FINAL TECHNICAL REPORT

- AWARD NUMBER: **04HQAG0112**
- RECIPIENT: Regents of the University of California
- PRINCIPAL INVESTIGATOR: Barbara Romanowicz
- TITLE: The BARD Continuous GPS Network:
  Monitoring active deformation and strain accumulation in
  northern California and the San Francisco Bay Area:
  Collaborative research with UC Berkeley,
  and U.S. Geological Survey, Menlo Park
- PROGRAM ELEMENTS: I & II

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THE BARD CONTINUOUS GPS NETWORK:
MONITORING ACTIVE DEFORMATION AND STRAIN ACCUMULATION IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA:
Collaborative research with UC Berkeley,
and U.S. Geological Survey, Menlo Park

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1. TECHNICAL ABSTRACT

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area and northern California . It is a cooperative effort of the Berkeley Seismological Laboratory (BSL), the United States Geological Survey (USGS), and several other academic, commercial, and governmental institutions. 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 and volcanoes for emergency response management.

During this reporting period, the BARD network expanded during the three years of this project (April 1, 2004 to March 31, 2007) from 25 to 30 sites. The BSL upgraded existing stations and four new dual-frequency stations. Procedures were improved for analyzing BARD data, both in near real-time and for long-term deformation analysis. Results from this analysis were used to study the M_w 6.0 2004 Parkfield earthquake. The results provided new constraints on the finite fault slip solution.

Analysis of data from BARD and other continuous stations in northern California and Nevada show that the horizontal interseismic deformation is consistent with a simple 10-parameter model using 6 rigid plates and 3 locked San Andreas system faults. Deformation can be partitioned into 2.4 mm yr^{-1} east-west extension across the Wasatch fault, 2.3 mm yr^{-1} east-west extension across the Central Nevada Seismic Zone, 3.6 mm yr^{-1} primarily right-lateral strike-slip on the Northern Walker Lane Belt and 37.2$\pm$1.0 mm yr^{-1} slip rate across the San Andreas system in the Bay Area. The Sierran-Great Valley block moves obliquely to the San Andreas system, with $\sim$2.4$\pm$0.4 mm yr^{-1} of fault-normal convergence being accommodated over a narrow ($<$15 km) zone, which may contribute to uplift of the Coast Ranges. All the results will be presented in an upcoming peer reviewed publication.

2. CURRENT NETWORK

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.,* 1998, *Houlie and Romanowicz,* 2006). It is a cooperative effort of the BSL, the USGS, and several other academic, commercial, and governmental institutions. Started by the USGS in 1991 with 2 stations spanning the Hayward fault (*King et al.,* 1995), by April 2004, the BARD network included over 70 continuously operating stations in the Bay Area and northern California, including 14 near Parkfield along the central San Andreas fault, and 17 near the Long Valley caldera near Mammoth. The arrival of the Earthscope-PBO network changed the C-GPS network configuration in the western US. Fifty sites are being transferred from BARD to PBO in the frame of the *PBO-nucleus* NSF-funded project. The BSL continues to operate 30 stations (26 dual-frequency and 4 mono-frequency receivers) mainly collocated with other geophysical sensors.

Recent additions to the BARD network in the Parkfield and San Francisco Bay area were made in cooperation with external companies. The Site EBMD was reactivated this year, and is providing 1Hz data. The objective of this site is to provide to East Bay Mud District Utilities (EBMD) updated reference site coordinates in order to constrain survey localizations. We are actively cooperating with PBO and East Bay Regional Parks, to convert the East Bay PBO sites into 1Hz. The goal of this pilot project is to provide Real Time correction (RTCM) to East Bay Park users . The BSL archive all the data collected in such collaboration. The newly collected dataset will be available through the Northern California Earthquake Data Center (NCEDC) facility (http://www.ncedc.org).

The BSL stations are either collocated with seismic instrumentation or are located near the San Andreas fault where real-time processing of the GPS data for earthquake notification is a high priority. We are working closely with UNAVCO to facilitate the transition of the 25 stations, including most of the Parkfield network, and are acting in an advisory role on siting issues for the planned new installations.

