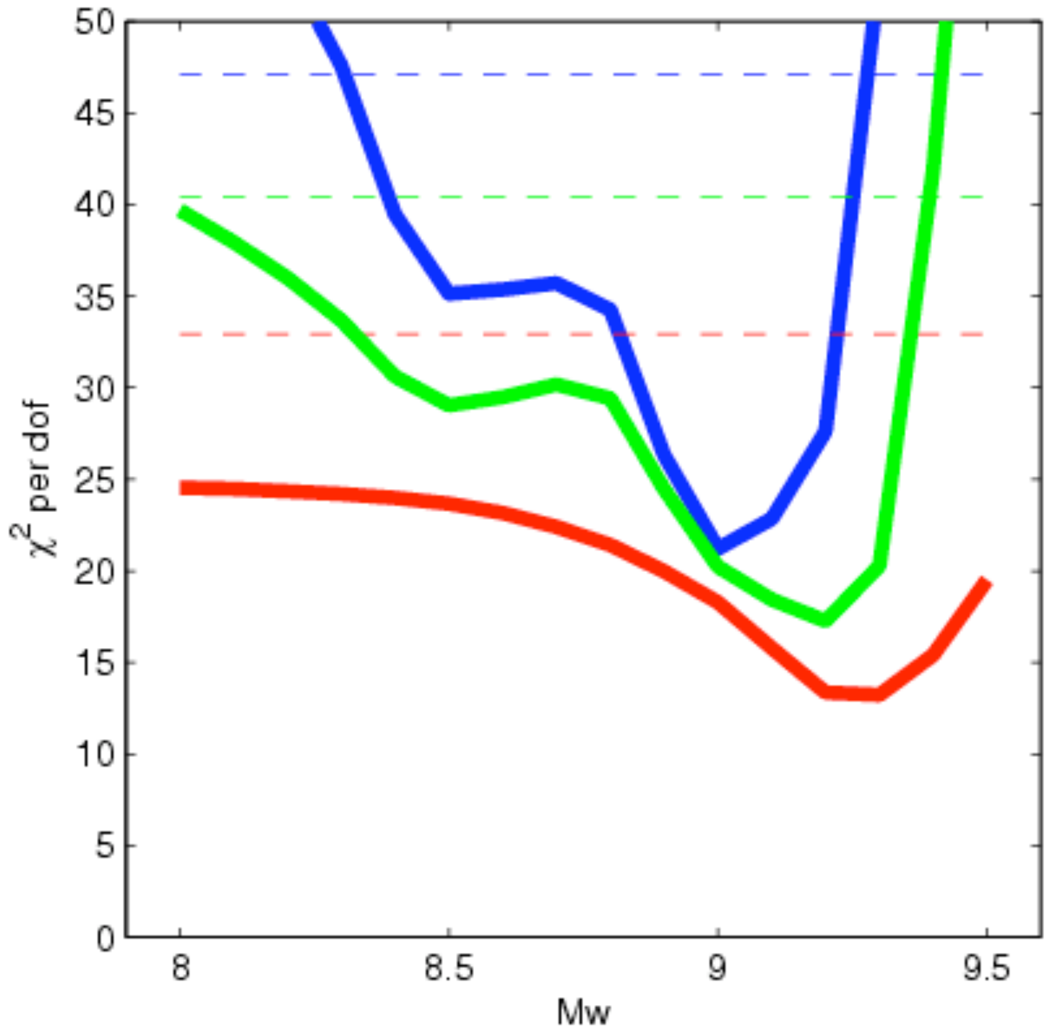


- Best fit models: $M_w = 8.9 - 9.1$
  rupture = 1000 km
- Blue
  - using all sites
- Green
  - no SAMP (300 km)
- Red
  - no SAMP (300 km)
  - no NTUS (900 km)

Estimated Orbits vs IGS Ultra-Rapid Orbits



Estimated Orbits (distorted to equalize scales)



IGS Ultra Rapid Orbits

Conclusions (1)

- Magnitude M_w controls tsunamigenic potential
  - Problem: Early seismic magnitudes saturate
- M_w can be estimated early with GPS
  - 15 min after earthquake origin time
  - Using initial epicenter from seismology
  - Using existing IGS data at 30 s
- Also GPS gives modeled displacement field
  - Hence vertical displacement of the ocean
- Suggests GPS can initialize real-time tsunami models
  - GPS → earthquake model → tsunami model → far field waves
  - Far field waves mainly sensitive to magnitude + location
  - Thus GPS and ocean sensors are complimentary

Conclusions (2)

- What is important to make this work ?
  - Real-time GPS data at 30 seconds near subduction zones
  - Real-time accurate orbits and 30-second clocks
  - Real-time global network for orbits and frame
  - Real-time operational analysis
  - Interface with tsunami models is rather trivial
- This is an example of an opportunity for IGS

Conclusions (3/3)

- Opportunities, Recommendations, and Questions
  - NASA/JPL already has a robust operational system to provide high accuracy GPS orbits and clocks in real time
    - Collaborate with JPL to develop these products to work for this application
  - JPL and IGS have stations transmitting data in real time
    - Expand this to regional networks in subduction zones
    - How do to pay/maintain these networks in third world countries ?
  - Cascadia subduction zone has an ideal network in place (PANGA/PBO)
    - Ideal test-bed for research and development
    - Could easily be converted to real time operation
  - Tsunami modelers could work with geodesists to explore how best to use the output of early GPS analysis
  - How to move from grass-roots research into a high-level operation?
    - Role of various agencies ?

False Alarm Analysis

- Estimate apparent offsets in the noise for no real earthquake
- "Min – Best – Max"

  95% confidence interval
- Except for earthquake:
  - All Min ~ 0 moment
  - Most Best ~ 0 moment
  - All Best ≤ M_w 7.75
- "Best" has no false alarms and correctly identifies M_w in tsunamigenic range