Rapid Determination of Earthquake Magnitude using GPS for Tsunami Warning Systems:

An Opportunity for IGS to Make a Difference

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Required Accuracy of Real-Time GPS Satellite Orbits

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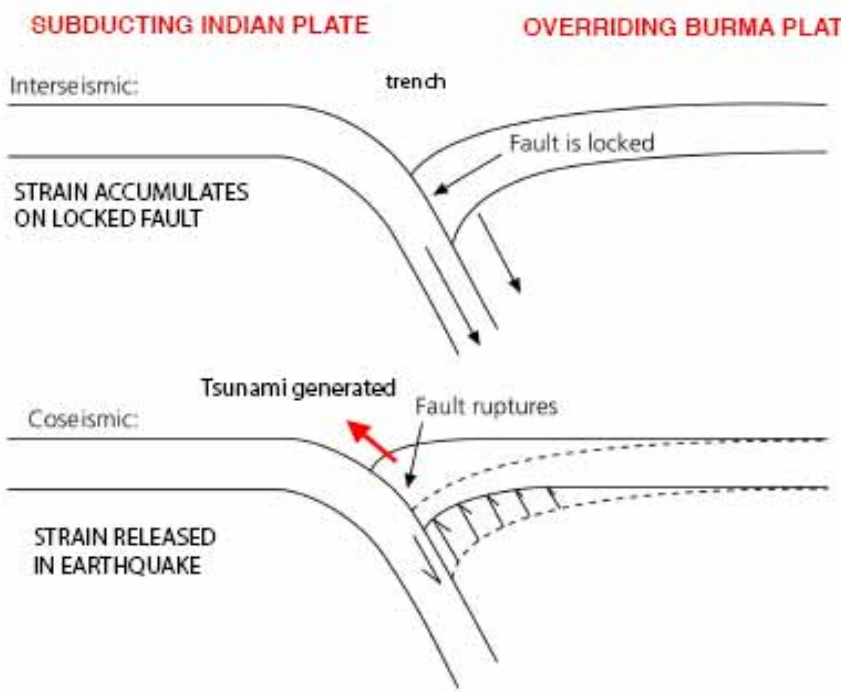
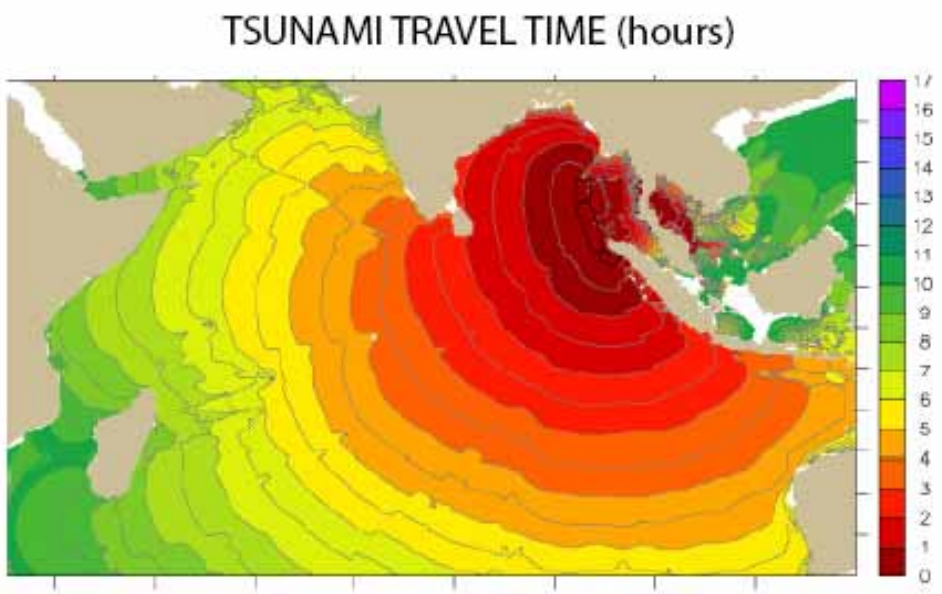
Oceanwide Tsunami Warning: The Challenge

