FINAL TECHNICAL REPORT

Upgrading the BARD continuous GPS network operated by the Berkeley Seismological Laboratory

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Abstract

The Bay Area Regional Deformation (BARD) network consists of 31 permanent, continuously operating GPS receivers, which monitor crustal deformation in the San Francisco Bay Area and northern California. Nineteen BARD stations are co-located with stations in the Berkeley Digital Seismic Network (BDSN). Each BDSN site consists of a broadband and strong motion seismic instrument, telemetered in real-time to the Berkeley Seismological Lab (BSL). Under this project, selected stations in the BARD network were upgraded with newer model receivers and antennas and six BDSN stations were upgraded with geodetic quality GPS instrumentation. The new stations are fully integrated into the data ingestion, archival and re-transmittal programs for the BARD network and are incorporated into daily processing and time series generation. The project also funded work to produce the computing resources necessary to generate position time series for each BARD station automatically and on a daily basis, as well as to make simple improvements to the network's website that allow these results to be easily communicated. Both of these tasks are complete with the results of automatic daily processing (using the GAMIT/GLOBK software package), as well as basic station information and data quality parameters posted to the BARD website on a daily basis.

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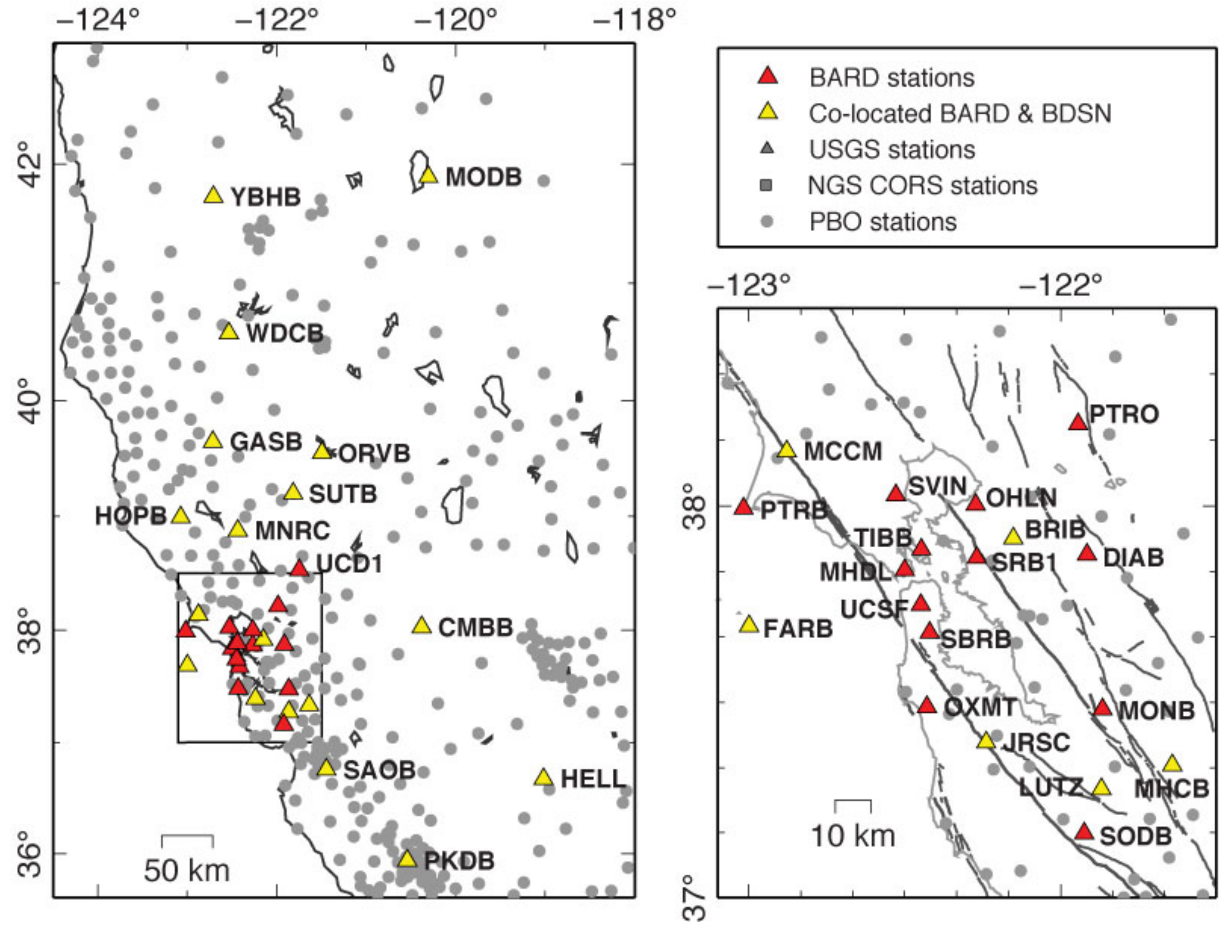
Introduction

