FINAL TECHNICAL REPORT

The BARD Continuous GPS Network: Monitoring Earthquake Hazards in Northern California and the San Francisco Bay Area, a collaboration between UC Berkeley and the USGS Menlo Park

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Abstract

UC Berkeley's Seismological Laboratory (BSL) maintains the Bay Area Regional Deformation (BARD) network of permanent Global Positioning System (GPS) stations to better understand crustal deformation in northern California and the timing and hazards posed by future earthquakes caused by strain accumulation along the San Andreas fault system in the San Francisco Bay area. During this 5-year project period, we completed enhancements to the existing network and operation procedures. This includes folding seven new stations into BARD operations, improving daily processing method and quality analysis routines, and establishing real-time streaming of data from all stations to the community. BARD data were used in a number of research projects; notably, real-time data streaming facilitated research into using these data for earthquake early warning applications. In particular, it facilitated the development of GlarmS, a geodetic-based earthquake early warning system that complements seismic-based warning systems by improving real-time magnitude estimates for very large earthquakes.

1. Major Goals & Activities of the Geodetic Project

The Bay Area Regional Deformation (BARD) network is a collection of permanent, continuously operating GPS receivers that monitor crustal deformation in the San Francisco Bay Area (SFBA) and Northern California. Started in 1992 with two stations spanning the Hayward Fault, BARD has been a collaborative effort of Univeristy of California's Berkeley Seismological Laboratory (BSL), the USGS, and several other academic, commercial, and governmental institutions. In the SFBA, nearly eight million people live in a geologically complex, tectonically active region that has experienced several historic earthquakes, including the 1868 Hayward, the 1906 San Francisco, and 1989 Loma Prieta earthquakes. In the 19th century alone, 16 M>6 earthquakes shook the region. Geological, seismological, and geodetic evidence suggest that the predominantly strike-slip deformation of the northwest-trending San Andreas fault system is an expression of the most active part of the boundary between the Pacific and North American plates.

The BARD network is designed to study the distribution of deformation in Northern California across the Pacific-North America plate boundary and interseismic strain accumulation along the San Andreas fault system in the Bay Area for seismic hazard assessment, and to monitor hazardous faults for emergency response. It also provides data in real-time for use in earthquake early warning (EEW) and rapid response applications. The BSL maintains and/or has direct continuous telemetry from 33 stations comprising the BARD Backbone, while additional stations operated by the USGS, US Coast Guard and others fill out the extended BARD network.

Since the completion of major construction on the Plate Boundary Observatory (PBO) portion of EarthScope in 2004, the number of GPS stations in Northern California has expanded to over 250. Together, BARD, USGS, and PBO stations provide valuable information on the spatial complexity of deformation in the SFBA and Northern California, while the BARD network has the infrastructure and flexibility to additionally provide information on its temporal complexity over a wide range of time scales and in real-time. All BARD Backbone stations collect data at 1 Hz sampling frequency and stream their data in real-time to the BSL. These data are in turn provided in real-time to the public. Furthermore, eighteen BARD Backbone sites are co-located with broadband seismic stations of the BDSN, with which they share continuous telemetry to UC Berkeley.

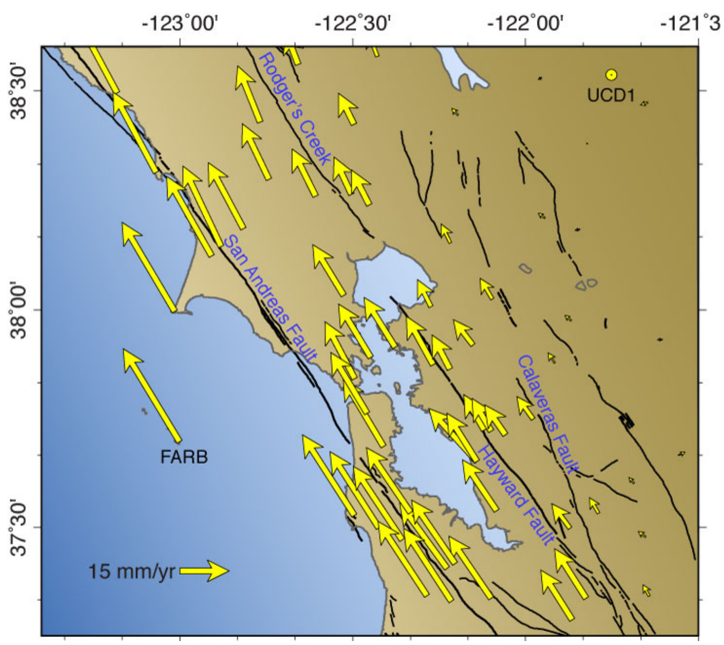

Figure 1: Interseismic velocities at BARD and PBO stations in the San Francisco Bay Area. Velocities are shown relative to site UCD1, located on the Sierra Nevada/Great Valley Block.

Since its inception, BARD has been an important asset to the scientific community, supplying a core set of continuous sites which provide daily positions to track time dependent motion and a stable set of reference stations for campaign observations. Subsequent deformation modeling confirmed what was observed using terrestrial surveying methods: that deformation is mostly right-lateral strike-slip, with the SAF system accommodating 35-40 mm/yr or 75-85% of the Pacific-North American relative plate motion [*Lisowski et al.*, 1991; *Freymueller et al.*, 1999]. Strain accumulation on the SAF system can be inferred from three-dimensional fault elastic dislocation modeling of the deformation field [e.g. *Bürgmann et al.*, 1997; *Murray and Segall*, 2001; *d'Alessio et al.*, 2005; *Houlié and Romanowicz*, 2011] and is an important input in seismic hazard evaluations.