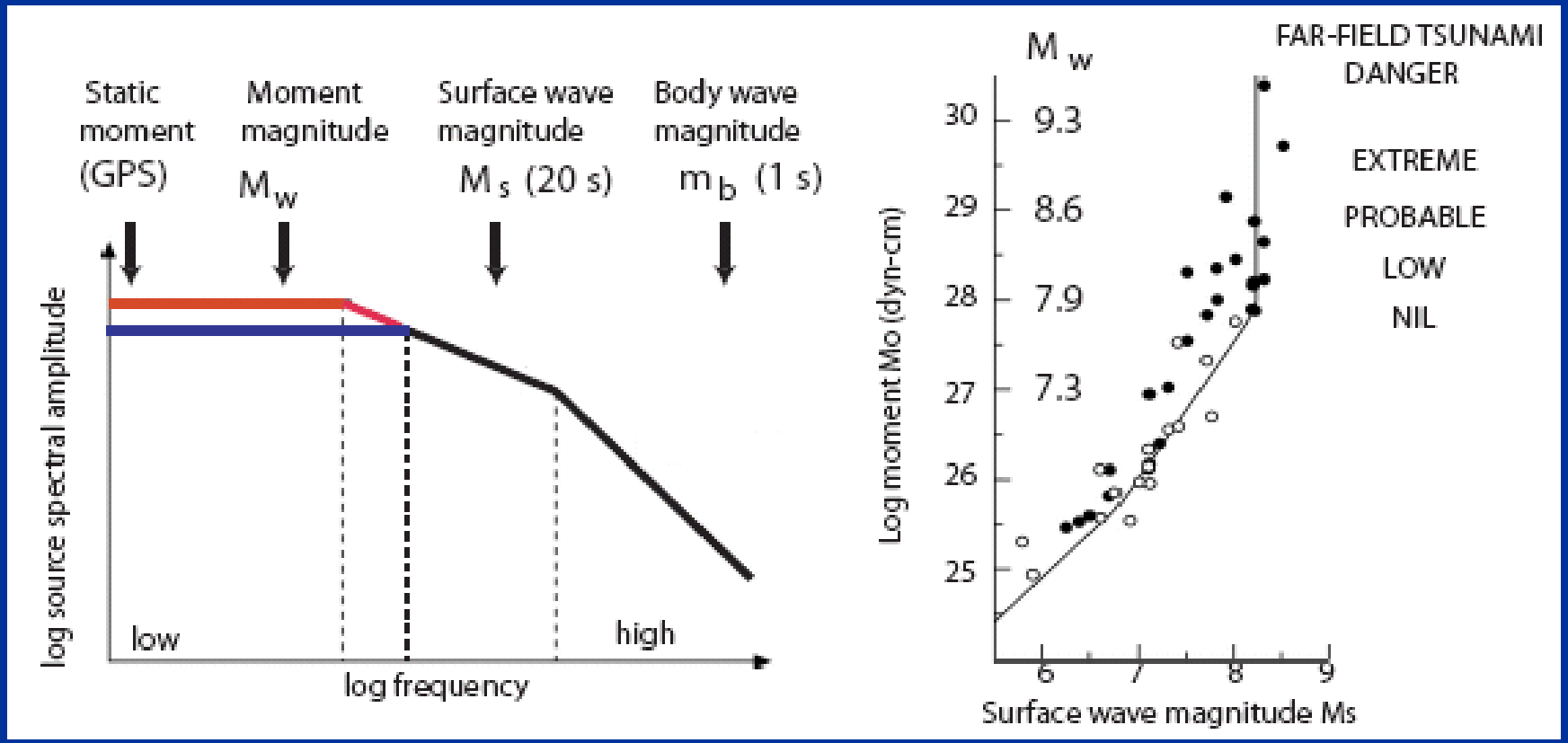




- First hour is important for early warning of oceanwide tsunamis
- Tsunamigenic potential directly relates to seismic moment

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

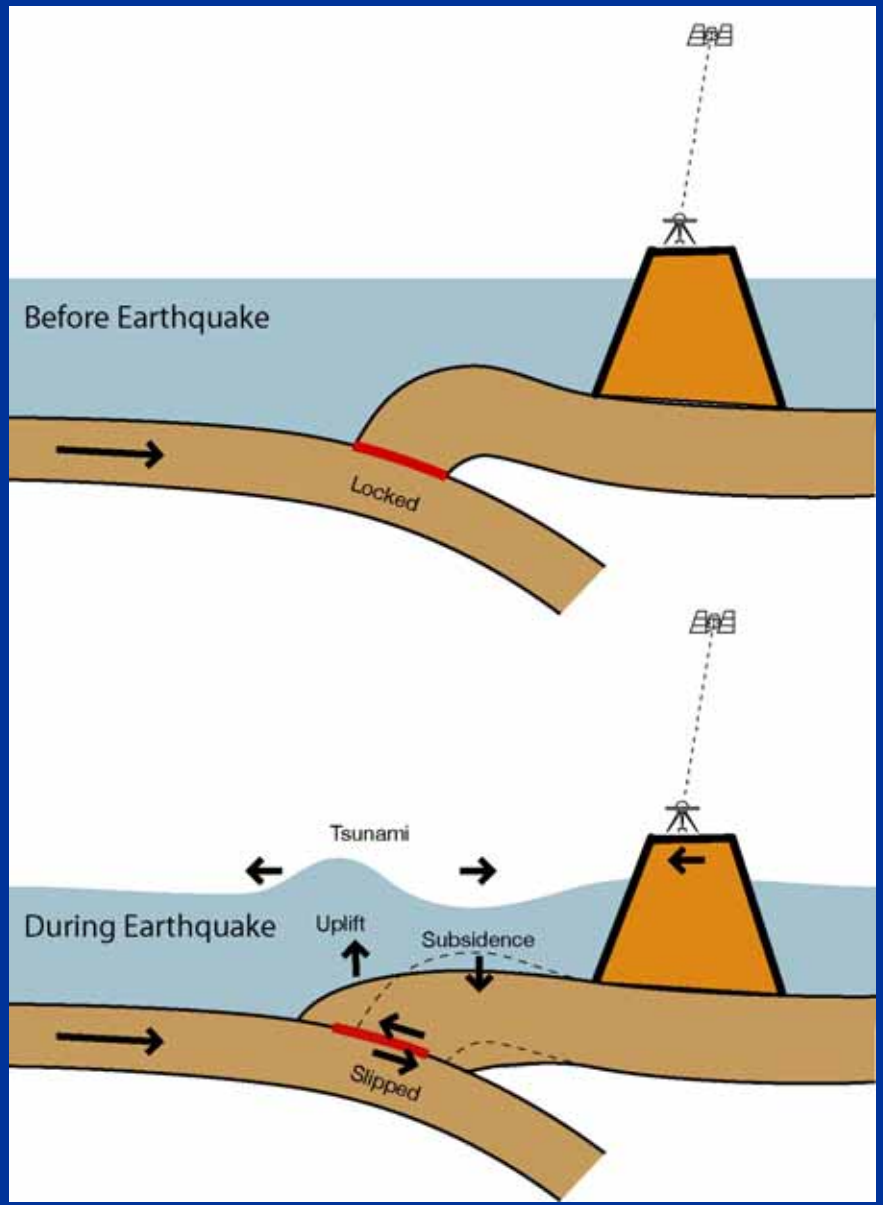
Seismic Magnitude Saturation: A Major Obstacle to Early Warnings



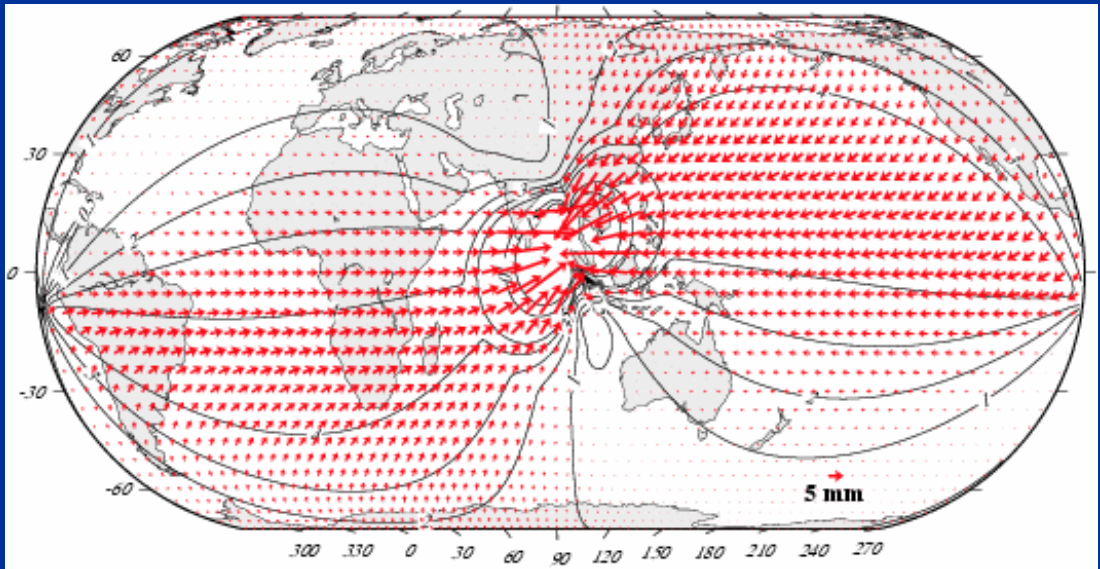
- Early seismic magnitudes saturate at 8–8.3 (Geller, 1976)
  - but oceanwide tsunamis typically require $M_w > 8.5$
- Can the static moment be estimated early using GPS?