In the San Francisco Bay Area, two 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. Geodetic measurements, which are particularly useful for detecting deformation and strain on deep structures throughout the earthquake cycle, show that Bay Area deformation is both spatially complex and varies with time. Understanding how this spatio-temporal variability affects strain accumulation on the faults is critical for assessment of the timing and hazards posed by future earthquakes.

The Bay Area Regional Deformation (BARD) network consists of permanent, continuously operating geodetic quality Global Positioning System (GPS) receivers, which monitor crustal deformation in the San Francisco Bay Area and northern California. BARD has been a collaborative effort between the Berkeley Seismological Laboratory (BSL), the USGS at Menlo Park, and several other academic, commercial and governmental institutions with the following goals: 1) to determine the distribution of deformation in northern California across the wide Pacific--North America plate boundary from the Sierras to the Farallon Islands; 2) to estimate three-dimensional interseismic strain accumulation along the SAF system in the Bay Area to assess seismic hazards; 3) to monitor hazardous faults and volcanoes for emergency response management; and 4) to provide geodetic infrastructure in northern California in support of related efforts within the surveying and other interested communities. Many of the BSL stations are collocated with broadband seismic stations of the Berkeley Digital Seismic Network (BDSN), allowing the acquisition of GPS data in real time through shared frame relay telemetry (Figure 1). The data are archived at the Northern California Earthquake Data Center (NCEDC), where they are available to the public over the internet. BARD has also made its data available to the community through the GPS Seamless Archive Center (GSAC). With new stations from this project, BARD now contains 31 stations, 30 are operated and maintained by the BSL (Figure 1).

BARD data are used in many applications, including the Bay Area Velocity Unification (BAVU) project. BAVU contains all available continuous and campaign data in Northern California and processes them in a consistent manner to produce a comprehensive and high-density velocity map showing strain accumulation across northern California and used to determine slip-rates on Bay Area faults (Figure 2, *d'Alessio et al*., 2005). BAVU relies on a network of continuous GPS stations to provide a framework on which the campaign data can be combined. With observations going back to 1992, BARD stations essential in providing such a framework. There is growing interest in collecting higher rates of data for a variety of applications. For example, GPS measurements can accurately track the propagation of earthquake dynamic motions both on the ground (e.g., *Larson et al*., 2003) and in the atmosphere (e.g., *Artru et al*., 2001, *Ducic et al.*, 2003), providing complementary information to seismic observations (calibration of integrated acceleration and velocity sensor data) and estimates of earth structure (direct observation of surface wave propagation over the oceans). Increasingly, GPS data also hold the potential to be used in real time to complement seismic data in providing robust real-time earthquake information, and, potentially, early warning (e.g. *Crowell et al*., 2009).



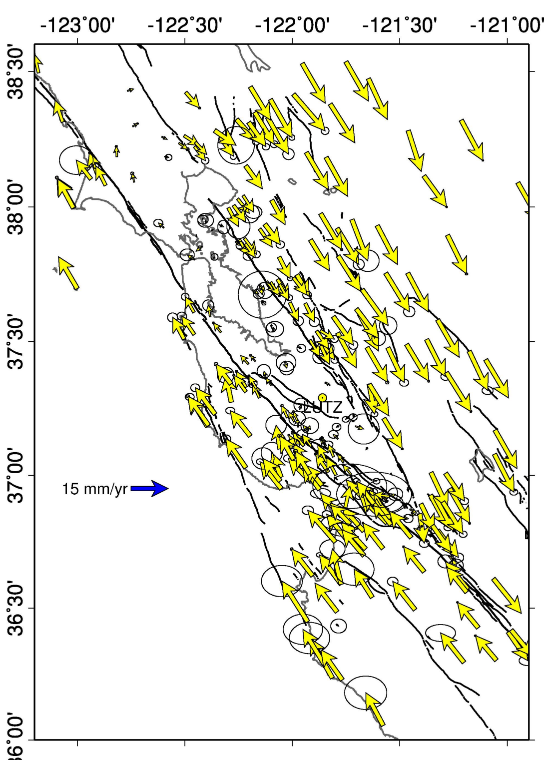


Figure 1 (above): Locations of stations in the BARD network (red and yellow triangles), highlighting those that are co-located with BDSN stations (yellow triangles), and in the context of other networks (grey symbols). Rectangle in large map at left is the extent of the smaller scale map at right. Fault lines are shown as thick grey lines on the small scale map at right.