The Working Group on California Earthquake Probabilities' UCERF2 report determines a 63% chance that a M6.7+ earthquake will occur in the SFBA before 2038 and a 31% chance of damaging earthquake on the Hayward fault [*Field et al.*, 2009]. The Hayward fault along the eastern side of San Francisco Bay is arguably one of the most hazardous faults in the world when one combines the probability of an earthquake with proximity to urban centers. Historical accounts suggest that the northernmost Hayward fault has not ruptured for at least 170 or perhaps even 230 years [*Toppozada and Borchardt*, 1998], but geodetic data suggest that the northern Hayward fault may be creeping within the seismogenic zone and thus may not be an independent source region for large earthquakes [*Bürgmann*, 2000; *Shirzaei and Bürgmann*, 2013].

Geodetic measurements and modeling in the Bay area reveal a spatially complex deformation field with evidence for time-dependent strain that may affect the timing of future earthquakes. Postseismic transient deformation has been documented to occur for decades following the 1906 San Andreas earthquake [e.g. *Thatcher*, 1983] and for at least 5 years following the 1989 Loma Prieta earthquake [*Bürgmann et al.*, 1997; *Segall et al.*, 2000]. Stress changes from the Loma Prieta earthquake also caused significant transient changes in shallow creep rates on the Hayward fault and the creeping SAF segment [*Lienkaemper et al.*, 1997; *Gwyther et al.*, 2000].

Strain transients can also be self-nucleating, i.e. not triggered by an earthquake or other event. Slow slip events, with durations from hours to years, have been observed by GPS, strain- and creep-meters, in subduction zone regions and strike-slip environments [*Linde et al.*, 1996; *Miller et al.*, 2002]. Multiple slow earthquakes have also been observed on the SAF near San Juan Bautista. In 1992, a slip transient was detected over a 10-day interval on several borehole strainmeters, followed by events in 1996, 1998, 2002 and 2004 [*Linde et al.*, 1996; *Gwyther et al.*, 2000; *McFarland et al.*, 2013]. The 1998 transient event included aseismic slip both preceding and following an M5.1 earthquake on the SAF. This event was fortuitously captured by borehole strainmeters, creepmeters, a BARD GPS site (SAOB), and a BDSN broadband seismometer [*Uhrhammer et al.*, 1999].

Slow slip events may occur wherever faults are creeping, this includes many faults throughout the Bay Area where they have not yet been observed. Triggered and spontaneous strain transients have been observed over a broad range of temporal scales and with over 20 years of operation, BARD network data is uniquely able to resolve past and longer-term slip-rate variations. The continued maintenance and operation of the BARD network will ensure that this long history of data collection continues into the future.

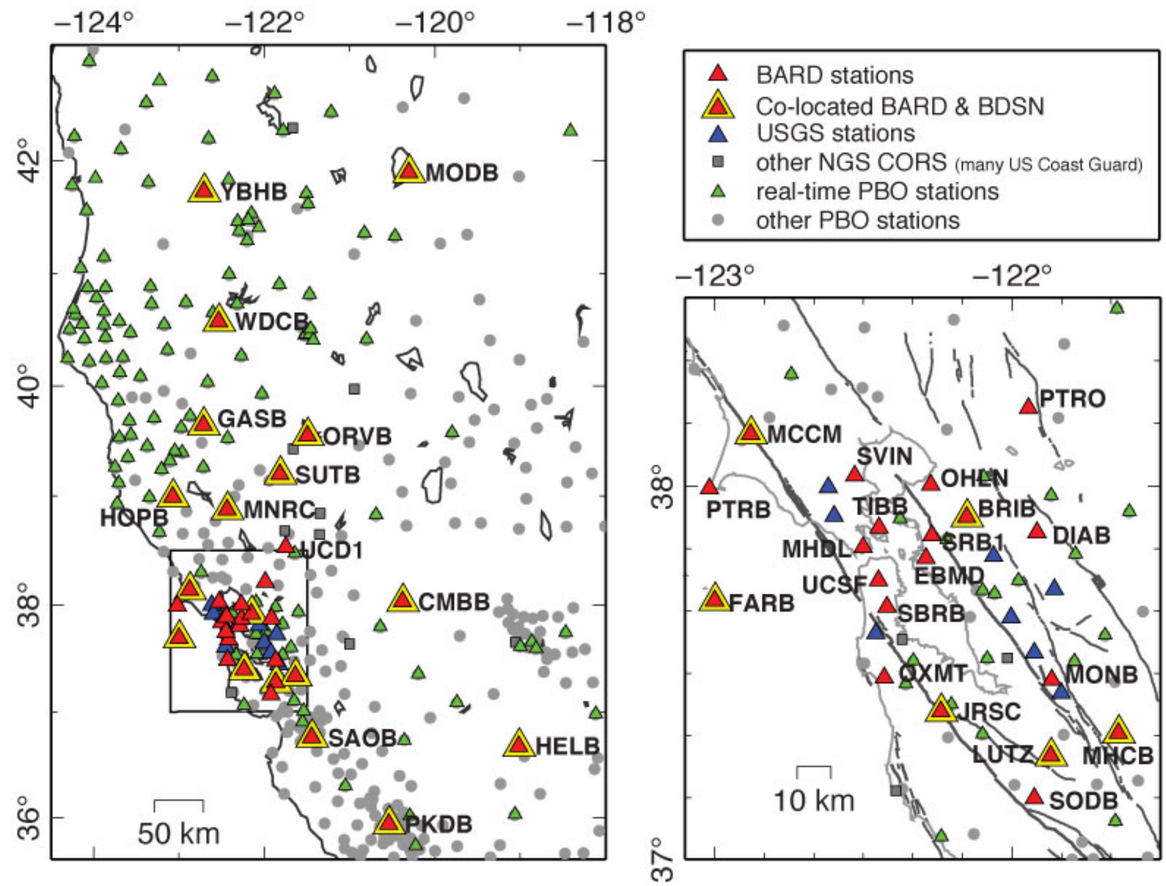

Figure 2: Map of the BARD network and surrounding PBO and USGS sites in northern California. Black rectangle in large scale map on left shows the extent of the small scale figure on the right.