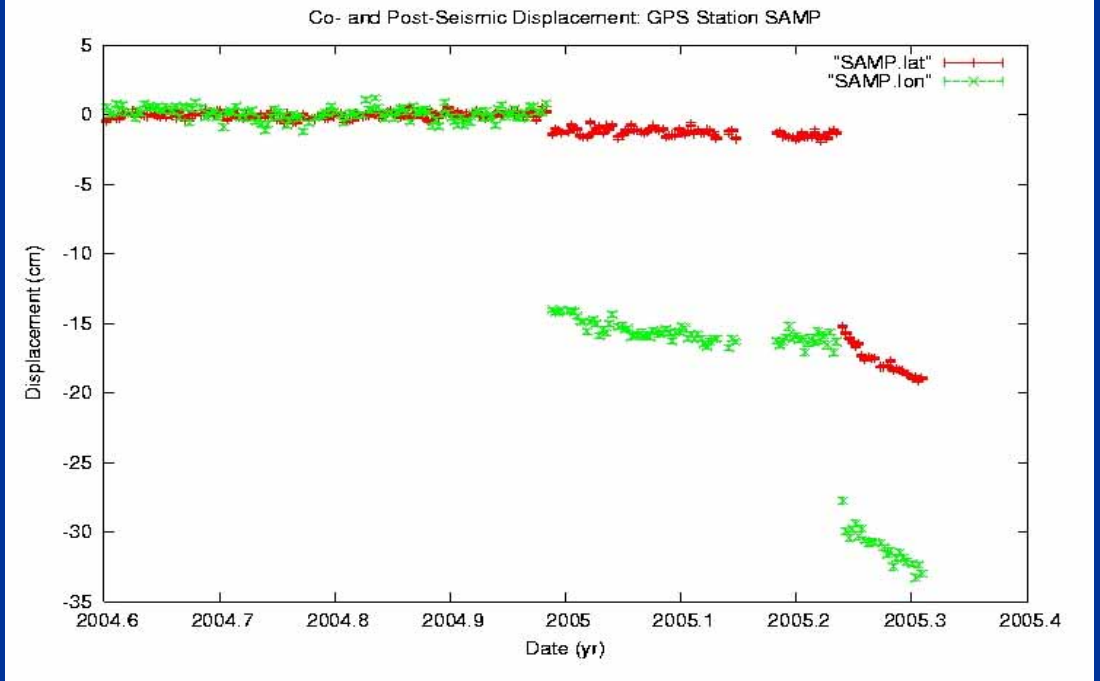
New Concept: GPS Displacement Method

- Before Earthquake
  - Plates are locked as stress builds up
  - GPS station located on the overiding plate
- During Earthquake
  - Plates slip by meters
  - Vertical motion of ocean floor causes tsunami
  - GPS station displaced
  - Invert GPS data for earthquake slip model
  - Input to tsunami model



2004 Sumatra Earthquake Displacements





- Post-event estimation of displacement field
  - global deformation!
  - > 10 mm as far as India
- Daily position t-series
  - 1-mm precision
  - Invert for magnitude and slip distribution
  - Provides ground truth to assess accuracy of rapid estimates
    - Compare displacements
    - Compare inverted models