Figure 2 (left): Velocities from BAVU3β, including BARD stations, as well as campaign, and PBO stations. Yearly velocities are relative to station LUTZ, marked by a yellow circle.

Project Results

The ARRA program funded three types of activities at the BSL: upgrade of equipment at existing BARD GPS stations, upgrade of BDSN stations with new GPS monuments, and generating the computing resources for automatic daily processing and publishing of time series. The BARD network now includes 19 out of 32 stations with ARRA funded Topcon Net-G3A GPS receivers. This represents the majority of the network and their performance has a major impact the overall performance of the network. During the course of the project, we encountered several problems with the receivers that required multiple site visits and many hours of additional work to debug and mitigate.

Problems encountered with ARRA provided equipment

An unanticipated major activity of the ARRA project was trouble-shooting and mitigating problems with the provided GPS receivers, Topcon Net-G3As. The two most major problems were a recurring loss of connectivity to the receiver, which would require power cycling (turning it off and on) to resolve and a failure of the automatic file rotation manager (AFRM), which resulted in failure to save data on-site.

The symptoms of the recurring connectivity problem are that the TCP/IP ports on the receiver become hung and do not allow any type remote connection. Data is still sometimes transmitted in

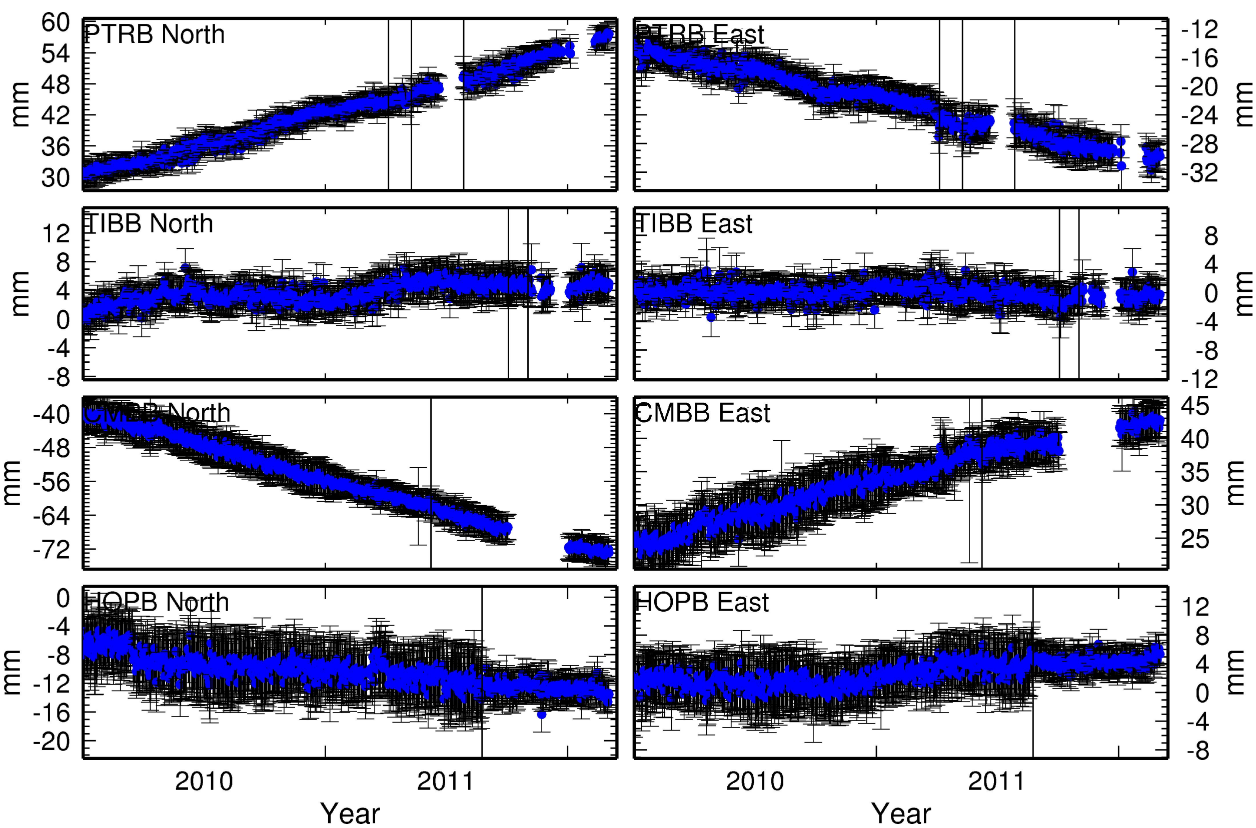


Figure 3: Time series of four stations with upgraded, Topcon Net-G3A receivers. Positions were stabilized in the ITRF2005 reference frame and then recast into a frame that holds station LUTZ stationary. All trends are therefore relative to LUTZ. Vertical black lines indicate times when the physical receiver was changed. PTRB, TIBB and CMBB all experienced data outages after being upgraded, which didn't occur prior to the upgrade (e.g. in 2010). Station HOPB is an example of a station whose position noise was markedly improved by its upgrade from a Trimble 4000SSI to a Topcon Net-G3A.

this mode, but once it is interrupted the only way to resume collecting data is to visit the site. This has resulted in numerous unanticipated visits to several sites, including 5 visits to station PTRB, a site that requires a full day of travel. The exact conditions for the failure are unknown, but three sites (PTRB, TIBB and CMBB) have been particularly affected, while some stations have never had a problem. For the AFRM failure, we were able to establish a work-around, where a script run in the lab remotely deletes files on the receiver, preventing it's file system from filling up. We have essentially duplicated a basic function of the receiver (that was required under the solicitation for bids): automatic data management, adequate to prevent loss.