Today, raw and RINEX data files from the BSL stations and the other stations run by BARD collaborators are archived at the BSL/USGS NCEDC(*Romanowicz et al.,* 1994). The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 2 hours of collection, to all BARD participants and other members of the GPS community through Internet, both by anonymous FTP and through the World Wide Web (`http://quake.geo.berkeley.edu/bard/`).

Many of the BARD sites are classified as CORS stations by the NGS, and are used as reference stations with the surveying community. We coordinate efforts with surveying community at meetings of the Northern California GPS Users Group and the California Spatial Reference Center, and are currently developing plans to use the existing infrastructure at the NCEDC to provide a hub for a high-frequency real-time surveying network in the Bay Area. Data and ancillary information about BARD stations are also made compatible with standards set by the International GPS Service (IGS), which administers the global tracking network used to estimate precise orbits and has been instrumental in coordinating the efforts of other regional tracking networks. The NCEDC also retrieves data from other GPS archives, such as at SIO, JPL, and NGS, in order to provide a complete archive of all high-precision continuous GPS measurements collected in northern California.

2.1 BARD Station Configuration

Most of the BSL BARD stations use a low-multipath choke-ring antenna, most of which are mounted to a reinforced concrete pillar approximately 0.5–1.0 meter above local ground level. The reinforcing steel bars of the pillar are drilled and cemented into rock outcrop to improve long-term monument stability. 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. Most use Ashtech Z-12 receivers that are programmed to record data once every 30 seconds and observe up to 12 satellites

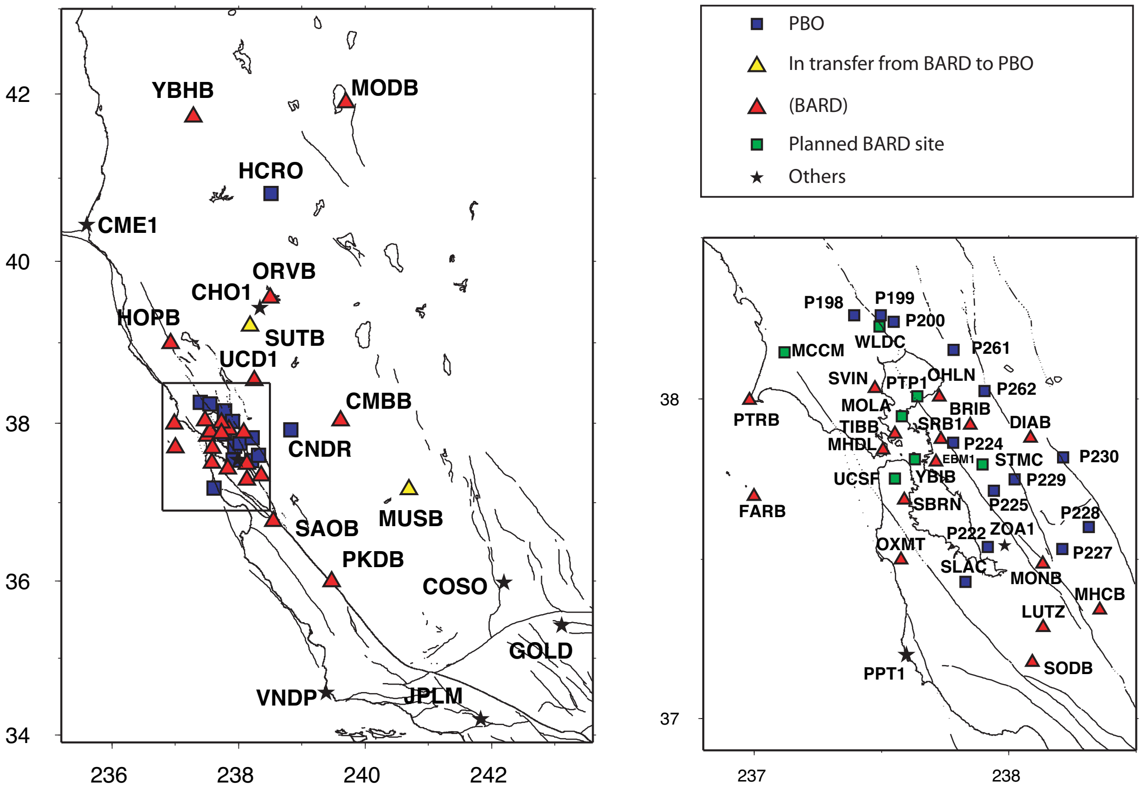


Figure 1: Map of the BARD network and surrounding GPS sites in northern California. In addition there are 4 L1 sites in the Berkeley Hills not indicated in the figure

