

2014 SCEC Project Report

Project # 14127

Contributions to the CGM and non-secular motion representation

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Abstract

We are undertaking the tasks of collating, analysing and combining processed time series to produce Community Geodetic Model (CGM) final products. This necessarily includes formalizing metadata documentation formats for distribution in the eventual CGM. We are also exploring advanced techniques for determining the variable nature of seasonal fluctuations in geodetic time series, as well as accounting for correlations between components and sites. Lastly, we have started to investigate techniques for the consistent and precise recovery of secular velocities in the presence of time-dependent deformation such as post-seismic decays. This is especially important but challenging in the case of little or no pre-earthquake data, such as for the 1992 Landers, 1994 Northridge and 1999 Hector Mine earthquakes. Accurate recovery of secular geodetic velocities requires accounting for on-going post-seismic motions, such as after the Parkfield, El Major-Cucapah and South Napa earthquakes, even where pre-earthquake data are available so that newer data may be incorporated into on-going motion estimates.

Technical Report

Community Geodetic Model GPS time series analysis

We have provided information to SCEC community members partaking in GPS measurements regarding survey sites with only one or two previous measurements and a long period since last observation. These have acted as primary targets for the SCEC community to form relevant and immediate-impact proposals in several areas of interest. We have engaged in other activities of the Community Geodetic Model (CGM) GPS Working Group, including attending group workshops at the SCEC Annual Meeting. We have initiated the comprehensive compilation of survey GPS measurements in southern California and beyond, which involves coordination between data collectors and current archivists to streamline data availability for processing institutions engaged in producing results for the CGM.

We have implemented algorithms capable of ingesting standard forms of GPS results (time series and velocity solutions) from SCEC working groups and converting them to UNAVCO's Plate Boundary Observatory (PBO) format (e.g. <http://www.unavco.org/projects/major-projects/pbo/pbo.html#documentation>). Specifically, we now have the capability to difference or average time series to perform first-order comparisons. This was demonstrated for several sites in southern California at the CGM Working Group meeting at the 2014 SCEC Annual Meeting. This facilitates collaboration and collation of data products for the CGM and our work.

Examples of the results being evaluated at the moment are shown in Figure 1. Two close sites are shown that illustrate some of the issues we continue to address in our research. The site at the top (P140) clearly shows mean differences between the estimates with the Central Washington University (CWU) solution (blue, GIPSY) being 13 mm below the Jet Propulsion Laboratory (JPL) solution (brown, GIPSY) and the New Mexico Tech (NMT) solution (black, GAMIT) being 7.5 mm below. These large mean differences are seen at only some stations. The lower figure show a nearby site (P276) where the mean differences are less than 3.5 mm, again with CWU differing from the JPL solution more than the NMT one differs. We believe these mean differences arise from local multipath at the sites that propagates into position estimates differently for different analyses due to the methods used to weight data as a function of elevation angle to the satellites. The other aspect that we continue to investigate is the weighting of the individual time series. As can be seen in the top part of Figure 1, the mean of the solution (cyan) closely follows the JPL and USGS solution (which are close to each other). These solutions dominate the estimates of the means because the error bars of the daily position estimates in these time series are smaller than those for the NMT and CWU solutions. These differences arise because of basic differences in the error models, sampling rates used in the analyses, and because the PBO time series have already been reweighted to make the NMT and CWU solutions comparable and to have the error bars that are consistent with the day-to-day scatter of the estimates. Appropriate weighting and correlations will be critical when generating the combined geodetic time series for the Community Geodetic Model (CGM).

The methods we are using were presented at the Community Geodetic Model workshop before the SCEC 2014 Annual Meeting. We discuss those presentations below. Our approach is the same basic methods as used the Plate Boundary Observatory (PBO) combination analysis. PBO uses SINEX files from GAMIT New Mexico Tech analysis and GIPSY Central Washington analysis which are processed separately into a common reference frame and combined to generate the PBO standard product. The NMT SINEX is full covariance matrix with weak site position constraints applied. Earth orientation parameters (EOP) are included in SINEX. The CWU SINEX has no site-to-site covariance elements and the position sigmas are small (1-2 mm). There are no EOP parameters in these files. To "loosen" CWU solutions we apply a translation and rotation covariance matrix thus allowing solutions to implicitly rotate and translate. Although not needed, the same loosening covariance matrixes are applied to the NMT solution as well (the translation loosening useful with orbits fixed).