2. March 2010 - February 2015 Accomplishments

2.1 *Station Upgrades and Current Configuration*

Major station upgrades and seven site installations during the past five years were made possible by a separate award under the American Recovery and Reinvestment Act (ARRA). Thirteen existing BARD stations were upgraded with newer model Topcon Net-G3A GPS receivers and three received new Topcon choke-ring antennas. Additionally, seven BDSN stations were upgraded with GPS equipment, resulting in seven new BARD stations: GASB, HELB, JRSC, MCCM, MNRC, PTRO, and WDCB. The BSL now maintains and operates 31 L1/L2 continuous GPS stations throughout Northern California (Table 1), which constitute the bulk of the BARD Backbone Network. Two additional backbone stations (UCD1 and EBMD) are operated by partner organizations UC Davis and the East Bay Municipal Utility District (EBMUD). Eighteen backbone stations are now co-located with broadband seismic stations of the Berkeley Digital Seismic Network (BDSN) with which they share continuous telemetry to UC Berkeley and five additional BARD stations are co-located with strainmeter/geophone stations installed as part of the "mini-PBO" project.

BARD station monumentations fall broadly into four types. Most are anchored into bedrock, either directly, via a steel-reinforced concrete cylinder, or with a PBO-style short-brace monument. The five mini-PBO stations have GPS antennas that are bolted onto the borehole casing, and four stations have antennas mounted on the roofs of buildings. Three stations installed under ARRA are mounted on the co-located seismic vault, a design that is unique to BARD. The seismic vaults are large structures, framed by a shipping container and cemented to bedrock. The GPS antennas are mounted on pipes embedded in the vault wall for this purpose, at the time of construction. One of these stations (MCCM) suffers from poor skyview and so it is difficult to isolate noise in the time series as due to monument instability. The other two (GASB and MNRC) both have daily position time series with RMS values below 1.7 mm in the horizontal, which is lower than the network average of 2.3 mm.

All BSL-operated BARD stations use a radome-equipped, low-multipath choke-ring antenna, designed to provide security and protection from weather and other natural phenomena, and to minimize differential radio propagation delays. A low-loss antenna cable is used to minimize signal degradation on the longer cable setups that normally would require signal amplification. Low-voltage cutoff devices are installed to improve receiver performance following power outages.

BSL-operated BARD stations now have one of two models of receiver: Trimble NetRS and Topcon Net-G3A. The Topcon Net-G3A receivers were installed starting in 2010 and are capable of observing all modern GNSS signals, including the newer GPS L5 observable and signals from GLONASS satellites. All BARD Backbone stations are continuously telemetered to the BSL at 1 sample-per-second (sps). Many use frame relay technology, either alone or in combination with radio telemetry. Other methods include a direct radio link to Berkeley or satellite telemetry (see Table 1). With frame relay being phased out by telecommunication companies, we have begun exploring alternatives for our sites that use it. Where possible, BARD stations have already been transitioned to internet-based and cell telemetry, which has been stable for daily use.

	Site	**Receiver**	**Ant.**	**Telem.**	**Samp. Rate**	**Real-time?**	**Colloc. Net.**	**Install Date**	***Location***
1	BRIB	NETRS	CR	T1	1Hz	yes	BDSN	8/6/93	*Briones Reservation*
2	CMBB	NET-G3A	CR	Int	1Hz	yes	BDSN	12/9/93	*Columbia College*
3	DIAB	NETRS	CR	FR	1Hz	yes		5/21/98	*Mt. Diablo*
4	EBMD	LEICA	AR10	R	1Hz	yes		8/2/99	*East Bay MUD Headquarters, (operated by EBMUD)*
5	FARB	NETRS	CR	R-FR	1Hz	yes	BDSN	1/27/94	*Farallon Islands*
6	GASB	NET-G3A	CR	R-FR	1Hz	yes	BDSN	6/17/11	*Alder Springs*
7	HELB	NET-G3A	CR	R-VSAT	1Hz	yes	BDSN	12/19/12	*Miramonte*
8	HOPB	NET-G3A	CR	R-FR	1Hz	yes	BDSN	8/26/95	*Hopland Field Station*
9	JRSC	NET-G3A	CR	Int	1Hz	yes	BDSN	11/30/11	*Jasper Ridge Biological*
10	LUTZ	NET-G3A	CR	FR	1Hz	yes	BDSN	5/18/96	*SCC Communications*
11	MCCM	NET-G3A	CR	VSAT	1Hz	yes	BDSN	9/28/11	*Marconi Conference Center*
12	MHCB	NETRS	CR	FR	1Hz	yes	BDSN	6/14/96	*Lick Observatory*