Each of these problems by themselves represents a reduction on our network's reliability and acting together they caused unrecoverable data loss at several sites when the connection to the receiver hung while no data was being logged to disk (Figure 3). For all the issues we encountered with the Topcon receivers, we informed both Topcon and the USGS of what we encountered. We also participated in meetings with Topcon engineering to further explain our difficulties. We provided Topcon with network access to one of our problem receivers in the field, as well as physical access when that receiver became unresponsive. We provided as much information as possible, including our receiver configurations and network structure, but Topcon was unable to point to a problem and both of these issues are still outstanding.

Station Upgrades

A total of 14 existing BARD stations were upgraded with newer model GPS receivers and three received new choke-ring antennas (Table 1). Because of delays in receiving the ARRA equipment, we went ahead and performed two receiver upgrades and two antenna upgrades with spare Trimble NetRS and Ashtech Choke-ring antennas from our pool of spare equipment. The ARRA equipment has now replaced these in our set of stand-by receivers and antennas. The equipment used at these sites have many of the same features as the Topcon Net-G3A and represent a similar upgrade in functionality as the Net-G3As. The twelve remaining stations were upgraded with Topcon Net-G3A receivers and one station received a new Topcon choke-ring antenna.

Despite our problems with the Net-G3As connectivity and on-site storage, the data we received from the upgraded stations integrated smoothly into the daily processing and time series generation. In a couple cases, the upgraded receivers produced smaller daily formal errors in GAMIT/GLOBK and, for station HOPB, improved position stability (Figure 3). Before the upgrade, HOPB had a Trimble 4000SSI receiver, which is an even older model than the other replaced receivers (Ashtech UZ-12). Overall, when data was successfully collected from the receiver, it produced positions that were consistent with prior results with similar or better uncertainties.

Station Installations

Six BDSN stations were upgraded with GPS equipment, resulting in six new BARD stations (Table 1). One installation is still pending because the various delays in equipment procurement and trouble-shooting the Topcon receivers pushed it past the return of winter bad weather. Nonetheless, a candidate site has been identified and telemetry already exists for the co-located seismic station, such that installation is ready to proceed once the ground dries out. We also encountered a problem with the proposed station at BDSN site HAST. More specific investigations into the geology around the site revealed that a nearby ridge, which was the candidate site, is composed of highly mobile landslide material and was therefore unsuitable for a GPS monument. The decision was made to instead install a station at Potrero Hill (PTRO), which had both a suitable site and an existing telemetry pathway, such that the GPS station could be installed without additional expense over HAST.