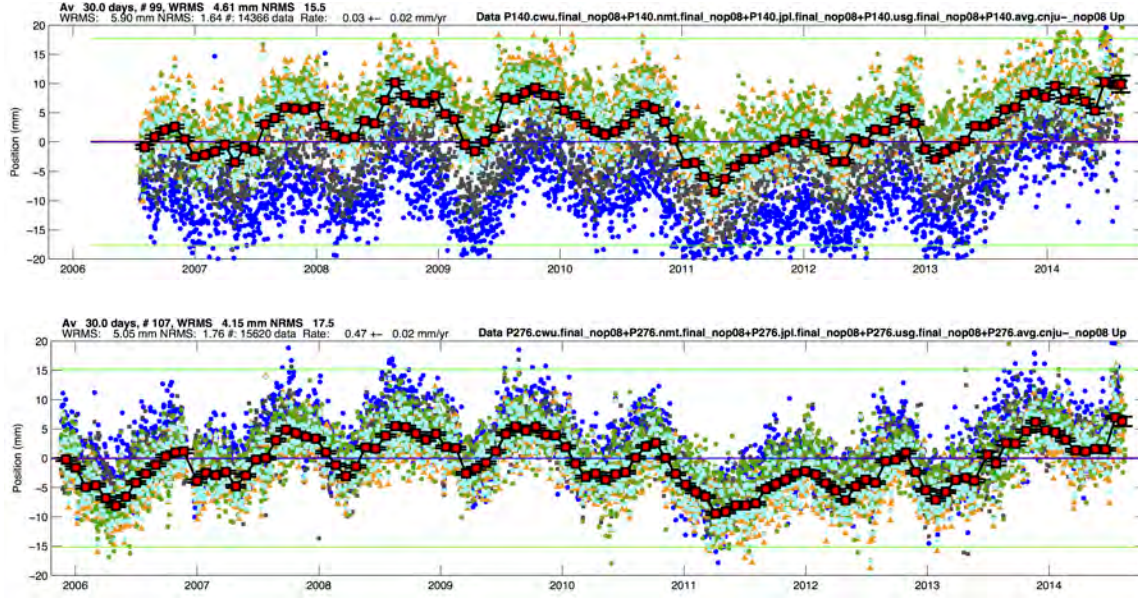


Figure 1: Examples of individual time series in height for two close GPS sites in the PBO array obtained by different analysis groups and the mean of the time series. The analysis centers and colors are: CWU, blue; NMT, black; JPL, brown; USGS, green; and the mean, cyan. The red symbols are 30-day averages. The scales are the same on both figures. All analyses except NMT use the GIPSY processing system. These two sites use the same GPS receiver and antenna types and are only 30km from each. The differences in the average values of the heights for the P140 site are most likely due to systematic local multipath.

Different error models and data sampling rates (2-minutes NMT, 5-minutes CWU) are used by the two analysis centers and the covariance matrices need to be scaled to ensure that each analysis receives and appropriate weight. The scale factors based on the fit to ~ 250 site PBO frame realization sites with the covariance matrices scaled so that the χ^2/f , where f is the degrees of freedom, of the fit to the frame sites is \sim unity. The average values of the variance factors are for NMT 0.7 and for CWU 4.8. When the SINEX files from the two centers are combined, these values are doubled so that all solutions have similar variances. These scale factors have remained constant since 2005. One aspect of the relative weighting is that the elevation angle dependent phase noise model used in the NMT analysis compared to the constant noise model used by CWU results in the heights from NMT analysis getting lower weights relative the horizontal components for most sites.

For each analysis center and the combination we used a reference frame realization based on a hierarchical list of stations on 500 km sided grid over the PBO region (Hawaii, Eastern Russia, Greenland, Caribbean). Some cells have only 1 site, some have none and others have up to 10 sites. The coordinate system is rotated and translated but not scaled to based align the estimated site coordinates with the a priori positions of the chosen reference frame sites on that day. The selection and ordering of the reference frame sites is based on random walk process noise values generated from time series analysis tools in the GAMIT analysis package. The North America frame used (NAM08) is generated by aligning initially to the 21 sites used for plate reference sites in the ITRF2008 plate motion model (Altamimi et al., 2012).