	Site	Receiver	Ant.	Telem.	Samp. Rate	Real-time?	Colloc. Net.	Install Date	*Location*
13	MHDL	NETRS	CR	R-FR	1Hz	yes	Mini-PBO	9/12/06	*Marin Headlands*
14	MNRC	NET-G3A	CR	VSAT	1Hz	yes	BDSN	7/7/11	*McLaughlin Mine*
15	MODB	NETRS	CR	VSAT	1Hz	yes	BDSN	11/11/9	*Modoc Plateau*
16	MONB	NET-G3A	CR	FR	1Hz	yes		7/31/98	*Monument Peak*
17	OHLN	NET-G3A	CR	FR	1Hz	yes	Mini-PBO	11/21/0	*Ohlone Park*
18	ORVB	NET-G3A	CR	FR	1Hz	yes	BDSN	11/21/9	*Oroville*
19	OXMT	NET-G3A	CR	FR	1Hz	yes	Mini-PBO	2/12/04	*Ox Mountain*
20	PKDB	NETRS	CR	R-VSAT-	1Hz	yes	BDSN	9/20/96	*Bear Valley Ranch*
21	PTRB	NETRS	CR	R-FR	1Hz	yes		8/14/98	*Point Reyes Lighthouse*
22	PTRO	NET-G3A	CR	FR	1Hz	yes	BDSN	12/8/11	*Potrero Hills*
23	SAOB	NETRS	CR	FR	1Hz	yes	BDSN	8/21/97	*San Andreas Observatory*
24	SBRB	NET-G3A	CR	FR	1Hz	yes	Mini-PBO	8/21/08	*San Bruno Replacement*
25	SODB	NET-G3A	CR	R-FR	1Hz	yes		5/18/96	*Soda Springs*
26	SRB1	NET-G3A	CR	Fiber	1Hz	yes		11/14/0	*Seismic Replacement Building*
27	SUTB	NETRS	CR	R-FR	1Hz	yes	BDSN	3/27/97	*Sutter Buttes*
28	SVIN	NET-G3A	CR	R-FR	1Hz	yes	Mini-PBO	11/20/0	*St Vincents*
29	TIBB	NET-G3A	CR	R-Int	1Hz	yes		6/16/94	*Tiburon*
30	UCD1	NETRS	CR	Int	1Hz	yes		5/19/96	*UC Davis (operated by UC Davis)*
31	UCSF	NET-G3A	CR	FR	1Hz	yes		12/5/07	*UC San Francisco*
32	WDCB	NET-G3A	CR	FR	1Hz	yes	BDSN	5/6/11	*Whiskeytown Dam*
33	YBHB	NETRS	CR	FR	1Hz	yes	BDSN	10/24/9	*Yreka Blue Horn Mine*

Table 1: BARD station information. Receivers are: Trimble NETRS, (NETRS) and Topcon Net-G3A (Net-G3A). Site EBMD, operated by the East Bay Municipal Utility District, has a Leica GX1230 receiver and Leica AR10 antenna. The telemetry types listed are FR = Frame Relay, R = Radio, Int = Internet, VSAT = Satellite, T1 = Private T1 line. Telemetry often includes a radio hop from the GPS site to the seismic vault, indicated by an initial R. All (except EBMD) are equipped with Ashtech or Topcon choke ring antennas (CR).

2.2 *GPS data for Real-time Earthquake Information*

Following a major earthquake, the mobilization of local, state, and federal disaster operations can be greatly enhanced by dependable, near real-time estimates of location, magnitude, mechanism, and extent of strong ground shaking. In particular, earthquake early warning (EEW) has great potential to improve earthquake response by providing tens of seconds of warning to some locations before strong shaking arrives. Rapid estimation of magnitudes for large events from seismic data alone is known to fail for great earthquakes, where a point source approximation becomes inadequate [*Hoshiba et al.*, 2011]. Real-time GPS has demonstrated great potential to reliably determine large magnitudes through finite fault models [*Crowell et al.*, 2009; *Colombelli et al.*, 2013]. The first step towards a geodetic-based EEW system was to make all BARD data streams available in real-time and at 1 sample-per-second data rate. This was completed soon after ARRA upgrades, which allowed the final stations to be converted to high data rate. Data are now streamed from the station to the lab in BINEX format, where they are simultaneously written to disk and converted on the fly to RTCM format, using the sharc software package (maintained by the USGS, Pasadena). Both the BINEX and RTCM data streams are then made available to the community over an Ntrip-caster. Access to the real-time data streams requires an account, though anyone may request and receive an account. Details are on the real-time streaming webpage (http://seismo.berkeley.edu/bard/realtime).

Multiple groups involved in testing and developing geodetic EEW pick up these streams, including the USGS, Scripps Institute of Oceanography, and Central Washington University. Real-time processing has evolved greatly over the past five years, with several groups now routinely producing real-time displacements using a variety of software (i.e. GlarmS, Figure 3) [*Crowell et al.*, 2009; e.g. *Grapenthin et al.*, 2014; *Langbein et al.*, 2014].