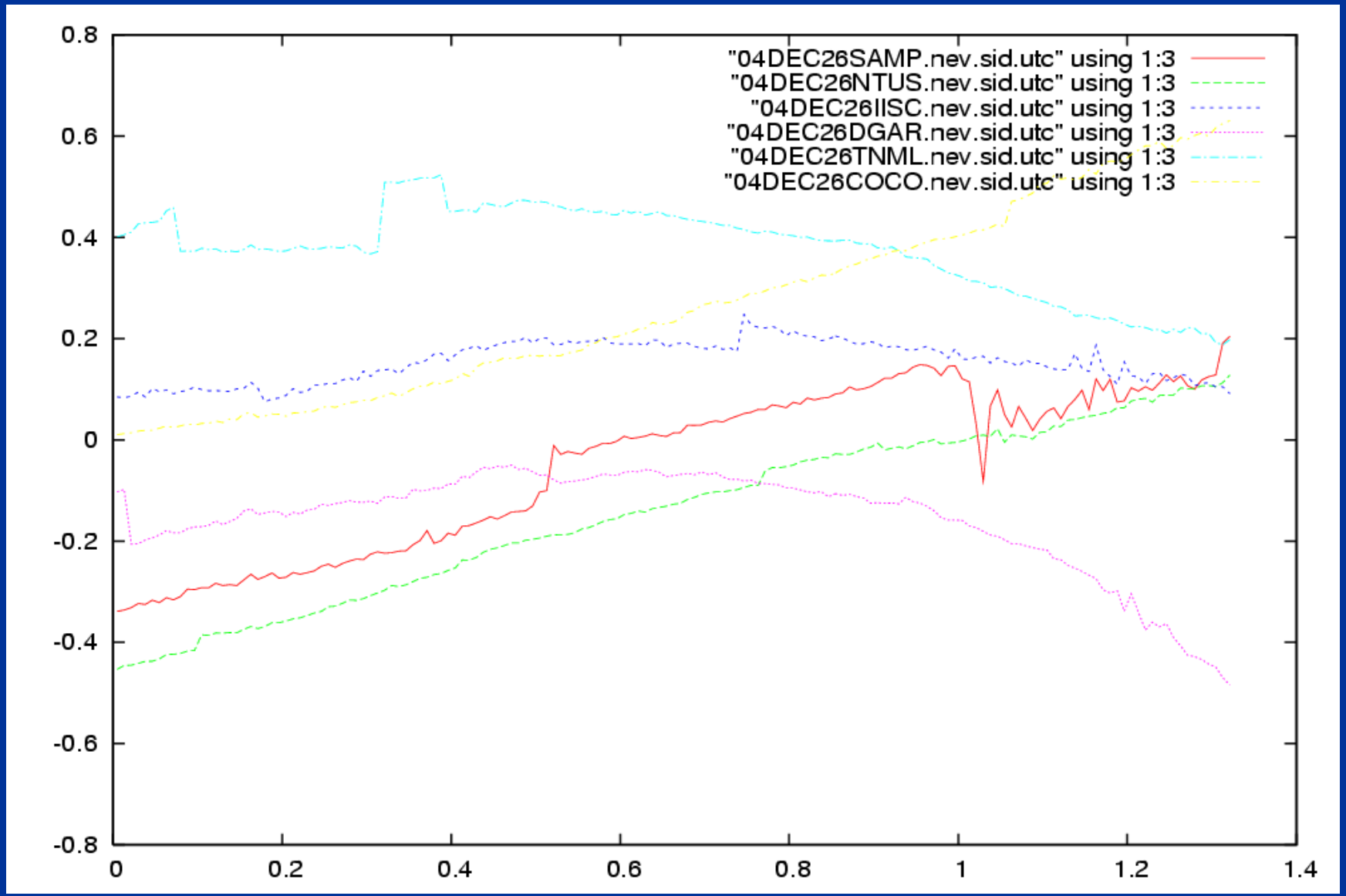
Broader Research Questions

- 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?

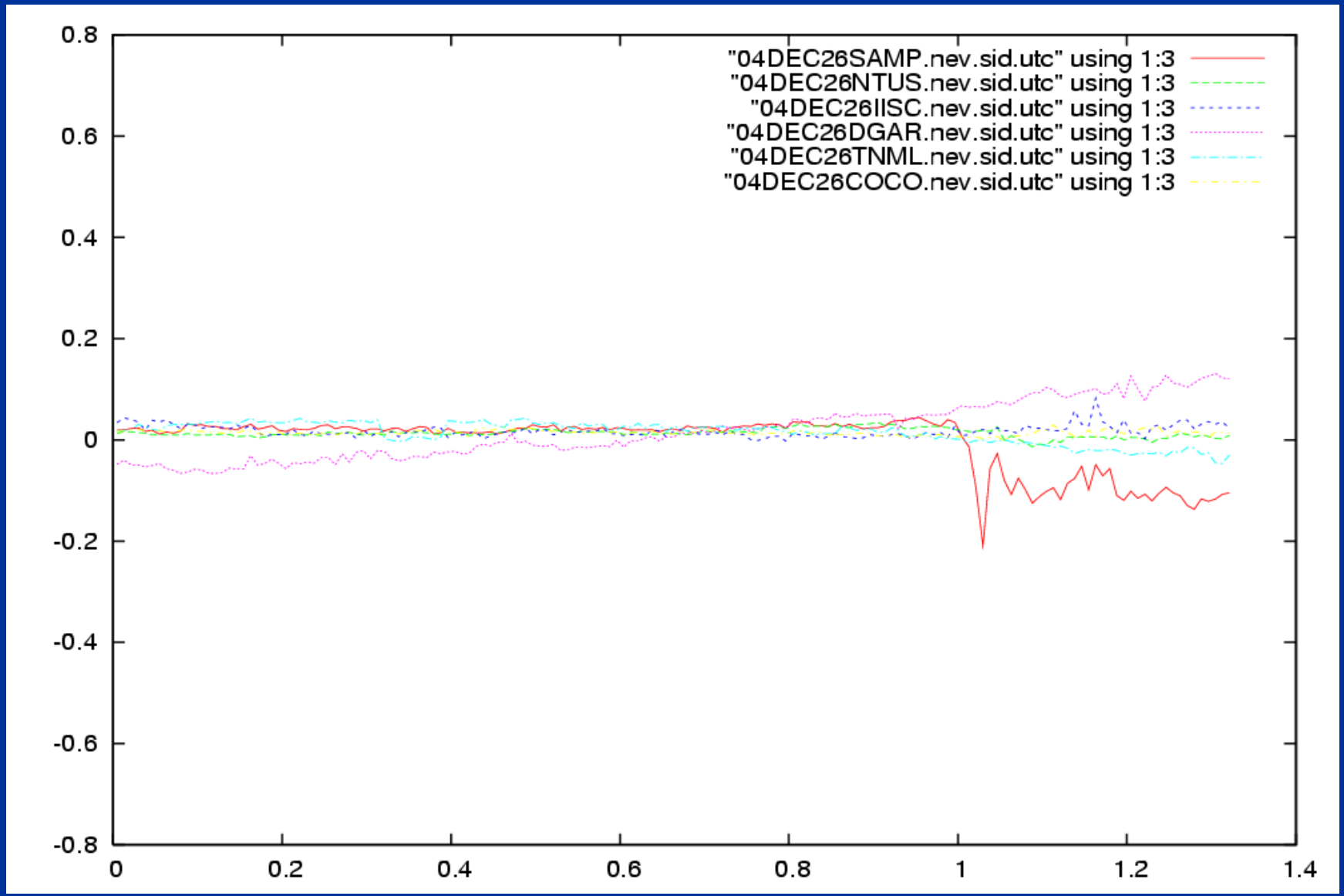
GPS Data Processing Strategy

- Analysis simulates a real-time situation
  - only use information that can be available in real time
  - 24 hours of 30-sec data up until 20 minutes after origin time
- Estimated Parameters
  - GPS satellite and station clocks (= double differencing)
  - Station positions
    - every 30 sec if < 3,500 km from source
    - as constant 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
- Various Orbit Strategies Compared
  - Broadcast / IGS Ultra Rapid Orbits / Custom Estimation

