Introduction

Over the past decade the number and size of continuously operating Global Positioning System (GPS) networks has grown substantially world-wide. A steadily increasing volume of freely-available GPS measurements, combined with the application of new approaches for mining these data for signals of interest, has led to the identification of a large and diverse collection of time-varying Earth processes.

The characteristics of transient slip events along fault zones, in particular their timing, duration, and magnitude, have yet to be fully understood in the context of how they affect stress release along faults over the course of the full seismic cycle. Quantifying the potential of such events to affect the likelihood of subsequent earthquakes is an area of ongoing investigation and has important implications for operational earthquake forecasting. While precursory signals have not yet been consistently recorded preceding large earthquakes in nature laboratory observations, combined with evidence for the self-similarity of earthquakes spanning several orders of magnitude, suggest that ongoing monitoring for and investigation of transient motion should be implemented.

Southern California, like many seismically-active areas worldwide, is now home to a large number of continuously recording GPS instruments. These data provide the opportunity to observe and track transient deformation in detail, should it occur, enabling further investigation of fault processes and perhaps informing short-term earthquake forecasts. At the current time, a coordinated and comprehensive geodetic monitoring system is not in place in Southern California, despite the high density of urban development, active faults, and potentially high reward for the identification of fault behaviors that may foreshadow a damaging earthquake. As the number of continuously recording geodetic networks that contain hundreds of stations grows, it becomes less feasible to analyze the ever-expanding volume of data without the use of systematic search tools that require little or no user input. The time is ripe to implement ongoing monitoring for anomalous ground deformation signals.

To address this need, the Southern California Earthquake Center (SCEC) community has supported an effort to establish operational capability for detecting transient signals using the dense network of continuous GPS observations now available in Southern California. SCEC has long been involved in the development of geodetic infrastructure for Southern California through its role in establishing the Southern California Integrated GPS Network (SCIGN) as well as through ongoing efforts supporting basic research that relies on the resulting data.

The SCEC automated transient detection effort began with a community blind test exercise focused on detecting transients in synthetic data and now is in a phase where the most successful and easy to implement algorithms can operate on a daily basis using real GPS data. Below, we summarize the setting and input for the blind test exercise and describe the suite of approaches that researchers explored during the test exercise. A key outcome of this year’s work has been the generation of a special section in SRL devoted to the blind test exercise.

Background

The development of automated transient detection algorithms has many aspects in common with operational earthquake forecasting (OEF). The goal of OEF is to use physical and statistical models, along with data from seismic networks, to quantify short-term regional earthquake probability gains relative to the long-term time-independent hazard forecast for a location (e.g., Jordan and Jones, 2010). In both OEF and transient detection, while retrospective tests are valuable for algorithm development, ultimately they must be tested prospectively on real data. Likewise, the two efforts confront similar difficulties, such as the short time span covered by available data relative to the recurrence interval of moderate to large earthquakes, continuous updating of algorithms by individual research groups, and the lack of quantitative methods for evaluating the quality of a detection. Despite these obstacles, the Collaboratory for the Study of Earthquake Predictability (CSEP) has established protocols for the evaluation of earthquake forecasting approaches (Zechar *et al.*, 2010), suggesting that other efforts, such as the detection of crustal strain transients, may also benefit from a rigorous testing environment.

One major issue with the implementation of operational geodetic transient detection is that, unlike with earthquake forecasting, there is no clear strategy for assessing the significance of an individual detected event. The time of occurrence, location, and magnitude of an earthquake can be objectively measured using seismic data, and as a result an earthquake forecast can be readily tested. False positives, false negatives, and correct forecasts can be easily delineated because the earthquake either will or will not occur within the forecast time window and geographic region. In contrast, similar ground truth for a detected transient signal is lacking. Determinations of the onset time, geographic extent, and amplitude of a transient signal are generally model-dependent. A second layer of complexity arises because time-varying geodetic signals may occur for a variety of reasons including tectonically driven processes such as fault slip, anthropogenic extraction or recharge of subsurface fluids, seasonal effects, local noise sources, or site-specific hardware problems, not all of which may be of interest. Therefore, in addition to evaluating whether an algorithm correctly detected a transient signal, the context in which that algorithm will be used becomes important, and a given algorithm may be better suited to one type of application than to another.

