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Time-Varying Deformation and Slip in the Eastern Bay Area from Two Decades of InSAR and GPS Data

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Abstract

In the course of this project we analyzed and modeled two decades of regional crustal deformation data in the San Francisco Bay region, with a focus on investigating time dependent processes on the Hayward fault in the Eastern Bay Area. This work builds on progress made during several years of NEHRP funded research and addresses the seismic potential and natural hazard presented by major faults in the San Francisco Bay Area through the use of space geodesy. Geodetic measurements provide information on the nature of elastic strain accumulation about seismogenic faults, their locking depth and slip rates, and any variations of those parameters in space and time due to time-dependent deformation processes.

A total of 831 interferograms were processed from 102 images collected between 1992 and 2011 by the ERS1, ERS2 and Envisat satellites. These are combined into a time series of surface range change using a method to identify stable pixels based on the phase noise estimated using wavelet analysis. The time history of creep on Hayward fault is then obtained by time-dependent joint inversion of the InSAR range change time series, surface creep data from alinement arrays and characteristically repeating earthquakes (CREs). The resulting time series of creep resolves long term features, such as a persistent large locked asperity on the Hayward fault near Oakland, that has been observed in non-time dependent creep inversions. It also resolves short term transient features, such as the 1996 slow slip event on the Hayward fault near Fremont and suggests a number of other significant variations in creep with time.
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This project addresses the seismic potential and natural hazard presented by major faults in the Eastern San Francisco Bay Area through the use of space-geodetic surface deformation measurements. We build on progress made during several years of NEHRP funded research, this time focusing on the time-variability of deformation as constrained by Global Positioning System (GPS) data and newly processed time series of Interferometric Synthetic Aperture Radar (InSAR) measurements. Geodetic measurements provide information on the nature of elastic strain accumulation about seismogenic faults, their locking depth and slip rates, and any variations of those parameters in space and time due to time-dependent processes. These data, collected by many groups, have been used in a large number of studies aimed at a better understanding of the nature and rates of active strain accumulation in the Bay Area [e.g. Murray and Segall, 2001; Prescott et al., 2001; Parsons, 2002; Manaker et al., 2003; Pollitz, 2004; Pollitz and Nyst, 2004; Savage, 2004; d'Alessio et al., 2005; Johanson and Bürgmann, 2005; Schmidt et al., 2005; Bürgmann et al., 2006; Johanson et al., 2006; Johnson, 2006; Funning et al., 2007; Ryder and Bürgmann, 2008; Jolivet et al., 2009]. These studies improved our estimates of slip rates on individual faults, the distribution of locked and creeping segments at depth, and the role of viscous processes at depth in the evolution of active deformation through the earthquake cycles of Bay area faults.

Assessment of earthquake potential along Bay Area faults is complicated by the recognition that the system is not static, but rather strain rates vary through time in response to a variety of phenomena. These can range from the small and quick, such as slow slip events (SSEs) to the large and protracted, such as viscous relaxation following the 1989 Loma Prieta or 1906 San Francisco earthquakes [e.g. Pollitz et al., 1998; Kenner and Segall, 2003; Pollitz and Nyst,
Time-variable strain affects hazard estimates in three ways. First, it changes our estimate of a fault’s slip budget when we realize that strain accumulation and creep rates are not steady over the entire earthquake cycle. Secondly, time-variable strain introduces changes in stress rate on individual fault segments that could have consequences for earthquake timing either through stress shadowing or event triggering [Dragert et al., 2001; Pollitz and Nyst, 2004]. Finally, characterizing the kinematics of time variable strain and fault slip leads to better constraints on earth structure and fault frictional parameters, which inform a variety of models, from those spanning multiple earthquake cycles to dynamic rupture models. Hayward fault monitoring by creepmeter, strainmeter and alinement array has detected a number of variations in creep rate on the Hayward fault [Bilham and Whitehead, 1997; Galehouse and Lienkaemper, 2003; McFarland et al., 2009]. The largest in 1996, when an alinement array survey detected a SSE that produced 18 mm of fault creep within at most 63 days [Lienkaemper et al., 1997]. The SSE also marked a change in longer-term creep rate, from nearly zero post-Loma Prieta to 3.9 mm/yr, still lower than the pre-Loma Prieta rate of ~9 mm/yr [Galehouse and Lienkaemper, 2003]. More recent alinement array surveys (since 2006) show an increased in creep rates on the southern Hayward fault by ~2-5 mm/yr over the long term average [Lienkaemper et al., 2011]. These events illustrate how the Hayward fault is capable of changes in creep rates on several time scales.