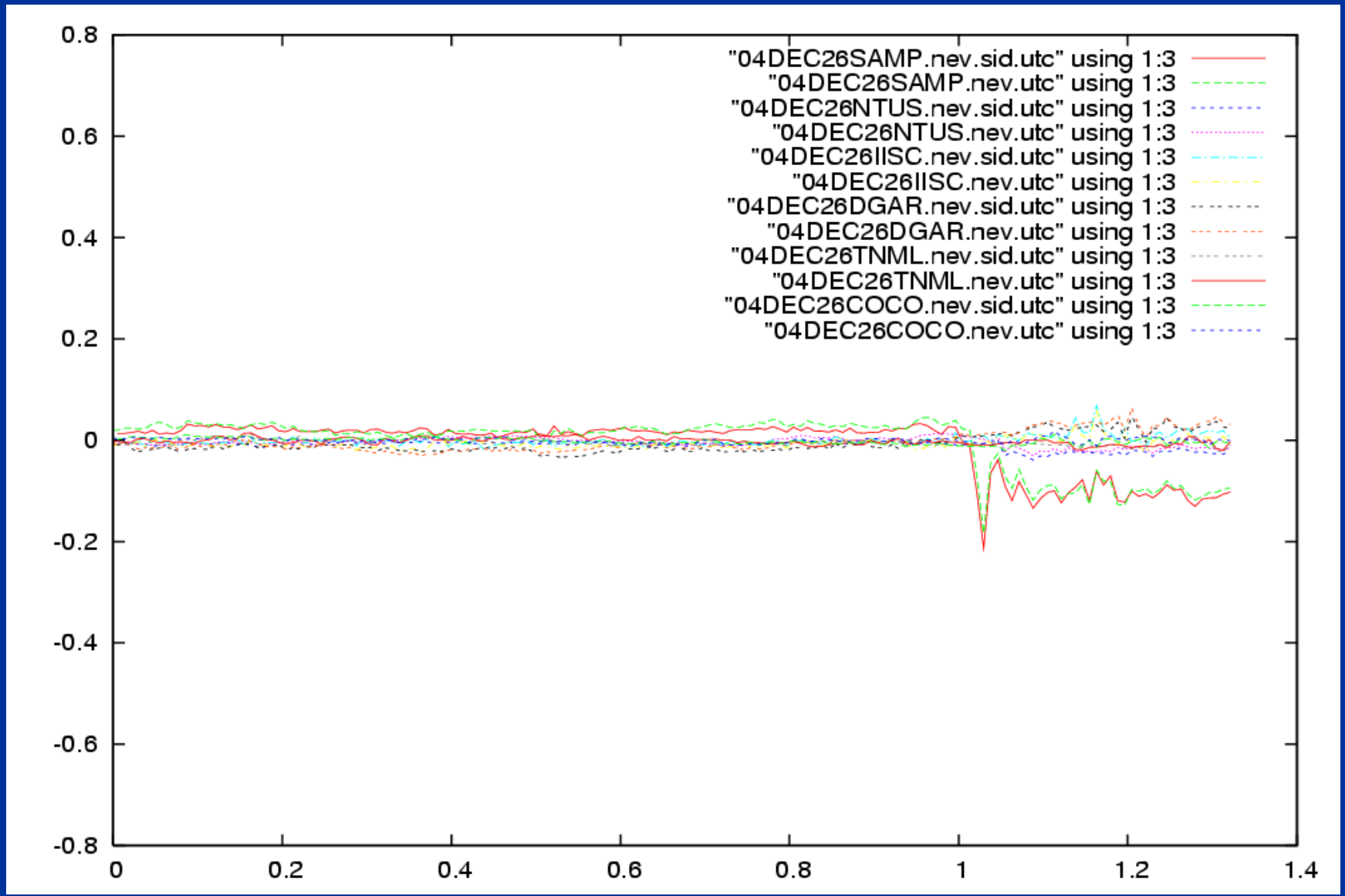
The Need for Accurate Orbits: 30-sec Time Series using Broadcast Orbits



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



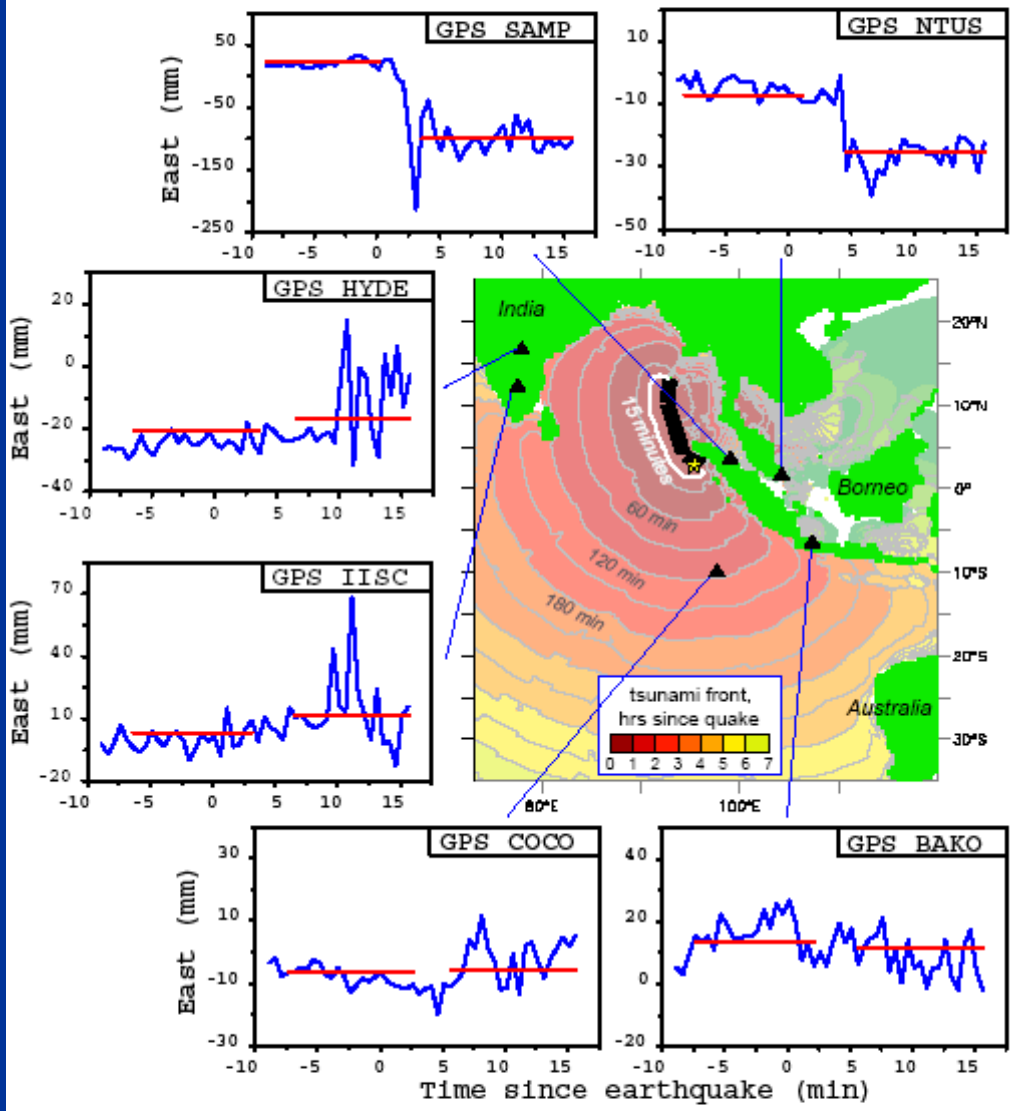
The Need for Accurate Orbits:
30-sec Time Series using Estimated Orbits