Three types of monument design were used in the station installations. Stations JRSC and

WDCB (and HELL) are short brace monuments, composed of four legs cemented into bedrock. A "vault-mounted" monument was used for three stations where there was adequate sky view directly above the seismic vault. The seismic vaults are large structures, framed by a shipping container and cemented to bedrock. The GPS antennas are mounted on pipe embedded in the vault wall, for this purpose, at the time of construction. These made them relatively cheap to install. Some work had previously been done to construct the monument at PTRO, so we continued the installation of a concrete post monument anchored to the underlying substrate with cemented reinforcing rods. This is a type of monument we have used for other BARD stations (e.g. MONB), which has shown to be stable.

Site	Lon.	Lat.	Cmplt. Date	Receiver	Antenna	Time Series RMS (mm)			Avg. Daily Uncert. (mm)		
						N	E	U	N	E	U
New Monuments - Vault Mounted											
GASB	-122.716	39.655	6/17/11	**Topcon Net-G3A**	**Topcon Choke-ring**	1.8	1.7	10.0	4.7	3.9	21.6
MCCM	-122.880	38.145	9/28/11	**Topcon Net-G3A**	**Topcon Choke-ring**	1.8	2.3	10.9	5.3	6.5	29.3
MNRC	-122.443	38.879	7/7/11	**Topcon Net-G3A**	**Topcon Choke-ring**	0.9	0.9	4.6	2.3	2.2	8.4
New Monuments – Short Brace											
JRSC	-122.227	37.406	11/17/11	**Topcon Net-G3A**	**Topcon Choke-ring**	0.6	1.0	5.5	2.1	2.0	7.6
WDCB	-122.541	40.580	5/6/11	**Topcon Net-G3A**	**Topcon Choke-ring**	1.7	1.7	7.5	6.0	4.9	22.4
New Monument – Anchored Concrete Post											
PTRO	-121.944	38.209	12/8/11	**Topcon Net-G3A**	**Topcon Choke-ring**	0.5	0.4	3.0	2.9	2.6	10.5
Existing Monuments											
BRIB	-122.153	37.919		Trimble NetRS	Ashtech Choke-ring	2.4	2.1	5.4	2.7	2.5	10.3
CMBB	-120.386	38.034	6/8/11	**Topcon Net-G3A**	Ashtech Choke-ring	0.8	1.4	5.4	3.6	3.7	13.9
DIAB	-121.916	37.879		Trimble NetRS	Ashtech Choke-ring	1.6	1.1	4.5	2.4	2.3	8.9
FARB	-123.001	37.697		Trimble NetRS	Ashtech Choke-ring	0.7	1.4	3.4	1.9	2.0	6.8
HOPB	-123.075	38.995	8/24/11	**Topcon Net-G3A**	Ashtech Choke-ring	1.5	1.3	10.1	3.2	3.1	13.6
LUTZ	-121.865	37.287	6/24/11	**Topcon Net-G3A**	Ashtech Choke-ring	2.4	1.0	3.8	2.3	2.3	8.0
MHCB	-121.643	37.342	10/17/10	**Trimble NetRS**	Ashtech Choke-ring	1.4	1.7	2.8	1.8	1.9	6.2
MHDL	-122.494	37.842	1/5/11	Trimble NetRS	**Ashtech Choke-ring**	1.8	2.0	9.5	3.3	3.0	12.5
MODB	-120.303	41.902		Trimble NetRS	Ashtech Choke-ring	1.4	1.6	7.1	3.3	3.2	12.4
MONB	-121.871	37.499	8/25/11	**Topcon Net-G3A**	Ashtech Choke-ring	0.8	1.3	3.3	2.1	2.1	7.2
OHLN	-122.274	38.007	1/6/11	**Topcon Net-G3A**	Ashtech Choke-ring	2.9	2.3	3.4	2.5	2.5	9.1