GPS has been the primary tool for crustal deformation measurements in the region since the early 1990s, providing mm-level precise measurements of motion in three dimensions at a relatively sparse number of locations. InSAR data provide dense spatial coverage, which makes them particularly valuable for resolving fine-scale deformation features and vertical motions, though orbit uncertainties can limit its usefulness for large, low-gradient deformation. InSAR range-change data, in conjunction with GPS surface velocities and the distribution and rate of repeating micro-earthquakes, have been used to estimate the creep distribution on the upper 12 km of the Hayward fault using dislocation modeling [e.g. Bürgmann, 2000; Schmidt et al., 2005]. Improved InSAR processing techniques relying on permanent-scatterer properties of isolated, stable points [e.g. Ferretti et al., 2004] allow for better coverage alongside Bay area faults and improve our ability to determine the subsurface slip distribution when combined with GPS velocities. To date, we have explored regional deformation and fault slip-rate estimates [d’Alessio et al., 2005] separately from focused analyses of elastic coupling along individual fault sections of the Rodgers Creek [Funning et al., 2007], Hayward [Schmidt et al., 2005], Calaveras [Manaker et al., 2003], and San Andreas [Johanson and Bürgmann, 2005; Ryder and Bürgmann, 2008] faults. A key goal of this project is to fully integrate the time-dependent analysis of regional fault slip rates and distribution of creeping and locked areas of faults in the eastern San Francisco Bay area, with a primary focus on developing a time dependent GPS and InSAR dataset spanning two decades and inverting the data for time dependent slip at depth.

**Geodetic Monitoring of Active Bay Area Deformation**

Imaging strain accumulation about faults with sufficient precision and spatio-temporal resolution is a difficult task, plagued especially by limits in the accuracy and spatial density of the surface measurements. This project incorporates time series processing of InSAR data that will span 19 years by 2011 and draws data from three satellites, together with 18 years of GPS acquisitions processed in a consistent manner to form BAVU (Figure 1). BAVU is a mix of campaign mode (SGPS) yearly GPS measurements and data from continuously operating GPS stations (CGPS). The sparsely distributed, but continuously operating CGPS BARD and PBO networks provide a
precise 3D geodetic framework with high temporal resolution. Repeated campaign GPS measurements in the Bay Area by our group and data obtained by the USGS provide some densification.

Data collected by InSAR satellites since 1992 form a valuable complement to the GPS measurements. Interferograms provide denser coverage and the data are often acquired routinely at monthly intervals. Traditional InSAR uses data from two passes of the SAR satellite (two scenes) to form an interferogram that represents the sum total of all the deformation that occurred in the intervening time. However, newer time series methods for InSAR, such as the Permanent Scatterer (PS) method or the SBAS approach, use multiple interferograms to construct a time series of deformation measurements for individual points and with time sampling of the satellite repeat time. One of the benefits of a time series approach is that it readily lends itself to temporal filtering, mitigating the effects of atmospheric noise, which is a significant error source in traditional InSAR. It can also more clearly delineate time dependent deformation and facilitates time-variable deformation models. PS-InSAR has been used successfully in the Bay Area to detect and model time dependent motion on landslides in the Berkeley Hills and creep on the Concord fault [Colesanti et al., 2003; Hilley et al., 2004]. However, the method uses an a priori model of the expected time dependence to separate deformation from atmospheric effects. This produces good results for deformation signals that are well characterized by other means, but can miss unexpected or non-steady deformation transients. Both SBAS and the wavelet-based method used here, use no a priori deformation model. While this can cause more scatter in the results, it can also capture more variation in ground motion.

**BAVU – Bay Area Velocity Unification**

Our GPS analysis relies on the GAMIT/GLOBK processing and analysis system developed at the Massachusetts Institute of Technology [Herring et al., 2010a; 2010b]. We combine daily ambiguity-fixed, loosely constrained solutions using the Kalman filter approach implemented by GLOBK [Herring et al., 2010b]. For Version 3.0β, we include data processed locally as well as solutions for the IGS, PBO and BARD networks processed by SOPAC at the Scripps Institution of Oceanography (http://sopac.ucsd.edu/). Using the Kalman filter, we combine all daily solutions to generate an average solution for each month, giving each observation equal weight. The final positions and velocities are fixed to the ITRF2005 global reference frame [Altamimi et al., 2007]. Average linear velocities for each station are estimated from the monthly files. One benefit of this data analysis approach lies in the increased ease in which the processing can be integrated with data products from the regional BARD and PBO GPS sites and the global IGS network, which significantly improves the reference stability and also the precision of our velocities. We continue to streamline and automate the BAVU processing scripts, which cover all the steps from data download to production and posting of time series and velocity tables and maps.

In official BAVU releases, the errors are scaled following the method used by the Southern California Earthquake Center's Crustal Motion Map team (SCEC CMM 3.0). White noise is added to the formal uncertainties of all stations with a magnitude of 2 mm/yr for the horizontal components and 5 mm/yr for the vertical component. Additionally, 1 mm yr$^{1/2}$ of Markov process noise is added to account for “benchmark wobble. For Version 3.0β an abbreviated process is used, and the uncertainties shown in Figure 1 are 1σ uncertainties in the line fits to the station time series. For Figure 1 a local reference frame is used, centered around station LUTZ (a BARD CGPS site on the Bay Block).
Figure 1. (A) The BAVU 3.0β velocity field (preliminary) referenced to local site (LUTZ) on the central Bay Block spanning 1992-2010. (B) Detail of complex deformation in the Southern Bay Area, at the junctions of the San Andreas, Calaveras and Hayward faults.