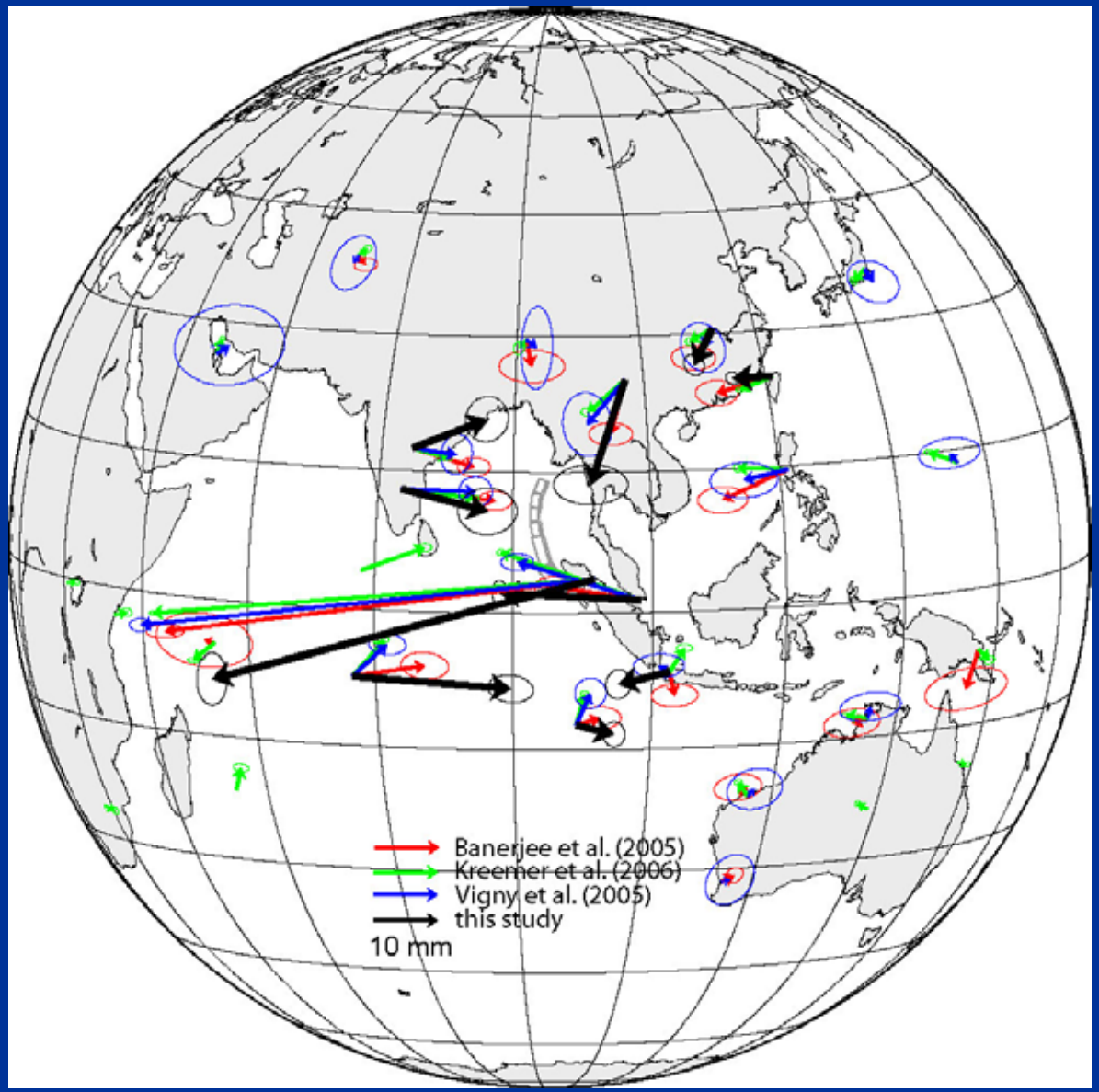
Results

- Using estimated orbits
- Rapid displacement
  - Data confirm that it arrives mostly with body waves
  - Can be resolved using 15-minutes after the quake
  - Accuracy ~ 7 mm
- Can be used to estimate earthquake slip model
  - Model displacements ~ 3 mm
- And keep in mind...
  - Network was far from optimal