For these reasons, as a first step the SCEC Tectonic Geodesy disciplinary group organized a blind test exercise where the true signals would be known to the organizer, allowing detections to be reliably assessed and the frequency of false positives and negatives quantified. The characteristics of the true signals spanned a range of processes likely to be observed and of interest including short and long-term slow slip signals, seasonal and common mode errors, and earthquakes. The blind test effort laid the groundwork for operational deployment of detection algorithms using real data.

Blind Test Exercise

Through a series of workshops and online, we provided four test phases, each with multiple (4-18) independent datasets. The synthetic geodetic data were generated using the Fakenet software developed for this project by Agnew (2013). This software allowed the inclusion of increasingly sophisticated transient behavior with each test phase and contamination of the synthetic data with realistic noise (Figure 1). The final phase also included a real dataset. Based on discussions with leaders of other similar exercises, such as the SCEC-sponsored rupture propagation code validation (Harris *et al.*, 2009), source inversion blind test (Page *et al.*, 2011), and Regional Earthquake Likelihood Models (RELM) projects (Field, 2007), it was clear that such efforts are most successful when they begin with very simple analogs to the target problem.

One of the key principles guiding organization of the transient detection exercise was that no approach to the problem should be discouraged simply because it did not meet a particular set of pre-conceived guidelines. For example, while one obvious goal of transient detection is to identify slip on faults, many of the detection methodologies were based on characteristics of the GPS signal rather than on the possible sources that could generate that signal. Therefore, participants could submit their detections in the form of either inferred time-evolution of slip on a fault plane, a description of the geographic and temporal extent of the transient surface deformation signal, or both.

Transient detection methods used by the participants spanned a wide range, including:

- Visual inspection of the raw time series and/or the signal to noise ratio (SNR) over a particular time window
- Time series analysis to flag statistically significant rate changes over a range of spatial and temporal scales in the presence of colored noise (e.g., Langbein, 2004)
- Fitting of a predetermined number of piecewise linear segments to the data at each site, and then identifying spatial and temporal correlations between the segments at surrounding sites (e.g., Zaliapin *et al.*, 2004)
- Application of image processing techniques to detect spatially and temporally coherent anomalies in time series (e.g., Granat *et al.*, 2013)
- Principle component analysis of the dataset, either with or without spatial and temporal filtering (e.g., Dong *et al.*, 2006; Ji and Herring, 2011, 2013; Granat *et al.*, 2013; Lipovsky and Funning, 2009)
- Application of Kalman filtering, with spatial basis functions based either on known faults (e.g., Segall and Matthews, 1997; Fukuda *et al.*, 2008) or on smooth functions with a range of scales (e.g., Ohtani *et al.*, 2010; Tape *et al.*, 2009)
- Modeling of the spatial strain field and the significance of its temporal variations (e.g., Holt and Shcherbenko 2013)

Each of these methods, in some sense, had the goal of detecting anomalous features of the data that exhibited spatial and/or temporal coherence to differentiate them from conditions that may affect a single geodetic benchmark or arise from occasional short-lived noise. Many had an initial stage of removing a linear model of secular motion and/or seasonal deformation (often represented by an annual and semiannual sinusoid) from each time series before processing. The approaches that simultaneously relied on spatial and temporal information were the most successful and robust in the presence of outliers. The approaches with the greatest potential for automation within a system for operational transient detection were those that easily incorporated new data and employed a metric for objectively flagging transients based on threshold values.

The larger displacement signals (Figure 1A, B) resulted in positive detections and good recovery of the spatial and temporal features of the actual transient displacement by most methods. However, many of the smaller synthetic signals were below the detection threshold of the algorithms being tested (Figure 1C). Some pitfalls identified during the testing process are relatively obvious – it is difficult for any algorithm to identify transients that have low signal-to-noise ratio or timescales that are similar to the length of time spanned by the available data, and when multiple transients occur it can be impossible for methods that are seeking the largest signal, by some metric, to identify all of them. However, different approaches can have complementary strengths and weaknesses. It is likely that a combination of multiple detection methods, running in parallel, will provide the most complete image of transients occurring across Southern California as a whole.