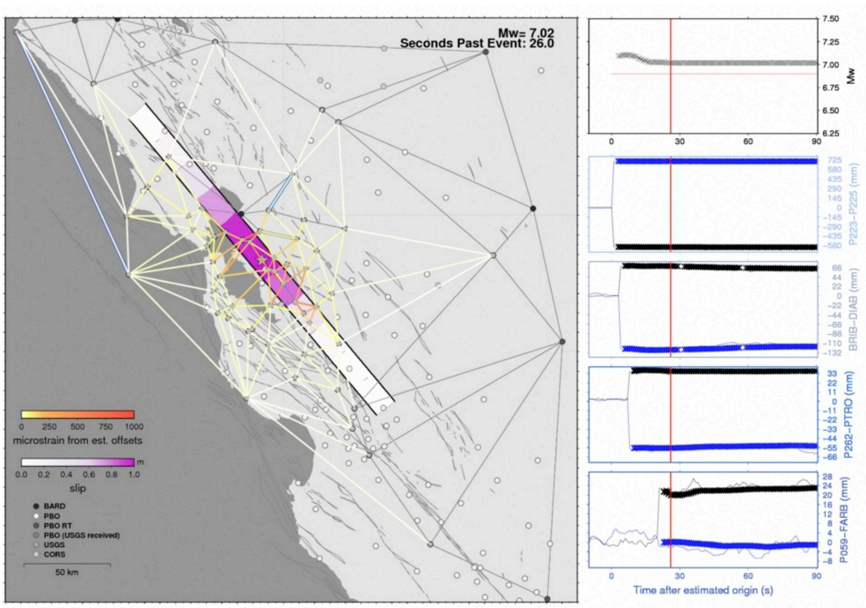

Figure 3: Snapshot during a real-time test of G-larms; the red line on the right side shows the timing of the snapshot. Top right figure shows the estimated earthquake magnitude for the slip model in magenta on the left. Test is based on a simulated M6.9 earthquake. G-larms begin estimating position after S-wave arrival (blue and black symbols). Offsets are updated and input into an inversion for fault slip every second. Testing was run in true real time; synthetic offsets were added to GPS position time series on-the-fly in order to capture true real-time noise and data availability.

UC Berkeley research projects were also greatly enhanced by operational support for real-time data streaming. In 2011, UC Berkeley, Caltech and the University of Washington received support from the Gordon and Betty Moore foundation to develop the USGS-funded California

ShakeAlert program into a West-Coast-wide prototype system that delivers warnings to industry partners. The Moore foundation grant also funded research and development to improve the system's performance. At the BSL, we concentrated on improving the performance of EEW for very large earthquakes using information from GPS. This included establishing real-time processing of incoming GPS data streams using TrackRT, method development to estimate earthquake magnitude and fault length in real-time [*Colombelli et al.*, 2013], and development of the Geodetic Alarm System (G-larmS, Figure 3) framework for implementation of real-time monitoring and warning [*Grapenthin et al.*, 2014].

2.3 *Daily Position Time Series and Quality Analysis*

Work during the project period included re-establishing daily position time series processing and making these results available to the community, as well as establishing the regular calculation and dissemination of quality analysis (QA) products for BARD data. In fact, daily time series are themselves a QA product, as changes in apparent position are sometimes the result of environmental noise (e.g. weed growth), rather than tectonics.

Daily updates to station coordinates are estimated from 24 hours of observations for BARD stations and other nearby continuous GPS sites using the GAMIT/GLOBK software developed at MIT and SIO [*Herring et al*., 2010a; 2010b]. GAMIT uses double-difference phase observations to determine baseline distances and orientations between ground-based GPS receivers. Ambiguities are fixed using the widelane combination followed by the narrowlane, with the final position based on the ionospheric free linear combination (LC). Baseline solutions are loosely constrained until they are combined together. GAMIT produces solutions as "H-files", which include the covariance parameters describing the geometry of the network for a given day and summarize information about the sites. We combine daily, ambiguity-fixed, loosely constrained H-files using the Kalman filter approach implemented by GLOBK [*Herring et al*., 2010b]. They are combined with solutions from the IGS global network and PBO and stabilized in an ITRF2005 reference frame. The estimated relative baseline determinations typically have 2-4 mm long-term scatter in the horizontal components and 10-20 mm scatter in the vertical.

Time series of station positions are produced with daily, automated updates. BARD data are processed within 24 hours using IGS rapid orbit information and the position time series are updated immediately. When rapid PBO and IGS global station solutions become available (usually within 2-3 days), they are combined with the rapid BARD solutions using GLOBK and the time series is again updated. Final processing with both GAMIT and GLOBK occurs when IGS final orbits and final PBO solutions become available (1-2 weeks); the time series is then updated for the last time with the final positions.