Coordinates and velocities are rotated to North America frame using ITRF2008 North America pole (NAM08). No translation is applied in this transformation and so the NAM08 frame is a center of figure frame as opposed to a center of mass frame.

In order to determine how comparable the GPS times are from different analysis groups, with the ultimate aim of combining the time series from the different groups together, we have been analyzing solutions from different processing groups (see below). For each group, we transform the time series into the PBO NAM08 reference frame using the methods discussed above. Once each time series is in the same reference frame, the time series from each group can be compared and ultimately all groups averaged. In fitting to the time series, we estimate annual sine and cosine terms, some post-seismic logs, offsets for earthquakes, antenna and/or radome changes and offsets that occur for unknown reasons (most often damage to antennas). We also generate IGS08 (no-net-rotation global frame) results by rotating the NAM08 coordinate frame back into the IGS08 frame and aligning the time series to this frame.

One issue we are addressing is the appropriate way of treating scale in the frame transformations. The GPS scale is well determined when the satellite antenna offsets are fixed (as they are in these analyses) and so the standard PBO reference frame is realized through only rotation and translation (no scale). Since scale directly effects heights, some differences in the height behavior between PBO and other analyses, is probably related to treatment of scale. (Most other analyses continue to estimate scale changes even though the scale uncertainty should be small.) In the analyses here, the periodic terms (seasonal signals) are not included in the a priori reference frame site coordinates.

Different analysis groups are contributing the time series being investigated. From PBO, we have the PBO combined series (PBO) and the individual series from NMT and CWU (2079 total sites; 1800-1900 per day currently). The series from University Nevada, Reno (UNR) is available in the UNR North America fixed frame (NA12) and in the IGS08 frame. These series are downloaded via a web interface http://geodesy.unr.edu/gps_timeseries/txyz/NA12/<site>.NA12.txyz2. IGS08 replaces the NA12 part of the URL for the IGS08 version. From JPL we have available time series in the IGS08 reference frame. The FTP URL is ftp://fringe.jpl.nasa.gov/incoming/JPL_xyzts_igs08.tar for all sites processed by JPL. The USGS has a series of tar files for sites in different regions in the IGS08 frame (referred to as ITRF2008 in the file names. For central California the FTP URL is ftp://ehzftp.wr.usgs.gov/svarc/USGS_ITRF2008_CentralCalifornia.tar.gz JPL, as part of the NASA MEASURES project, generates combined (JPL and SIO) solutions that can be downloaded from the MEASURES project site. The latest version we could find for the CGM workshop was (in the IGS08 frame): rawXyzTimeSeries.MEASURES_Combination.20130929.tar. We name this series MEA. We rotate and translate each time series into PBO NAM08 frame (each day align each series). The standard deviations are scaled to make fit to frame have $\chi^2/f \sim 1$ for each of the series.

One of the early realizations from these comparisons was that UNR is using a version of GIPSY that had the wrong sign for the east component of the GPS antenna

phase center model and consequently there a large east differences (up to 10 mm for some specific antennas) for some sites. The frame realization method is also affected by these systematic east differences resulting in them propagating into other sites and components. The UNR solutions will not be usable until the error is corrected in the time series. At the time of these comparisons, the MEASURES Cartesian time series files did not have XY, XZ, YZ correlations and for MEASURES we assume height variance is 10 times greater than horizontal to be able to approximate the effects of these correlations while computing the NEU covariance matrix from the XYZ (initially diagonal) covariance matrix. New versions of the MEASURES time series files have changed the format and added the correlations.

Initially to validate these times series and to see how consistent the position estimates are we generated secular velocity fields (while incorporating other parameters as well) and compared these fields. This comparison allows an assessment of the consistency of the secular temporal variations. Table 1 shows this comparison. In most cases, the median WRMS difference between the velocity fields is <0.1 mm/yr, horizontal, and 0.5 mm/yr vertically. The UNR solutions here are most likely affected by the error in the east coordinates that maps into the time series evolution and reference frame realization.

