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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First hour is important for early warning of oceanwide tsunamis

Tsunamigenic potential directly relates to seismic moment

\[ \sim (\text{fault slip}) \times (\text{rupture length}) \times (\text{rupture width}) \]

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 overriding 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
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 $\rightarrow$ earthquake model $\rightarrow$ tsunami model $\rightarrow$ 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?