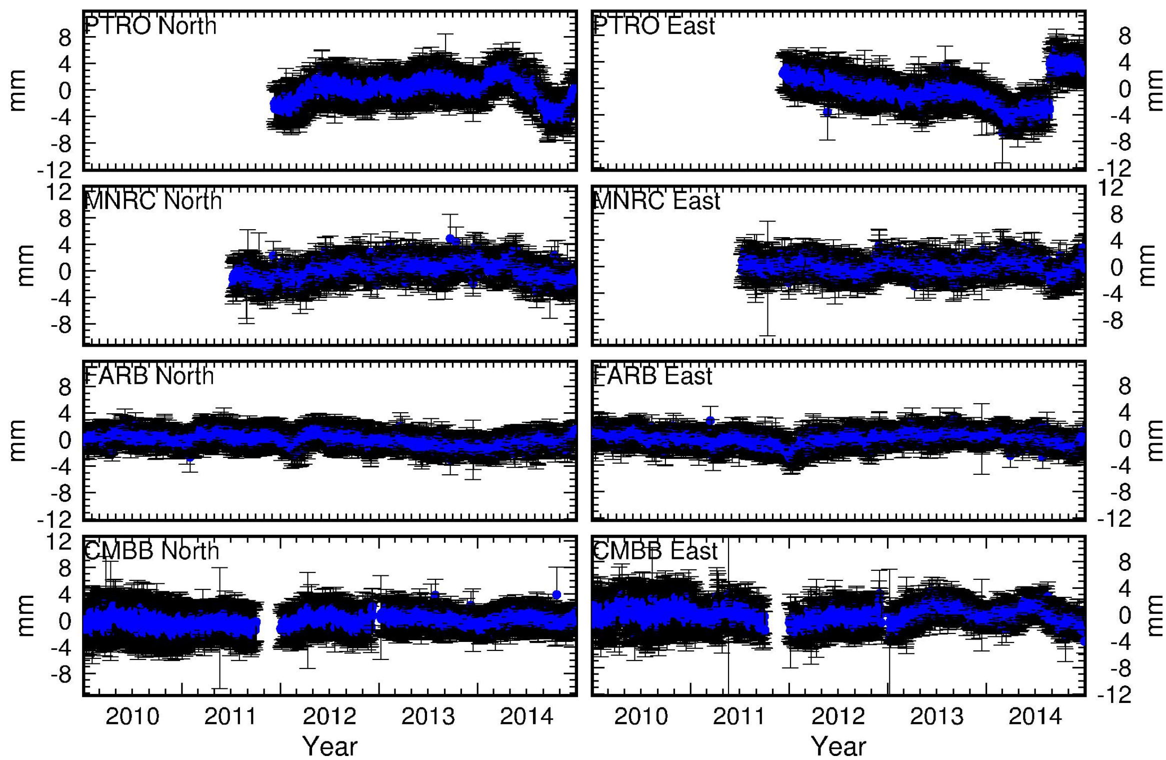

Figure 4: Examples of detrended position time series for four BARD stations. PTRO and MNRC were newly installed this project period under ARRA funding. The offset in the east component of PTRO is due to the August 24, 2014 South Napa Earthquake. Formal uncertainty estimates for station CMBB visibly decreased in 2010 when it's receiver was upgraded to a new model.

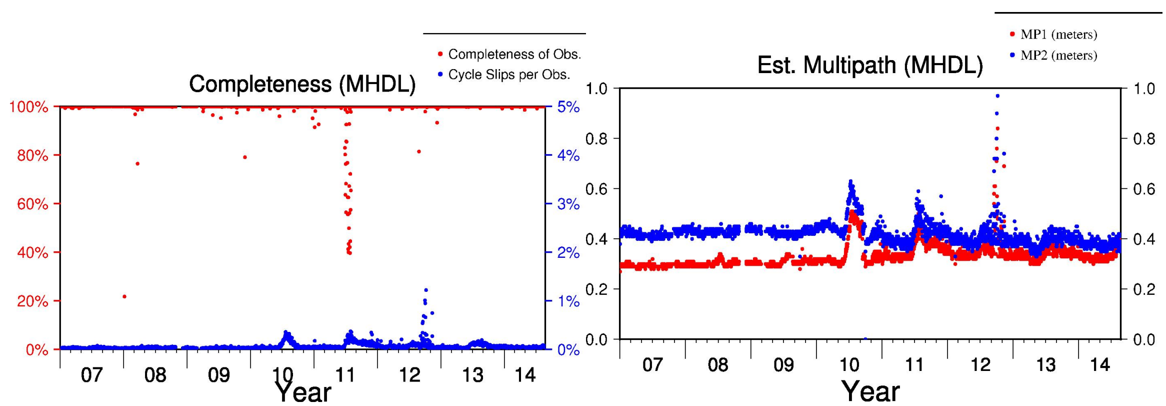

Figure 5: Examples of data quality plots posted on the BARD website. These plots cover the lifetime of station MHDL and show increased data loss and signal multipath on an annual basis, starting in 2010. These have been determined to be due to the growth of weeds and other brush nearby; excursions on these plots indicate when its time to visit the site to cut down the overgrowth

After each update, the time series are cleaned by removing outliers and common mode noise. Common mode noise is estimated by stacking the difference between observations and modeled motion for all stations. The model is derived from *a priori* values for station velocity, coseismic offsets and postseismic decay, determined using the program est_noise [*Langbein*, 2004]. The cleaned data is then used to re-estimate the *a priori* model parameters in an iterative process. Outliers are identified as points whose misfit to a linear trend is greater than 4σ on any single component of motion (North, East, or Up). Overall time series scatter is low; with average RMS values across the BARD network of 1.8 mm, 2.9 mm, and 5.8 mm for the North, East and Up directions respectively. Plots of station time series are posted daily on the BARD website (http://seismo.berkeley.edu/bard/timeseries).

Quality analysis using TEQC (maintained by UNAVCO) is performed daily on low-rate (15s) RINEX files are posting automatically to the BARD website. The QA products include data completeness, which is the percent of expected epochs present in the data file, and the percentage of epochs containing cycle slips. The first of these parameters is an indication of the telemetry quality and station uptime, as missing epochs are most likely due to loss over the telemetry line or non-operation of the station. While our primary data source is the real-time stream, if there is low data completeness on any given day, data files are downloaded from the receiver and to backfill the missing data in the NCEDC archive. The RMS of multipath estimates on the L1 and L2 frequencies are also estimated as a QA product and posted to the station webpages. These quantities are affected by objects in the station's environment that might increase or decrease the prevalence of multipath signals. Multipath degrades the quality of the GPS data and can cause apparent changes in position, such that crosschecking perturbations in daily time series with multipath estimates is an important check on their origin.

2.4 *Data Management Practices*

Continuous data archival

All data collected from BARD/BSL stations are publicly available at the NCEDC (http://www.ncedc.org, ftp://www.ncedc.org/pub/gps), both as raw data and converted into RINEX format. High-rate (1 Hz) data are additionally downsampled to 15-sec sampling and archived in RINEX format to facilitate low-rate processing. The NCEDC also archives raw and RINEX data from 8 continuous stations operated by the USGS, Menlo Park, on a daily basis, as well as from those that are telemetered directly to the BSL though operated by another agency (UCD1 & EBMD).

We participate in the UNAVCO-sponsored GPS Seamless Archive Center (GSAC) project, which provides access to survey-mode and continuous GPS data distributed over many archives. We have been in contact with personnel from UNAVCO regarding GSAC2.0 and intend to pursue federated status when it is released. This will allow easier web access from central portal sites to NCEDC GPS data. Data from five of our sites (HOPB, MHCB, CMBB, OHLN, YBHB) are sent to the National Geodetic Survey (NGS) in the framework of the CORS (Continuously Operating Reference Stations) project (http://www.ngs.noaa.gov/CORS/). The data from these five sites are also distributed to the public through the CORS ftp site.