Soln	#	Horz	Chi	Up	Chi	Solution
		mm/yr		mm/yr		
JPL-PBO	1508	0.09	1.214	0.41	1.256	
CWU-PBO	2056	0.05	0.661	0.24	0.683	
NMT-PBO	2056	0.08	1.011	0.27	0.845	
MEA-PBO	1558	0.11	1.488	0.41	1.288	
UNR-PBO	1994	0.14	1.744	0.61	1.778	
UNR-PBO	2041	0.21	2.638	0.51	1.395	NA12
USGS-PBO	1120	0.07	1.040	0.37	1.243	
CWU-JPL	1499	0.10	1.278	0.44	1.316	
NMT-JPL	1516	0.10	1.303	0.39	1.308	
UNR-JPL	1470	0.13	1.692	0.55	1.725	
MEA-JPL	1471	0.11	1.436	0.35	1.177	
USGS-JPL	1020	0.06	0.966	0.26	0.980	
USGS-JPL	1021	0.08	0.726	0.26	0.787	IGS08

Table 1: Comparison of differences of the secular velocity estimates from the analysis of different analysis groups. The median weighted root-mean-square (WRMS) differences and the square root of c^2/f (Chi) are given for horizontal components (sum of North and East velocities) and the height component. The series are transformed into NAM08 except as noted in the solution column.

We also computed the WRMS scatter of the position estimates to the fit to the model for each of the analyses and these results, for the main PBO sites, are shown in Table 2. (Since each of the analyses uses different sites of varying quality, e.g., PBO and UNR include many lower quality CORS sites, the restriction to primary PBO sites allows the comparison over a similar group of sites.). In general, each of the

analyses in a North America (regional frame) has median WRMS scatters of ~ 1.0 mm for the horizontal components and < 5 mm for the vertical. Results in a global IGS08 reference frame show more scatter because of large scale, not well understood, regional position variations (so called common-mode errors) that are reduced in the regional reference frame realizations.

Center/System	WRMS N	WRMS E	WRMS U	chiN	chiE	chiU	Num
	mm	mm	mm				
CWU	1.0	1.0	4.7	0.44	0.64	0.68	778
JPL	1.0	1.1	3.9	1.19	1.24	1.45	776
MEA	0.7	0.8	3.2	0.59	0.68	0.91	771
NMT	0.8	0.8	4.3	0.47	0.58	0.81	778
PBO	0.8	0.9	4.3	0.54	0.75	0.90	778
UNR / NA12	1.0	0.8	3.9	1.13	1.09	1.46	775
UNR	1.0	0.8	4.4	1.05	1.15	1.60	775
USGS	0.8	0.9	3.2	0.44	0.66	0.61	710
JPL / IGS08	1.6	2.0	4.9	1.90	2.37	1.85	776
MEA / IGS08	1.1	1.3	3.8	1.01	1.15	1.08	771
USGS / IGS08	1.6	1.9	5.2	0.88	1.33	0.98	710

Table 2: Median WRMS scatter and Chi (see Table 1) of the position residuals to fits to the time series. Frame definition is NAM08 unless otherwise noted. Only the core PBO sites are included so that each analysis is based on the same group of stations.

Survey GPS data acquisition in the North San Francisco Bay Area

We have contributed data gathering for inclusion in the wider California CGM by undertaking further GPS surveys in the North San Francisco Bay Area, covering the San Andreas, Rodgers Creek, southern Maacama, and West Napa Faults from San Pablo Bay in the south to Clear Lake in the north. These surveys are extensions of surveys undertaken over the last six years by M. Floyd and G. Funning (UC Riverside) in an area that has a relatively sparse distribution of continuous GPS sites, operated by PBO, USGS and BARD, compared to the Greater Bay Area or southern California. The data acquired therefore contribute significantly to the broader California geodetic velocity solution and, ultimately, the Community Geodetic Model. In the latest solution for this area (Figure 2, left), median inter-GPS site distance has been reduced from ~ 16 km with only the PBO, USGS and BARD continuous GPS networks to ~ 7 km including the UCR-MIT and USGS survey GPS sites (but excluding The Geysers). The majority of sites are now down at the nominally-sought 1 mm/yr velocity uncertainty level and are therefore useful for rigorous tectonic analyses, which we continue to perform. These data will be made available to the community via the UNAVCO public archive and contribute significantly to geodetic constraints on slip rates on faults in the North Bay Area.