Operational Transient Detection System Components

While the blind test phases of this validation exercise focused on development of geodetic transient detection tools, the longer term goal is for such tools to be used operationally. We have begun to implement a system for testing continuously operating automated transient detection algorithms modeled after that of CSEP (Zechar *et al.*, 2010). CSEP has four main components designed to foster reproducibility of results: testing centers that use accepted protocols for running and evaluating algorithms; agreed-upon standards for input, output, and assessment of results; testing regions chosen to have sufficient, community-accepted data sets to be useful for experiments; and protocols for communicating results to the prospective users, including the public.

A testing framework for transient detection algorithms will have components that follow from the CSEP model, namely:

- *A community testing center where the individual algorithm codes can be housed, compiled and tested*

  Within the framework of the test center, participants' codes will run automatically. Participants will write their algorithms in a programming language of their choice and then provide an executable which will accept input and return results in the agreed-upon formats. Participants will have access to the development system for testing their code in continuously operating mode before automatic deployment, but once the code is running automatically participants will not be able to intervene. Improvements to the algorithms will be uploaded as new versions of the code.
- *Automatic download of daily GPS solutions from a source agreed upon by the participants*

  Both the Plate Boundary Observatory (PBO; Silver, 2000; http://pbo.unavco.org/) and NASA MEaSUREs solutions provided through the Scripps Orbit and Permanent Array Center (SOPAC)/Jet Propulsion Laboratory GPS explorer program (http://geoapp03.ucsd.edu/gridsphere/gridsphere) are already produced on a regular basis and widely used by the Earth sciences geodesy community. The current testing center provides the PBO Stable North American Reference Frame (SNARF) solution, version 1.0, available at ftp://data-out.unavco.org/pub/products/position/pbo.snf01.pos.tar.gz. A current earthquake catalog from the Global Centroid Moment Tensor (GCMT; Ekström *et al.*, 2012) project is also available.

- *Standardized formats for the detection results of each algorithm*

  Algorithm output may include a binary yes/no detection for the test region on a daily or weekly basis, and/or more detailed information such as the spatial extent of the detected signal and its onset time. Our system uses this information to automatically generate a summary of each algorithm's results (including a map depicting locations of detected signals) and emails this to the participants.
- *An agreed upon testing region*

  The testing region for this exercise is all of California, but the system allows user-based subsetting of the region (e.g., a participant can decide to mask out data in part of the region, or apply the algorithm to a subregion of interest).
- *A communication plan*

  At this stage, information regarding transients detected by the algorithms is only provided to test exercise participants. In the future, after thorough testing, we will determine in what form such information will be disseminated to a wider audience including government agencies that will respond to events and the public.

As noted earlier, there is no objective ground truth against which to evaluate detections made using real data. Thus far, alerts generated by algorithms that are running in the prospective transient detection testing center are sent to the respective method developers who can inspect them and assess their validity. This is, in some respects, similar to a way in which detection methods are likely to be used in an operational setting: to alert scientists to look more closely at data from a certain region. However, more systematic testing of detections could be achieved by comparison of results from different algorithms to see if several methods flag anomalies at the same place and time, and by correlating detected geodetic signals with seismicity patterns. As geodetic transient detection methods mature, a logical next step would be to extend algorithms to identify likely transient sources or to incorporate calculation of short-term earthquake probability changes; the transient detection testing center could facilitate these efforts. Enforcing standardized input and output and providing automated reporting of results permits many more realizations of tests, whether with real or synthetic data, to expand upon the findings from the blind-test phases already completed. This will allow better understanding of the algorithms' capabilities in different situations and the likelihood of false positives (or negatives), as well as tuning for the ability to detect transient events with particular sets of characteristics. Tests with real data could also be used to provide an empirical basis for relating transient signals to earthquake probability.

To help participants adapt their codes to the automated prospective testing system we have provided example code that reads the input GPS data in the format supported by the test exercise, applies a very simple detection algorithm (e.g., does the signal at any station exceed that predicted from the long-term rate at a specified confidence level), and produces the standardized outputs required by the testing center. Inclusion of algorithms in the operational test center is not restricted to those which underwent initial testing in the blind test phases of the exercise. New participants, or those who wish to further develop their existing approaches, may utilize the archived test data sets or generate their own synthetic data using the Fakenet (Agnew, 2013) software package described in this special section.