Figure 2: The LOS velocity from 1992-2010 InSAR time series before removing the regional trend. Red and blue colors indicate movement toward and away from the satellite, respectively. The satellite incidence angle and heading angles are 23° and 188°.
**Figure 3:** Time slices from the time-variable slip inversion of InSAR and alinement array data. Blue dots are the locations of background seismicity. Slip shown is cumulative.

**Figure 4:** Slip inferred from the time-variable slip inversion of InSAR and alinement array data for the time of the (A) 1996 creep transient near Fremont (data spanning 11/10/95-03/29/96) and (B) the 2007 creep transient following the M 4.2 July 20th earthquake near Oakland (data spanning 12/23/06-08/25/07). Blue dots are the locations of background seismicity during the respective time intervals.

**Modeling Time Variable Fault Slip from InSAR data**

In work done by post-doc Manoochehr Shirzaei, we extend the analysis of transient slip on East Bay Area faults to include 18 years of InSAR data collected by the ERS-1, ERS-2 and Envisat satellites. A total of 831 interferograms were processed from 102 images collected between 1992 and 2011. These are processed into a time series of surface range change (Figure 2) and used as input in the time-variable modeling (Figure 3). The time history of creep on Hayward fault is obtained by time-dependent joint inversion of the InSAR time series and surface creep data. To this aim we employ a method consisting two main operators: (i) a L1-norm minimization operator and (ii) a recursive filter, Kalman Filter (KF), to generate time series of the creep. These two operators are combined in an iterative manner [Shirzaei and Walter, 2010]. Figure 3 summarizes the results of the time-variable slip modeling, by showing time slices of cumulative slip from 1992 to 2010.

The InSAR data are complemented by constraints from characteristically repeating earthquakes (CREs) on the Hayward fault. CREs are a group of events that have nearly identical waveforms (e.g., with a cross-correlation coefficients \( \geq 0.95 \)) and that have hypocenters that are coincident to resolutions of a few meters. The location, magnitude and recurrence interval properties of the sequences are used to infer the spatial and temporal distribution of deep aseis-
mic slip rates. Using the Northern California Seismic System earthquake catalog, collaborator Taka’aki Taira from the Berkeley Seismological Laboratory, brought the set of 97 CREs used by Schmidt et al. (2005) up to date by identifying new occurrences up to 2009. We also identified ~30 new sequences along the Hayward fault (Figure 5).

The slip history identifies the distribution of slip from the large 1996 creep transient near Fremont (Figure 4A) and suggests a number of other significant variations of creep with time. The slip transient following the July 20th 2007 M 4.2 earthquake (Figure 4B) is not well resolved in the InSAR data alone.

Figure 5A shows the average rate of creep in comparison with seismicity and the distribution of repeating micro-earthquakes. Similar to the models of Schmidt et al. [2005] and Funning et al. (in prep), there is a large low-creep/high-coupling asperity in a deep-seated portion of the fault between Oakland and Fremont. This asperity has a lack of repeating events, which also suggests a high degree of fault coupling.

In October 2011, a series of three M>3 earthquakes occurred on the Hayward fault under Berkeley (Figure 5A, green squares). The sequence eventually included 27 events in the ~1-month period following the Mw 3.95 event. Based on the occurrence of CREs, creep rates in the vicinity of the events increased from 5 mm/year to 10 mm/year beginning approximately 250 days before the earthquake series. Additionally, there is a marked increase of creep rate following the mainshock for about 100 days to as much as 40 mm/yr. Shirzaei et al. [2012] found that these creep rate changes affected the stress state of the surrounding fault by as much as the earthquakes.
and contributed to the 0.15% increase in the 1-day probability of a major Hayward fault event that this earthquake sequence caused.

The InSAR derived slip model also shows that these events were located in a patch of high coupling bordered by two high-creep zones. Similarly to how fault creep regulates the occurrence of CREs (though on a smaller scale), the fault creep focuses stress on the intervening “stuck patch”, leading to both the 2011 earthquake series and a similar series in 2006-07. Such an earthquake swarm and associated slow-slip transient near the edge of the primary locked zone represent a possible nucleation scenario of a larger 1868-like Hayward fault event.

This project addresses the seismic potential and natural hazard presented by a major fault in the Eastern San Francisco Bay Area through the use of space-geodetic surface deformation measurements and CREs. We build on progress made during several years of NEHRP funded research, focusing on the time-variability of deformation and seek to improve our estimates of slip rates on individual faults and of the distribution of locked and creeping segments at depth, with a view towards enhancing our overall knowledge of the evolution of active deformation through the earthquake cycle of the Hayward fault.

References


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**Publications from this work**