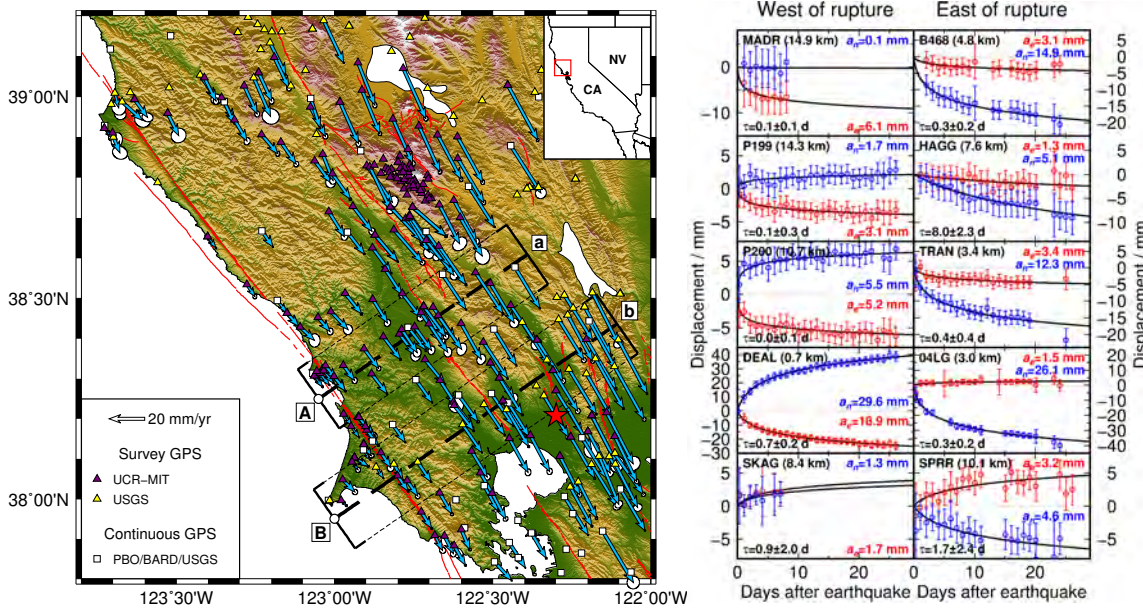


Figure 2: Left: Current GPS velocity solution relative to the Pacific plate in the North San Francisco Bay Area, which contributes denser GPS data to the Community Geodetic Model in this region. Velocities do not include data from after the 2014-08-24 South Napa earthquake (red star; discussed below). Right: Displacement of near-field survey GPS sites (except P199 and P200) operated continuously from within one day of the South Napa earthquake. Time series are plotted from the day of the earthquake relative to their pre-earthquake velocities shown in the left-hand figure and fit with a logarithmic decay function $x = a \ln\left(1 + \frac{t-t_{eqk}}{\tau}\right)$.

Analyses of post-seismic motions after the 2014-08-24 South Napa earthquake

We also collected GPS data, alongside the USGS and with support from UC Berkeley, in the immediate aftermath of the 24 August 2014 South Napa earthquake across the UCR-MIT and USGS networks (Figure 2, right). The former network includes sites that had been measured by M. Floyd with G. Funning (UC Riverside) only seven weeks prior to the earthquake (see *Survey GPS data acquisition in the North San Francisco Bay Area* above). The near-field survey sites were operated continuously from within a few hours of the earthquake for nearly three weeks to track the evolution of post-seismic motion in the near-field. Further episodic measurements have since taken place. Analysis of the displacement time series confirms surface observations of shallow afterslip in the first hours and days after the earthquake, which decays over a period of weeks to months. Geophysical modeling provides insight into the spatial extent and temporal evolution of the afterslip. This has been conducted, in combination with InSAR data, by M. Floyd and G. Funning (UC Riverside) in collaboration with researchers at the Universities of Leeds and Oxford in the United Kingdom. The findings are in preparation and will be submitted to a peer-reviewed journal presently.