Conclusions

The articles collected in this special section span a range of topics that includes the generation of synthetic GPS data with realistic noise and transient deformation signals (Agnew, 2013), to two very different approaches for identifying transients within a given set of GPS data. Ji and Herring (2013) present details of their approach, which relies on principle component analysis of filtered time series and has been applied to data outside of Southern California (Ji and Herring, 2011). Granat et al (2013) present results of three separate detection approaches applied to the synthetic data, all based on spatial and temporal coherence of the signals instead of relying on a physical model for the underlying deformation. Holt and Shcherbenko (2013) describe an approach for detection of transients that seeks to identify time-varying patterns in the strain rate field derived from GPS data. Future efforts may evolve to focus on fault-related deformation events, but there may be equal or greater interest in the characteristics of deformation features related to the hydrologic cycle and the extraction and injection of subsurface fluids.

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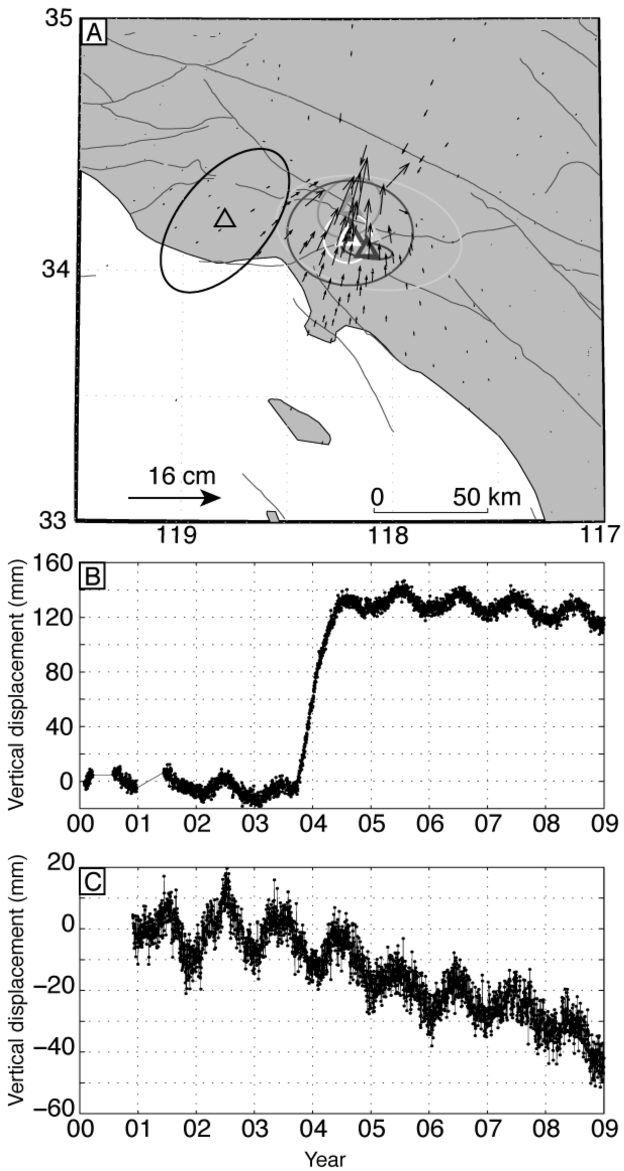

Figure 1: Example dataset from Phase IIa (003923). A) Map view of the predicted horizontal deformation that occurred during the transient event (vectors). Triangles and associated ellipses indicate the location and deforming region found by each participant that analyzed this particular dataset. B) Vertical displacement time history at station with maximum displacement, showing the large magnitude of the signal (detectable by eye). C) Vertical displacement time history for a more challenging time series (001253), that resulted in zero detections by the group of participants.

Intellectual merit and broader impacts

This work is critical to efforts aimed at establishing a system of automated detection of potential geodetic transients in Southern California. While the most obvious application of such a detection system is the characterization of seismic hazard, it also may have the side benefit of enabling better characterization of hydrologic signals. The applications to seismic hazard and anthropogenic deformations also constitute the broader impacts of this study.

Publications/presentations

This work has resulted in a special section of SRL, with four papers in addition to an introduction paper by the PI, now in press.