simultaneously at elevations down to the horizon. The Z-12 receivers are aging and a large number of failures occurred in the last months. We started to upgrade sites (BRIB, MHDL, and MODB) with Trimble NETRS receivers. This will allow us to increase the sampling rate at sites where the bandwidth is limited. The BARD sampling rate objective is 1Hz. The antennas are equipped with SCIGN antenna adapters and hemispherical domes, designed to provide security and protection from weather and other natural phenomena, and to minimize differential radio propagation delays.

Data from most BSL-maintained stations are collected at 30-second intervals and transmitted continuously over serial connections. Station TIBB uses a direct radio link to Berkeley, and MODB uses VSAT satellite telemetry. Most stations use frame relay technology, either alone or in combination with radio telemetry. Fourteen GPS stations are collocated with broadband seismometers and Quanterra data loggers. With the support of IRIS we developed software that converts continuous GPS data to MiniSEED opaque blockettes that are stored and retrieved from the Quanterra data loggers (*Perin et al.*, 1998), providing more robust data recovery from onsite disks following telemetry outages.

Data from DIAB, MONB, POTB, and TIBB in the Bay Area, the 4 Mini-PBO stations, and 13 stations in the Parkfield region (all but PKDB), are now being collected at 1-second intervals. Collecting at such high-frequency (for GPS) allows dynamic displacements due to large earthquakes to be better measured, such as was demonstrated by several studies following the 2002 Denali fault earthquake. However, this 30-fold increase in data rate create telemetry bandwidth limitations. Data from the Parkfield stations are collected on an on-site computer, written to removable disk once per month, and sent to SOPAC for long-term archiving (decimated 30-sec data is acquired daily via the BSL frame relay circuit). In the Bay Area, we have converted stations that have sufficient bandwidth and are currently assessing bandwidth issues at other stations. We are planning to convert to 1-second sampling where possible during the next year.

The BSL also operates several Wi-Lan VIP 110-24 VINES Ethernet bridge radios. These 2.4 GHz spread spectrum radios use a tree structure to create a distributed Ethernet backbone with speeds up to 11 Mbps. Each system uses a directional antenna to talk to its "parent" in the tree, and an omni-directional antenna to talk to its children, if multiple, or a directional antenna if it has only 1 child. These radios offer several advantages over the Freewave radios used at other sites, including TCP/IP Ethernet control, higher bandwidth, and greater flexibility for setting up networks. We installed a set of Wi-Lan radios at the SVIN Mini-PBO station to transmit data from the site to the frame relay circuit, and are assisting EBMUD in converting their continuous stations to real-time telemetry using Wi-Lan radios.

3. 2004-2007 DEVELOPMENTS

Here we review some of the important developments of the BARD network during the contract period.

3.1 Bay area

We are planning to install five sites in the SF bay area in order to densify the BARD coverage in the north bay. The new sites will be collocated with seismic existing instruments. The sites have been recognized and the contact with project managers done.

A new site (SRB1), has been installed in the seismically safe SRBI building, at the intersection of Hearst and Oxford avenues. This site is operating a Trimble 4000 SST receiver with a Trimble Zephyr antenna. This site is operational since August 2006.

In September 2006, the first observations at Marin Headlands (MHDL) started to be recorded and included in the NCEDC. This site was the last pending site of the mini-PBO network. The mini-PBO network now include five sites (MHDL, OHLN, OXMT, SBRN and SVIN). Each site is collocated with borehole strain-meters and geophones.