Site	Lon.	Lat.	Cmplt. Date	Receiver	Antenna	Time Series RMS (mm)			Avg. Daily Uncert. (mm)		
						N	E	U	N	E	U
ORVB	-121.500	39.555		Trimble NetRS	Ashtech Choke-ring	0.9	1.3	7.0	2.4	2.3	8.5
OXMT	-122.424	37.499	3/29/11	**Topcon Net-G3A**	Ashtech Choke-ring	1.3	1.6	5.9	3.0	2.7	12.1
PKDB	-120.542	35.945		Trimble NetRS	Ashtech Choke-ring	1.7	1.1	4.4	2.9	2.9	11.3
PTRB	-123.015	37.996	4/5/11	**Topcon Net-G3A**	Ashtech Choke-ring	1.1	1.5	4.0	2.2	2.2	7.5
SAOB	-121.447	36.765		Trimble NetRS	Ashtech Choke-ring	1.2	1.2	3.3	2.3	2.4	8.3
SBRB	-122.411	37.686	4/15/11	**Topcon Net-G3A**	Ashtech Choke-ring	1.8	3.4	6.3	4.5	3.8	17.6
SODB	-121.926	37.166	6/24/11	**Topcon Net-G3A**	Ashtech Choke-ring	2.4	1.8	5.2	3.4	3.2	13.1
SRB1	-122.267	37.874	3/30/11	**Topcon Net-G3A**	**Topcon Choke-ring**	3.8	1.2	4.0	2.7	2.5	9.9
SUTB	-121.821	39.206	3/11/10	**Trimble NetRS**	Ashtech Choke-ring	2.2	2.2	4.4	2.5	2.3	8.2
SVIN	-122.526	38.033	3/21/11	**Topcon Net-G3A**	Ashtech Choke-ring	0.9	1.3	4.3	2.0	1.9	7.0
TIBB	-122.448	37.891	10/3/11	**Topcon Net-G3A**	Ashtech Choke-ring	1.3	1.3	3.3	2.3	2.4	9.0
UCD1	-121.751	38.536		Trimble NetRS	Trimble Choke-ring	1.4	1.8	12.6	2.3	2.3	8.2
UCSF	-122.458	37.763	9/23/11	Trimble NetRS	**Ashtech Choke-ring**	1.8	1.4	4.3	2.6	2.4	9.3
YBHB	-122.711	41.732		Trimble NetRS	Ashtech Choke-ring	2.8	3.9	7.7	2.9	2.6	10.6

Table 1: Table of BARD stations with receiver and antenna type. Sites with names and equipment in bold type were upgraded under this project. Cmplt. Date is date ARRA work was completed. Time Series RMS is the RMS of the cleaned time series residuals after removing earthquake offsets and secular velocity and represents the repeatability of the station positions. Average daily uncertainty is the average formal error determined independently for each day by GAMIT/GLOBK.

Monument Performance

All of the monuments have performed well in the short time they have been operational. Table 1 lists the RMS of the station time series and the average daily uncertainty, which together can inform us on the station's current performance and potential future performance. For all the new stations, we still have less than a year of data, so the evaluation necessarily must be for short-term stability. The longer-term stability of the monuments will need to be evaluated after 2-3 years.

The average daily uncertainty is calculated from the formal error estimated independently by GAMIT/GLOBK during each day of processing. This quantity will be large if there is poor sky view and/or large amounts of multi-path at the site. For GASB, MCCM and WDCB, this value is higher than typical for BARD stations (Figure 4, Table1). These sites all have challenging sky view environments, but we nonetheless believe they are adequate based on the RMS values (see below). Better nearby sites were not available for any of these sites and we were constrained in our ability to choose locations by the necessity of sharing telemetry with the BDSN station.

The time series RMS is a measure of the scatter in the cleaned time series and thus represents the short-term stability of the monument. Both poor satellite coverage and a "wobbly" monument can