The study has implications for our understanding the potential magnitude of shallow afterslip following an earthquake on strike-slip faults in California. The

West Napa Fault was not one that was known to exhibit creep behavior, nor has a high slip rate, but both shallow and deep afterslip are evident as well as off-fault triggered slip, which may be on-going. All of these observations suggest that, if such transient behavior is more characteristic of faults in California than previously thought from current creep observations alone, aseismic slip processes may have more of a significant contribution to the earthquake cycle than is accounted for in current probabilistic seismic hazard analyses and earthquake rupture forecasts.

The continuous GPS sites near the earthquake continue to show clear post-seismic motions, which may be due to on-going afterslip, triggered off-fault slip or visco-elastic stress redistribution processes and will require further study. An example of such post-seismic transient motion is observed at site P261, which had the largest coseismic motion of any continuous site in the region. The time series of its position estimates since its installation in mid-2004 is shown in Figure 3. The post-seismic trend is very clear although there are other time variable signals in this site that do increase the uncertainty in the estimates of the post-seismic signals. These smaller transient signals are most likely due to ground water changes in the region. Both log and exponential functions fit the time series currently. When 100-day exponential is used the amplitudes of the north and east exponential terms are similar to the coseismic offsets. We will continue observing the post-seismic evolution at the sites in the region.

Both the survey-mode and continuous GPS data here provide a new opportunity to analyze methods for recovering secular velocities in the presence of non-linear motions with very short or no periods of data prior to a large earthquake. Here, very good pre-earthquake velocities are known at about 20 sites within a 25 km radius (approximately twice the rupture length). From both the cGPS sites and continuing observations at the survey sites, whenever possible, we are currently building a contemporary and relevant geodetic data set for experimenting with such techniques.

