Transient deformation from daily GPS displacement time series: postseismic deformation, ETS and evolving strain rates

Yehuda Bock\textsuperscript{1}, Peng Fang\textsuperscript{1}, Lina Su\textsuperscript{1}, Dara Goldberg\textsuperscript{1}, Angelyn Moore\textsuperscript{2}, Sharon Kedar\textsuperscript{2}, Zhen Liu\textsuperscript{2}, Susan Owen\textsuperscript{2}, Margaret Glasscoe\textsuperscript{2}, Brendan Crowell\textsuperscript{3}

\textsuperscript{1}Scripps Institution of Oceanography
\textsuperscript{2}Jet Propulsion Laboratory
\textsuperscript{3}University of Washington

G42A-02 Time-Dependent Deformation in Geodetic Data: Advances in Detection, Modeling, and Interpretation I
2016 Fall AGU Meeting, San Francisco
December 15, 2016
Postseismic Deformation
\[ \sum_{j=1}^{n_k} k_j \left(1 - e^{-\frac{(t_i - T_{kj})}{\tau_j}}\right) H(t_i - T_{kj}) \]

Exponential ("EXP") – mantle process

\[ \sum_{j=1}^{n_k} k_j \log \left(1 + \frac{t_i - T_{kj}}{\tau_j}\right) H(t_i - T_{kj}) \]

Logarithmic ("LOG") – afterslip, fault-process

\[ \sum_{j=1}^{n_k} \left[1 - \frac{2}{\alpha} \coth^{-1} \left(\frac{t_i - T_{ij}}{e^{\tau_j / \alpha}}\right)\right] H(t_i - T_{kj}) \]

Velocity Strengthening ("COTH"), fault-process

Maxwell Rheology, multi-layer (Devries, Meade 2013)

Burgers Rheology (Wang, Hu, He 2012)

Rate- and State-Dependent Friction (Jiang, Lapusta 2016)
Global & Regional Continuous GNSS Stations Analyzed by SESES
Fault Mechanisms for Earthquakes with Modeled Postseismic Motions
Estimation of Postseismic Parameters through Principal Component Analysis

- Identification Global CMT
- Interpolate Gaps
- Extract Time Series Residuals
- Principal Component Analysis (PCA)
- Iterate Time Constant
  - Apply to All Stations
- Re-estimate velocities & offsets
- Apply Optimal Model to Time Series
  - Post GPS Explorer

Mw 9.0 Tohoku-oki
(2011-03-11)
Postseismic Deformation – 2011 Mw9.0 Tohoku-oki earthquake

Velocity of TSKB

- $k = -32.25$ (log)
- $k = -81.44$ (exp)
- $k = -154.13$ (coth)

Log decay 131 days

- $k = 130.41$ (log)
- $k = 329.17$ (exp)
- $k = 623.61$ (coth)

- $k = 27.18$ (log)
- $k = 68.97$ (exp)
- $k = 129.96$ (coth)
Postseismic Deformation – 2004 Mw6.0 Parkfield Earthquake

LOG
First Mode 96.4%

EXP
First Mode 86.2%

COTH
First Mode 95.1%

RMS = 1.9

RMS = 4.0

RMS = 1.6

Agrees with result of Barbot, Fialko, Bock, 2008 with 3 years of data
Postseismic Deformation – 1991 Mw7.1 Hector Mine Earthquake

M7.1 Hector Mine earthquake, Oct 16, 1991

Log decay time for Hector Mine earthquake (days)

<table>
<thead>
<tr>
<th>Fault Parallel Distance (km)</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>28</td>
<td>28</td>
<td>25</td>
<td>29</td>
<td>37</td>
</tr>
<tr>
<td>200</td>
<td>175</td>
<td>156</td>
<td>199</td>
<td>177</td>
<td>172</td>
</tr>
<tr>
<td>300</td>
<td>271</td>
<td>225</td>
<td>278</td>
<td>253</td>
<td>245</td>
</tr>
<tr>
<td>400</td>
<td>693</td>
<td>474</td>
<td>628</td>
<td>542</td>
<td>506</td>
</tr>
<tr>
<td>500</td>
<td>1,047</td>
<td>794</td>
<td>856</td>
<td>625</td>
<td>580</td>
</tr>
<tr>
<td>600</td>
<td>976</td>
<td>792</td>
<td>816</td>
<td>632</td>
<td>541</td>
</tr>
</tbody>
</table>
ETS
Examine time-dependent episodic tremor and slow slip in Cascadia subduction zone

- Conventional view of episodic tremor and slip (ETS): slip always accompanied by tremor but not vice versa. Tremor as proxy of slip

- Recent “Tremorless” slip as reported by Bartlow and Welch [2014]

- Examine how slow slip and tremor relate using SESES combined time series and time-dependent slip inversion

- Report results on automated SSE detection, time series modeling and slip/tremor investigation for selected event
A relative strength index (RSI) based transient detection approach

- Use SESES filtered, cleaned detrended time series
- Single station based approach
- Employ financial momentum oscillator RSI to detect deviation above normal variance for E, N, U components
- Use Kurtosis minimization to quantify transient probability

The size of the circles are the normalized average transient probability.

Crowell, Bock, Liu [JGR 2016, in press]
Time Series Modeling

- Initial ETS time based on RSI detection and visual examination

- We perform a grid search to identify the optimal centroid time ($t_j$) and duration ($\tau_j$) for each ETS event

- Long time span of time series reduces potential trade-off between seasonal terms and transient signals

- Time series that remove inter-ETS velocities, seasonal and offset are used in the modeling

\[
d(t) = a + v \cdot t + c \cdot \sin(2\pi t) + d \cdot \cos(2\pi t) + e \cdot \sin(4\pi t) + f \cdot \cos(4\pi t) + \sum_{i=1}^{m} g_i \cdot H(t - t_i) + \sum_{j=1}^{n} h_j \cdot (1 + \tanh \left( \frac{t - t_j}{\tau_j} \right))
\]
Considerable variability in surface deformation patterns are observed for recurrent SSEs, indicating the complexity of transient source.
Time dependent slip modeling of 2011/06-2011/09 ETS event

- Time-dependent kalman filter approach [McGuire & Segall, 2013; Liu et al., 2015]
- Migrating event with a duration of ~3 months
- Complex slip with and without tremor

Total displacement

Model fit to data at selected station (magenta box, left panel)

Red dashed line: model; Black dots: data
Spatiotemporal slip history of 2011 June-Sept. ETS event

- 2011 June ETS event initiated at the central margin and migrate towards the north.

- There appears “tremorless” slip period of ~2011/07/12 to 2011/07/24

- Tremor tends to overlap high slip area but also occur downdip of high slip or moving slip front at different stages of slip evolution

- Similar “tremorless” slip was also observed in 2014 November event [Liu et al., 2015], prompting revisit of conventional view of “ETS” and its underlying mechanism
Conclusions

• NASA SESES project maintains dynamic reference system based on weekly updated combined JPL and SIO displacement time series

• The SESES time series of ~2500 regional and global stations includes rigorous quality control

• The SESES Earth Science Data Records (ESDRs) are a starting point for analysis of transient deformation (gave examples of postseismic and ETS)

• ESDRs can be found at SOPAC archive and NASA’s CDDIS