Campaign data archival

As part of the activities funded by the USGS through the BARD network, the NCEDC is the principal archive of the 7000+ survey-mode occupations collected by the USGS since 1992. The initial dataset archived was the survey-mode GPS data collected by the USGS Menlo Park for northern California and other locations. Significant quality control efforts were implemented by the NCEDC to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS-MP GPS data transferred to the NCEDC (1992-2011) have been archived and are available for distribution through the NCEDC ftp server (http://www.ncedc.org/ncedc/gps.html).

Real-time streaming

Our data dissemination program includes real time streaming from all BARD/BSL sites in both RTCM3.0 and BINEX formats. The BSL is also the public portal for real-time streams from the 8 continuous GPS stations operated by the USGS, Menlo Park. The NTRIP-caster we are using to stream the BARD and USGS data is also being used to relay RT17 (Trimble proprietary format) data from stations in the Parkfield area to UC San Diego. Access to the real-time data streams requires an account, though anyone may request and receive an account. Details are on the streaming webpage (http://seismo.berkeley.edu/bard/realtime).

Metadata

The BARD website houses station information and data quality information, as well as providing links to full station metadata, housed at the NCEDC. The BARD website (http://seismo.berkeley.edu/bard) includes individual station pages with basic information and links to daily time series figures and results. We perform basic data quality evaluation for BARD stations, including keeping track of data completeness (number of recorded epochs per number expected), the number of cycle slips detected and the RMS of the estimated multipath parameters for L1 and L2. All are obtained from the program TEQC, developed by UNAVCO. These quantities are updated daily and posted in graphical form to each station's individual webpage.

The authoritative source for BARD station metadata is in IGS format log files, housed at the NCEDC, which are up-to-date and compliant with the most current IGS recommended format. Data quality plots are updated daily, while other information is updated in concert with the log files.

References

Bürgmann, R. (2000), Earthquake Potential Along the Northern Hayward Fault, California, *Science*, *289*(5482), 1178–1182, doi:10.1126/science.289.5482.1178.

Bürgmann, R., P. Segall, M. Lisowski, and J. Svarc (1997), Postseismic strain following the 1989 Loma Prieta earthquake from GPS and leveling measurements, *J. Geophys. Res.*, *102*, 4933–4955.

Colombelli, S., R. M. Allen, and A. Zollo (2013), Application of real-time GPS to earthquake early warning in subduction and strike-slip environments, *J. Geophys. Res.*, n/a–n/a, doi:10.1002/jgrb.50242.

Crowell, B. W., Y. Bock, and M. B. Squibb (2009), Demonstration of Earthquake Early Warning Using Total Displacement Waveforms from Real-time GPS Networks, *Seismological Research Letters*, *80*(5), 772–782, doi:10.1785/gssrl.80.5.772.

d'Alessio, M. A., I. A. Johanson, R. Bürgmann, D. A. Schmidt, and M. H. Murray (2005), Slicing up the San Francisco Bay Area: block kinematics and fault slip rates from GPS-derived surface velocities, *J. Geophys. Res.*, *110*(B06403), doi:10.1029/2004JB003496.

Field, E. H. et al. (2009), The Uniform California Earthquake Rupture Forecast, Version 2, *Bull. Seismol. Soc. Am.*, *99*(4), 2053–2107, doi:10.1785/0120080049.

Freymueller, J. T., M. H. Murray, P. Segall, and D. Castillo (1999), Kinematics of the Pacific-North America Plate Boundary Zone, northern California, *Journal of Geophysical Research*, *104*(B4), 7419, doi:10.1029/1998JB900118.

Grapenthin, R., I. A. Johanson, and R. M. Allen (2014), Operational Real-time GPS-enhanced Earthquake Early Warning, *Journal of Geophysical Research*, (submitted).

Gwyther, R. L., C. H. Thurber, M. T. Gladwin, and M. Mee (2000), Seismic and aseismic observations of the 12th August 1998 San Juan Bautista, California M5.3 earthquake, *3rd San Andreas Fault Conference*, 209–213.

Herring, T. A., R. W. King, and S. C. McClusky (2010a), *GAMIT: GPS Analysis at MIT - Release 10.4*, MIT.

Herring, T. A., R. W. King, and S. C. McClusky (2010b), *GLOBK: Global Kalman filter VLBI and GPS analysis program - Version 10.4*, MIT.

Hoshiba, M., K. Iwakiri, N. Hayashimoto, T. Shimoyama, K. Hirano, Y. Yamada, Y. Ishigaki, and H. Kikuta (2011), Outline of the 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0)— Earthquake Early Warning and observed seismic intensity—, *Earth Planets Space*, *63*(7), 547–551, doi:10.5047/eps.2011.05.031.

Houlié, N., and B. Romanowicz (2011), Asymmetric deformation across the San Francisco Bay Area faults from GPS observations in Northern California, *Physics of the Earth and Planetary Interiors*, *184*, 143–153.

Langbein, J. (2004), Noise in two-color electronic distance meter measurements revisited, *Journal of Geophysical Research*, *109*(B4), doi:10.1029/2003JB002819.

Langbein, J., J. R. Evans, F. Blume, and I. A. Johanson (2014), Response of Global Navigation Satellite System receivers to known shaking between 0.2 and 20 Hertz, *U. S. Geological Survey Open-File Rep. 2013-1308*, doi:10.3133/ofr20131308.

