From the earthquake cycle to mantle structure – current and future uses of dense GPS

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PY09: GNSS-derived Troposphere Delays & Applications of IGS Products for Geodesy and Geophysics Research
From the earthquake cycle to mantle structure – current and future uses of dense GPS

- Using data from $O(10^3)$ sites in Japan for inter-/co-/post-seismic deformation associated with the 2011 Mw 9 Tohoku-oki, Japan earthquake

- Using Earthscope/PBO to image aseismic transients and their relationship to tremor

- Using dense networks to measure the response to ocean tidal loads and thus constrain depth variations in elastic and density parameters in the upper mantle.
Seismogenic Behavior of Subduction Megathrusts

A sampling of important intertwined questions

- Do major seismogenic “asperities” only slip seismically?
- Do creeping segments only creep?
- Role of conditional stability (e.g., near trench)?
- What are the relationships between post-seismic creep, transients, tremor and seismicity (rate, repeat intervals, location…)?
2011 March 11
05:46:10 UTC

1 sample/sec GPS observations - sidereally filtered
2011 Tohoku-Oki, Japan

Co-seismic slip:
- 1sec GPS, DART, seafloor geodesy
- 80 m peak slip over a small region
- M7.8 aftershock

Post-seismic afterslip:
- Total time = 1.5 years
- Negligible overlap of co-/post-seismic
- Post-seismic pattern ~constant
Post-seismic (1.5 yrs)

F. Ortega, Ph.D. thesis
Slip transients and Tremor: Cascadia

Rogers and Dragert (2003)
Finding Transients

- With no *a priori* information on the physical mechanisms responsible for transients, we cannot only assume time functions corresponding to specific physical descriptions, i.e. exponential or logarithmic decay.

- Use a flexible time parameterization using functions that resemble our expectation of transients (*over-complete dictionary* of “behaviors”).

- Secular and periodic components + integrated 3rd-order B-splines of different scales and center times (not orthogonal).

![Diagram](image)

Penalize the # of non-zero coefficients in $\mathbf{m}$:

$$\mathbf{m} = \arg\min_{\mathbf{m}} \| \mathbf{d} - \mathbf{Gm} \|_2^2 + \lambda \| \mathbf{m} \|_0$$
Sparsity-Promoting Regularization

• Penalize the *number* of non-zero coefficients in $m$:

$$m = \arg\min_m \|d - Gm\|_2^2 + \lambda \|m\|_0$$

where $\| \cdot \|_0 = L_0$-pseudo-norm, or the “counting norm”

• **Sparse-compression**: represent time series by a small set of $B^i$-splines

• But using the $L_0$-pseudo-norm is a hard combinatorial problem

• Use $L_1$-norm relaxation (iterative reweighting) to make problem convex (Candes et al., 2007):

$$m = \arg\min_m \|d - Gm\|_2^2 + \lambda \|m\|_1$$

$$\|m\|_1 = \sum_i |m_i|$$
Slip transients and Tremor: Cascadia

![Graph showing east displacement and tremor activity](image)

- **ALBH**
- **Continuous Seismic Records**
- **East Displacement (mm)**
- **Tremor Activity (hrs over 10 days)**

**Rogers and Dragert (2003)**

**Map of Cascadia subduction zone**

- **49°N**
- **48°N**
- **125°W**
- **124°W**
- **123°W**
- **122°W**

**References and Notes**

1. B. F. Atwater
2. K. Satake, K. Shimazake, Y. Tsuji, K. Ueda
3. S. M. Peacock
4. K. Obara
5. M. M. Miller
6. 9. S. M. Peacock
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9. 4. K. Obara
10. 3. M. M. Miller

Include this information when citing this paper.

*www.sciencemag.org* on September 27, 2012
Spatial Sparsity Weighting for Cascadia
ALBH GPS Time Series

- Use sparsity-promoting regularization to fit time series and determine elements of $\mathbf{m}$ with the largest amplitudes (effectively we are compressing the data).

- Form reduced $\mathbf{G}$ and estimate reduced $\mathbf{m}$ using standard least squares:

$$\tilde{\mathbf{m}} = \left( \tilde{\mathbf{G}}^T \mathbf{C}_d^{-1} \tilde{\mathbf{G}} \right)^{-1} \tilde{\mathbf{G}}^T \mathbf{C}_d^{-1} \mathbf{d}$$

← Episodic SSE reconstruction with only 6 $B^i$-splines

← $B^i$-spline scalogram: Localized, high amplitudes for short duration $B^i$-splines
Posterior Uncertainties

• Standard least squares formulation allows for estimation of posterior covariances for \( B^i \)-spline coefficients:

\[
\tilde{C}_m = \left( \tilde{G}^T C_d^{-1} \tilde{G} \right)^{-1}
\]

• Extend to posterior covariances for data fit:

\[
\tilde{C}_d = \tilde{G} \tilde{C}_m \tilde{G}^T
\]

← Posterior data covariance matrix for modeled transient displacement
Cascadia 2010 SSE: Slip rate + tremor

Issues (not addressed today)

- Controls on location and temporal evolution? Role of fluids? Ubiquitous, yes/no/why?
- Relationship to regions of big EQ and eventual post-seismic deformation?
- Relationship to forearc/slab structure?

Approach

- Detect/reconstruct/model transient ground deformation in GPS time series due to SSE using sparsity-based approaches
  - Slab interface: McCrory et al. (2004)
- Tremor epicenter locations: Pacific Northwest Seismic Network (http://www.pnsn.org/tremor)

Analysis and models: Bryan Riel
Cascadia 2010 SSE: Slip rate + tremor

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Measuring OTL response with dense GPS networks

0.00 hours

Particle motion ellipses (PMEs)
OTL response as an opportunity: Constraining properties of the upper mantle

Next

- Confirm with much longer time series
- Improve estimates of positions
- Explore sensitivity to:
  - Newer OTL models
  - Approach to removing solid earth tides
- Improve geodynamical interpretation
- Explore other regions (1D)
- Go to 3D

For each cGPS site, we should establish empirical tidal corrections and use to improve transient detection

Ito & Simons, 2011
Goal: Elastic and density structure of a craton
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• Tohoku-oki
  - Relatively constant pattern of post-seismic after slip (with notable exceptions)
  - Lack of overlap between co-seismic/post-seismic distribution of fault slip
  - Consistency of co-seismic and inter-seismic
  - Consistency of co-seismic and post-seismic
  - Importance of high-rate GPS (and in near real time)

• Cascadia aseismic transients
  - New rigorous methods for automatic transient detection based on sparsity and overcomplete dictionaries.
  - Slip transients and tremor co-located in space and time

• OTL load response to probe upper mantle structure
  - Ability to separate depth variation of density and elastic moduli.
  - Needs careful analysis of sensitivity to processing approach