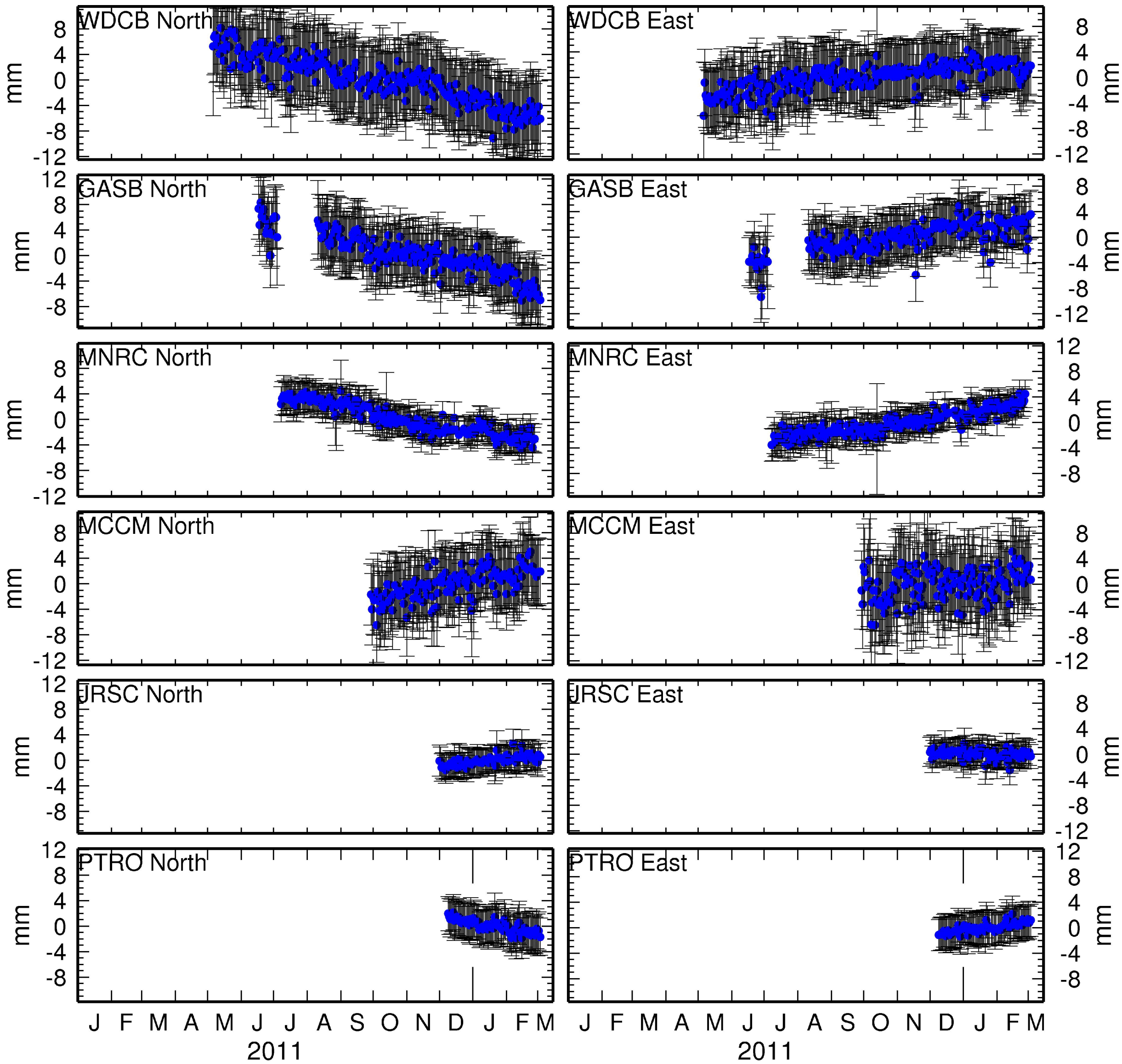


Figure 4: Time series from six new BARD stations, co-located with BDSN sites. Positions were stabilized in the ITRF2005 reference frame and then recast into a frame that holds station LUTZ stationary. All trends are therefore relative to LUTZ. The size of the error bars and visible scatter in the data can be compared with the calculated values in Table 1.

contribute to a high RMS. All the new stations have RMS values on a par with those of existing BARD stations. Furthermore the stations with slightly higher RMS (GASB, MCCM, WDCB) are also those with higher average uncertainty, suggesting that their scatter results from their environment, rather than from monument instability. On this time scale, there is therefore no indication that the vault-mounted monuments are less stable than the short brace. A further analysis when 2-3 years of data are available will show whether these monuments are stable on longer time periods and correctly reflect tectonic motion.

Data Management Practices

All data collected from BARD/BSL stations are publicly available at the Northern California Earthquake Data Center (NCEDC, http://www.ncedc.org, ftp://www.ncedc.org/pub/gps), both as raw data and converted into RINEX format. Data from new stations were generally available to the community within 24 hours of installation. All sites collect data at 1 Hz rate and are additionally down-sampled to 15-sec sampling and archived in RINEX format to facilitate low-rate processing. We also 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.

Data from all BARD stations are also available to the community as a real-time stream in BINEX and RTCM formats. Again, these streams were generally available within 24 hours of station installation. For information on accessing these streams, see http://seismo.berkeley.edu/bard/realtime.

Daily processing for position time series

The ARRA program supported development of computing resources to establish automatic daily processing of BARD data and improvements to the website to facilitate communicating the results. BARD data are now processed within 24 hours using IGS rapid orbit information and station time series are updated immediately. The BARD network is processed as two subnetworks in GAMIT (*King and Bock*, 2000; *Herring et al*., 2010a), which are combined using GLOBK (*Herring et al*., 2010b) to produce the complete BARD solution. Station positions are stabilized in the ITRF2005 reference frame (*Altamimi et al*., 2007) and the time series are updated. 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 updated again. All of the data are processed for a second time, using GAMIT, once final IGS orbits become available (2-3 weeks) and are combined with IGS and PBO final solutions. The time series is then updated for the last time with the final positions.