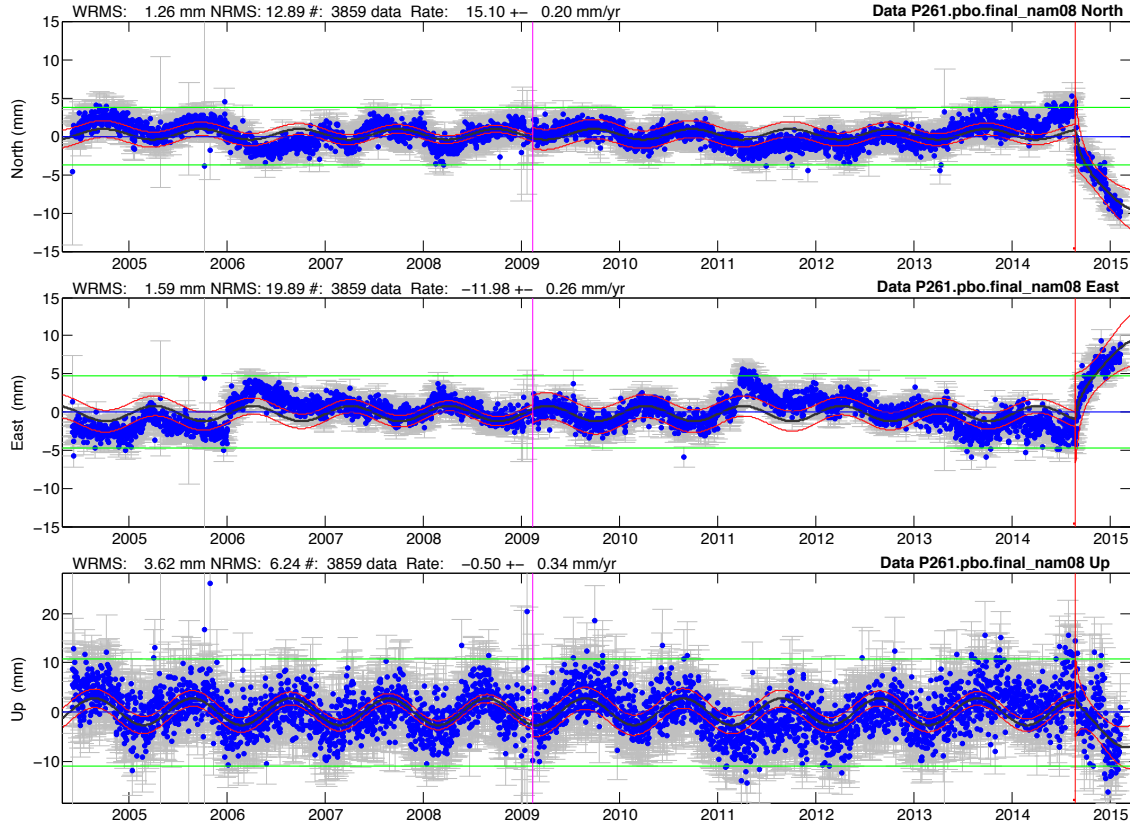


Figure 3: Time series in north, east and height for PBO site P261 that had the largest coseismic offset for the continuous GPS sites in the region. In this figure, coseismic offsets of -13.0, 26.4 (± 0.4 mm) and 7.1 ± 1.3 mm have been removed as the coseismic displacement in north, east and up (NEU). The post-seismic model shown is a 10-day log function. The log coefficients are -3.4, 3.9 (± 0.2) and -4.2 ± 0.6 mm in NEU. Other time constants for the log have similar levels of fit but do generate different coseismic and log coefficients. An exponential function with a time constant of 100 days has a similar level of fit. The difference between a log and exponential fit will come more apparent as more data are collected.

Analysis of GPS velocities across the San Bernardino Mountains

We have contributed raw GPS data and assisted with advice on the processing and implications of GPS velocities for study of a large swath of the Pacific-North America plate boundary across the San Bernardino Mountains. This work has been led by S. McGill (CalState San Bernardino) for many years as part of community outreach and engagement. Our data-sharing collaboration and technical support partnership has been fostered through and supported by SCEC and includes R. Bennett and J. Spinler (University of Arizona) and G. Funning (UC Riverside). The result of this work is in press (McGill et al., 2015).

The new geodetic velocity solution in this area provides a means by which to assess the distribution of fault slip rates in a complex region of the San Andreas Fault system. This area has also been studied extensively with paleoseismological and

geomorphological techniques, to which these geodetic results may be compared. This comparison is particularly stimulating considering the clear evidence for rapid and significant shallow afterslip following the South Napa earthquake, as discussed in *Post-earthquake analyses of the 2014-08-24 South Napa earthquake* above.

Intellectual Merit & Broader Impacts

Our research is contributing to the development of the Community Geodetic Model through data acquisition, organization and analysis. These activities are targeted at developing an understanding of the complex deformation modes California and the relationship of this deformation to earthquake occurrence. Our current analysis of continuous GPS solutions is very technical as we assess the agreement and differences between results generated by different analysis groups. Once this phase is completed and we will be able to generate with confidence a combined time series motion model for California with realistic assessments of the noise and systematics in the series.

The opportunity presented by the South Napa earthquake in particular, with the rich geodetic data set acquired, is unique even by California standards. High-quality pre- and post-earthquake measurements allow us to map zones of differing co- and post-seismic behavior on the fault plane with high spatio-temporal evolution. We may then infer whether such processes occur on other faults throughout California, how such processes may be related to physical characteristics, such as frictional variations, and their influence on the earthquake cycle as we currently understand it. Continued exploitation and study of such examples anywhere in California is therefore highly valuable to the SCEC community and beyond.

Publications

- Ji, K. H., T. A. Herring and A. L. Llenos (2013), Near real-time monitoring of volcanic surface deformation from GPS measurements at Long Valley Caldera, California, *Geophys. Res. Lett.*, *40*, 1054–1058, doi:10.1002/grl.50258.
- McGill, S. F., J. C. Spinler, J. D. McGill, R. A. Bennett, M. A. Floyd, J. E. Fryxell and G. J. Funning (2015), Kinematic modeling of fault slip rates using new geodetic velocities from a transect across the Pacific-North America plate boundary through the San Bernardino Mountains, California, *J. Geophys. Res.*, in press, doi:10.1002/2014JB011459.