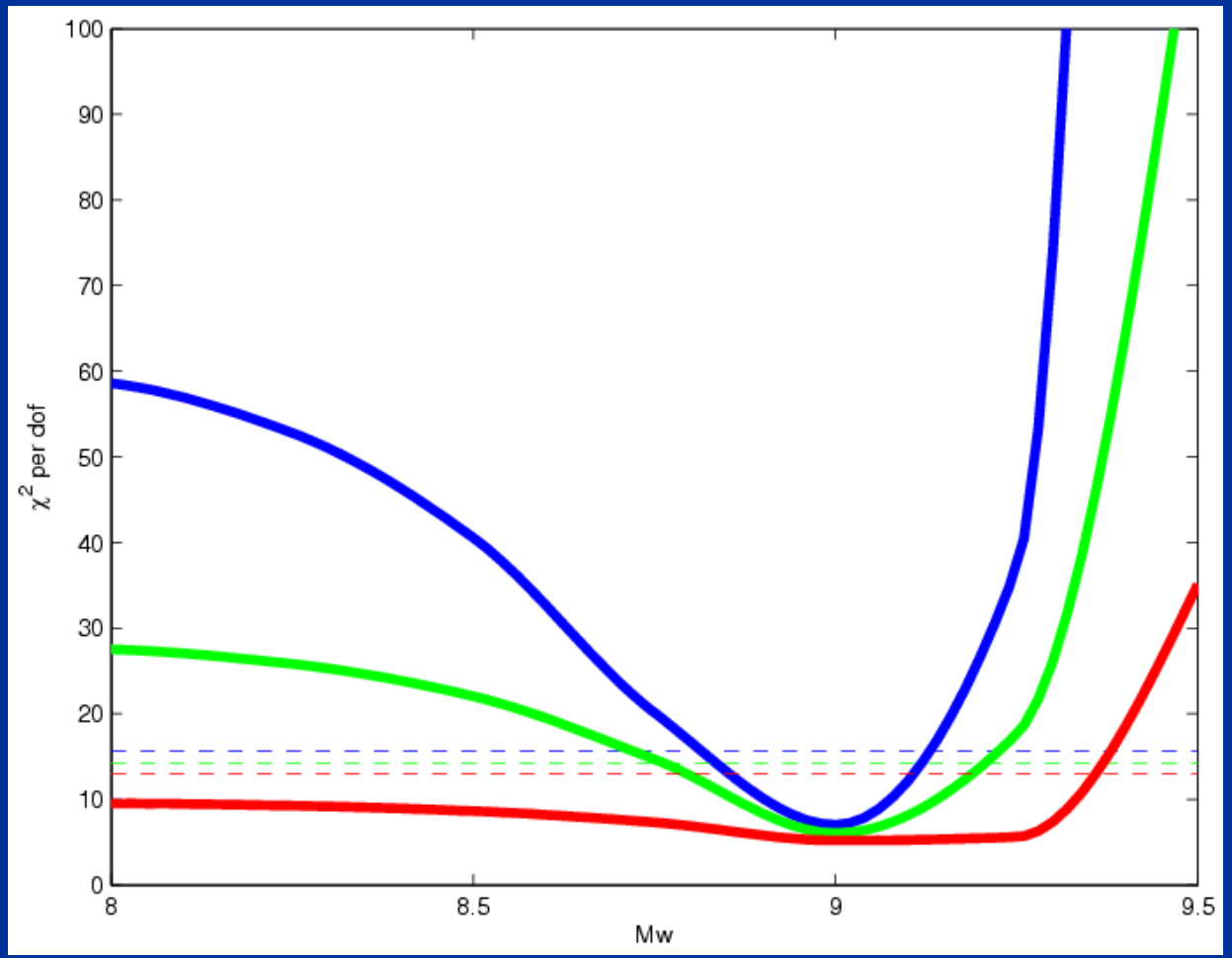
GPS 30-sec Series



Rapid Displacement Field



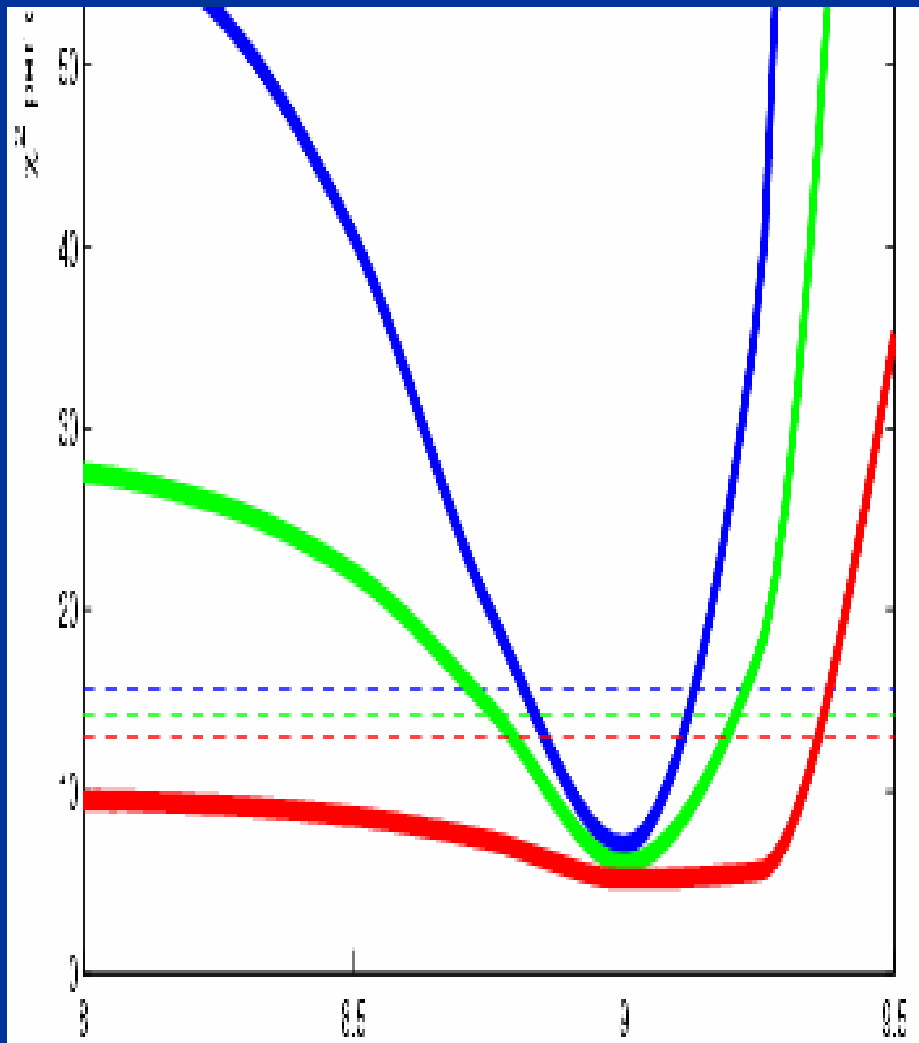
Rapid Moment Magnitude Estimation



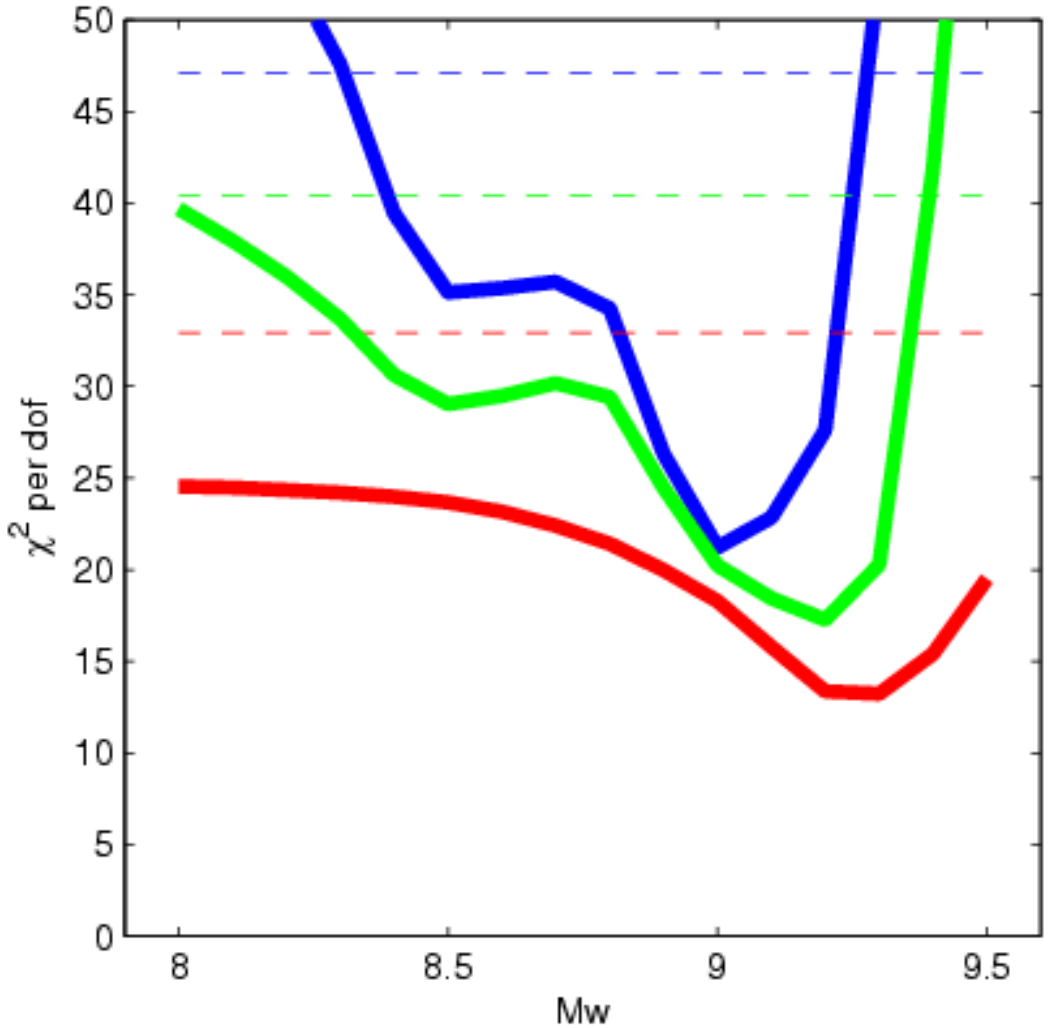
- Best fit models: M_w = 8.9 – 9.1

  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)

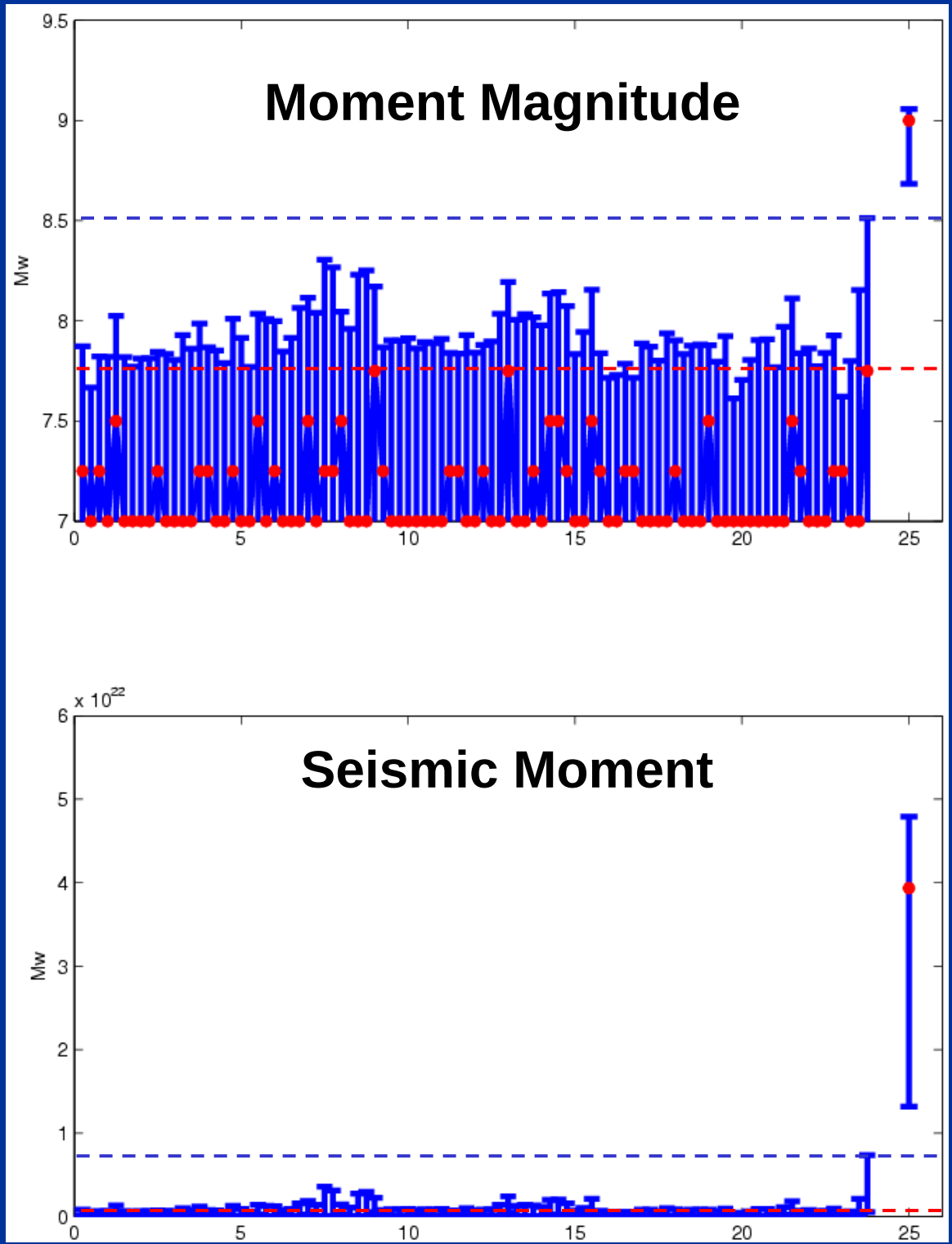


IGS Ultra Rapid Orbits

False Alarm Analysis

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

  95% confidence interval
- Except for earthquake:
  - All Max $\leq M_w$ 8.5
  - All Best $\leq M_w$ 7.75
- "Best" has no false alarms and correctly identifies M_w in tsunamigenic range



Conclusions

- Magnitude M_w can be estimated using 15 min GPS data
  - Inversion 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
- GPS orbit accuracy is crucial (for such great quakes)
  - Demonstrated to work using real-time estimated orbits
- Opportunities
  - IGS initiative toward real-time data and (eventually) orbits
  - NASA/JPL operational system – real-time orbits and positions
  - NOAA/PMEL next-generation real-time tsunami models driven by earthquake slip models –a “plug-in” interface
  - NSF/PBO GPS in Cascadia/Alaska – upgrade to real-time?