Lienkaemper, J. J., J. Galehouse, and R. Simpson (1997), Creep Response of the Hayward Fault to Stress Changes Caused by the Loma Prieta Earthquake, *Science*, *276*(5321), 2014–2016.

Linde, A. T., M. Gladwin, M. Johnston, R. Gwyther, and R. Bilham (1996), A slow earthquake sequence on the San Andreas fault, *Nature*, *383*(6595), 65–68.

Lisowski, M., J. C. Savage, and W. H. Prescott (1991), The velocity field along the San Andreas Fault in central and southern California, *Journal of Geophysical Research*, *96*(B5), 8369, doi:10.1029/91JB00199.

McFarland, F. S., J. J. Lienkaemper, and S. J. Caskey (2013), Data from Theodolite Measurements of Creep Rates on San Francisco Bay Region Faults, California, 1979-2012, v. 1.4, *U. S. Geological Survey Open-File Rep. 2009-1119*, 1–18.

Miller, M. M., T. Melbourne, D. J. Johnson, and W. Q. Sumner (2002), Periodic slow earthquakes from the Cascadia subduction zone, *Science*, *295*(5564), 2423–2423.

Murray, M. H., and P. Segall (2001), Modeling broadscale deformation in northern California and Nevada from plate motions and elastic strain accumulation, *Geophysical Research Letters*, *28*(22), 4315–4318.

Romanowicz, B., D. Neuhauser, B. Bogaert, and D. Oppenheimer (1994), Accessing northern California earthquake data via Internet, *Eos Trans AGU*, *75*(23), 257, doi:10.1029/94EO00934.

Segall, P., R. Bürgmann, and M. Matthews (2000), Time-dependent triggered afterslip following the 1989 Loma Prieta earthquake, *J. Geophys. Res.*, *105*(B3), 5615–5634, doi:10.1029/1999JB900352.

Shirzaei, M., and R. Bürgmann (2013), Time‐dependent model of creep on the Hayward fault from joint inversion of 18 years of InSAR and surface creep data, *Journal of Geophysical Research*.

Thatcher, W. (1983), Nonlinear strain buildup and the earthquake cycle on the San Andreas Fault, *Journal of Geophysical Research*, *88*(B7), 5893, doi:10.1029/JB088iB07p05893.

Toppozada, T. R., and G. A. Borchardt (1998), Re-evaluation of the 1836 “Hayward fault” and the 1838 San Andreas fault earthquakes, *Bulletin of the Seismological Society ….*

Uhrhammer, R., L. Gee, and M. Murray (1999), The Mw 5.1 San Juan Bautista, California earthquake of 12 August 1998, *Seismological Research Letters*.

Publications using data from the project

Amos, C. B., P. Audet, W. C. Hammond, R. Bürgmann, I. A. Johanson, and G. Blewitt (2014), Uplift and seismicity driven by groundwater depletion in central California : Nature : Nature Publishing Group, *Nature*, *509*, 483–486, doi:10.1038/nature13275.

Chaussard, E., R. Bürgmann, H. Fattahi, R. M. Nadeau, T. Taira, C. W. Johnson, and I. Johanson (2015), Potential for larger earthquakes in the East San Francisco Bay Area due to the direct connection between the Hayward and Calaveras Faults, *Geophysical Research Letters*, *42*(8), 2734–2741, doi:10.1002/2015GL063575.

Evans, E. L., J. P. Loveless, and B. J. Meade (2012), Geodetic constraints on San Francisco Bay Area fault slip rates and potential seismogenic asperities on the partially creeping Hayward fault, *Journal of Geophysical Research*, *117*(B3), B03410, doi:10.1029/2011JB008398.

Grapenthin, R., I. A. Johanson, and R. M. Allen (2014a), Operational Real-time GPS-enhanced Earthquake Early Warning, *Journal of Geophysical Research*, (submitted).

Grapenthin, R., I. A. Johanson, and R. M. Allen (2014b), The 2014 Mw 6.0 Napa earthquake, California: Observations from real‐time GPS‐enhanced earthquake early warning, *Geophysical Research Letters*, *41*(23), 8269–8276, doi:10.1002/2014GL061923.

Houlié, N., and B. Romanowicz (2011), Asymmetric deformation across the San Francisco Bay Area faults from GPS observations in Northern California, *Physics of the Earth and Planetary Interiors*, *184*, 143–153.

Presentations

Johanson, I., R. Turner, T. Taira, R. Nadeau, R. Bürgmann, Creep variability and seismicity at the junction of the San Andreas and Calaveras faults, Abstract G32B-04 presented at 2013 Fall Meeting, AGU, Dec. 9-13, San Francisco, CA, 2013.

Johanson, I., R. Grapenthin, and R. Allen, "G-larmS: Real-time GPS at UC Berkeley”, Special Topic Session: High rate, real-time GPS for studies of earthquakes, volcanic eruptions and other major events, UNAVCO Science Workshop, March 4-6, 2014; Broomfield, CO

Johanson, I., R. Grapenthin, P. Lombard, D. Dreger and R. Allen, “High-rate GPS for Earthquake Early Warning and Rapid Response, Caltech Seismological Lab Seminar, March 14, 2014.

Johanson, I., “The BARD network: Two Decades of Multi-scale Deformation Measurements in

Northern California", California Spatial Reference Center Coordinating Council Semi-Annual Meeting, May 1, 2014

Johanson, I., D. Dreger, "Real-time GPS Strategies for Rapid Response Applications", AGU Fall Meeting 2012, December 3-7, 2012; San Francisco, CA

Johanson, I., "Earthquake Early Warning and Cascadia" GeoPRISMS/EarthScope Planning Workshop for the Cascadia Primary Site, April 5-6, 2012; Portland, OR