After each update, both raw and clean time series are generated. Cleaning consists of removing offsets from earthquakes and postseismic transients, removing outliers, and common mode errors. Earthquake offsets, postseismic decay, and station velocities are estimated using est_noise (*Langbein*, 2004), which also analyzes the noise structure of the time series, providing estimates for the white and random walk noise. The common mode errors are determined by stacking the residuals after removing the earthquake parameters and trend for all BARD and selected Bay Area PBO stations.

Website improvements

While the proposal's reviewers did not find it necessary for us to make large changes to our website, we were asked to make, and have accomplished making, simple changes to improve how the daily processing results and other information are accessed. The BARD website now houses station information and data quality information, as well as providing links to full station metadata, housed at the NCEDC. Improvements to the BARD website (http://seismo.berkeley.edu/bard) include creating individual station pages that include photos, a brief description of the station, its location, its current equipment and links to available data. Each station page includes plots and links to data files of station displacement time series, which are updated daily. Figures summarizing the data quality parameters are also shown on the station page, with plots over the entire lifetime of the station and over the past year.

Time series are available for each station from their individual station page (e.g. http://seismo.berkeley.edu/bard/bard_station_book/brib.html for station BRIB). Station pages are accessible from http://seismo.berkeley.edu/bard/bard_station_book/bard_station_book.html

Aggregates of time series for the past year can also be found at the following locations.
Raw time series: http://seismo.berkeley.edu/bard/timeseries/timeseries_raw.html
Raw, detrended timeseries: http://seismo.berkeley.edu/bard/timeseries/timeseries_cln.html
Clean time series: http://seismo.berkeley.edu/bard/timeseries/timeseries_raw_res.html
Clean, detrended time series: http://seismo.berkeley.edu/bard/timeseries/timeseries_cln_res.html

Conclusions

Fourteen stations in the BARD network were upgraded with newer model receivers and antennas and six BDSN stations were upgraded with geodetic quality GPS instrumentation. The new stations are fully integrated into the data ingestion, archival and re-transmittal programs for the BARD network and are incorporated into daily processing and time series generation. While three of the new sites have challenging sky views that lead to higher uncertainties in their daily position, the position stability, over the time since they've been installed, is good. This leads us to have confidence that these sites will all be reliable members of the network. The project also funded work to produce the computing resources necessary to generate position time series for each BARD station automatically and on a daily basis, as well as to make simple improvements to the network's website that allow these results to be easily communicated (http://seismo.berkeley.edu/bard). Both of these tasks are complete with the results of automatic daily processing (using the GAMIT/GLOBK software package), as well as basic station information and data quality parameters posted to the BARD website on a daily basis

References

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B., & Boucher, C. (2007). ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. *J. Geophys. Res.*, *112*(B9), B09401–. American Geophysical Union. doi:10.1029/2007JB004949

Artru, J., Lognonné, P., & Blanc, E. (2001). Normal modes modelling of post-seismic ionospheric oscillations. *Geophys. Res. Lett.*, *28*(4), 697–700.

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

d'Alessio, M. A., Johanson, I. A., Bürgmann, R., Schmidt, D. A., & Murray, M. H. (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

Ducic, V., Artru, J., & Lognonné, P. (2003). Ionospheric remote sensing of the Denali Earthquake Rayleigh surface waves. *Geophys. Res. Lett.*, *30*(18). doi:10.1029/2003GL017812

Herring, T. A., King, R. W., & McClusky, S. C. (2010a). *GAMIT: GPS Analysis at MIT - Release 10.4* (pp. 1–171). MIT. Retrieved from http://www-gpsg.mit.edu/~simon/gtgk/GAMIT_Ref.pdf

Herring, T. A., King, R. W., & McClusky, S. C. (2010b). *GLOBK: Global Kalman filter VLBI and GPS analysis program - Version 10.4* (pp. 1–95). MIT. Retrieved from http://www-gpsg.mit.edu/~simon/gtgk/GLOBK_Ref.pdf

King, R., & Bock, Y. (2000). Documentation for the GAMIT GPS Analysis Software - Release 10.0. *MIT/SIO*, 1–206. Retrieved from http://www-gpsg.mit.edu/~simon/gtgk/GAMIT.pdf

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

Larson, K., Bodin, P., & Gomberg, J. (2003). Using 1-Hz GPS data to measure deformations caused by the Denali fault earthquake. *Science*, *300*(5624), 1421–1424.