3.2 Mini-PBO Station Installations

The *Mini-PBO* program supported the installation of stations along the Hayward and San Andreas faults in the San Francisco Bay area to complement existing instrumentation (Figure 1). From July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers. The strainmeters were recently developed by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. Installation of pore pressure sensors and 2-component tiltmeters was completed at all the stations by the USGS in Spring 2003. The last site MHDL was installed during the last period and the first GPS and seismic data are available since the end of the summer 2006.

The BSL developed an experimental GPS mount for the top of the borehole casings to create a stable, compact monument. The antennas, using standard SCIGN adapters and domes for protection, are attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level is cemented fully to the surrounding rock. The current design, which has been adopted by PBO for use at their borehole strainmeter stations, uses a flange that is permanently attached to the top of the casing, which allows access to the borehole for instrument maintenance, and a top plate with the vertical pipe and antenna adapter that is bolted to the flange. Several dowels between the flange and top plate ensure that the top plate can be removed and reattached with better than 0.1 mm repeatability.

The first velocity and coordinates solutions are available for the mini-PBO sites. These accuracies are similar to those obtained with more typical monuments, such as concrete piers or braced monuments, but it is too early to assess the long-term stability of the borehole casing monument, which might also be affected by annual thermal expansion effects on the casing.

3.3 Parkfield Network

The Parkfield network is maintained in close collaboration with USGS and the SOPAC group at U.C. San Diego. BSL is in charge of retrieving the data for the rinex format. The data are included in the NCEDC server from where PBO is retrieving the data. The real-time streaming and real-time analysis have not been completed because the bandwidth available between Parkfield and BSL is not able to handle continuous important data flow. The data are still retrieved hourly.

3.4 Station Upgrades and Maintenance

During the contract period, we upgraded and performed routine maintenance on a number of the GPS stations in the BARD network. Some of the highlights include:

1) In the Fall 2005, all the Ashtech receivers bought to operate the mini-PBO network have been repaired to solve a capacitor defect.

2) In September 2006, the first observations at Marin Headland site (MHDL) started to be recorded and included in the NCEDC. This site was the last pending site of the mini-PBO network. The mini-PBO network now includes five sites (MHDL, OHLN, OXMT, SBRN and SVIN).

3) In the fall 2006, BSL signed an agreement to maintain 12 sites in Northern California. which will be converted to PBO standards in the next year. BSL is in charge of downloading data at theses sites. The raw data are sent to PBO by FTP.

3.5 Data Archival and Distribution

Raw and Rinex data files from the BSL stations and the other stations run by BARD collaborators are archived at the BSL/USGS Northern California Earthquake Data Center (NCEDC) data archive maintained at the BSL (*Romanowicz et al.*, 1994). The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 2 hours of collection, to all BARD participants and other members of the GPS community through Internet, both by anonymous ftp and through the World Wide Web (`http://quake.geo.berkeley.edu/bard/`).

Data and ancillary information about BARD stations are also made compatible with standards set by the International GPS Service (IGS), which administers the global tracking network used to estimate precise orbits and has been instrumental in coordinating the efforts of other regional tracking networks. The NCEDC also retrieves data from other GPS archives, such as at SIO, JPL, and NGS, in order to provide a complete archive of all high-precision continuous GPS measurements collected in northern California.

Many of the BARD sites are classified as CORS stations by the NGS, which are used as reference stations by the surveying community. All continuous stations operating in July 1998 were included in a statewide adjustment of WGS84 coordinates for this purpose. Members of the BARD project regularly discuss these and other common issues with the surveying community at meetings of the Northern California GPS Users Group.

Since 1997, the NCEDC has collaborated with UNAVCO and other members of the GPS community on the development of the GPS Seamless Archive Centers (GSAC) project. This project allows a user to access the most current version of GPS data and metadata from distributed archive locations. The NCEDC is participating at several levels in the GSAC project: as a primary provider of data collected from core BARD stations and USGS MP surveys, as a wholesale collection point for other data collected in northern California, and as a retail provider for the global distribution of all data archived within the GSAC system. We have helped to define database schema and file formats for the GSAC project, and for several years have produced complete and incremental monumentation and data holdings files describing the data sets that are produced by the BARD project or archived at the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings. Currently, the NCEDC is the primary provider for over 74,000 data files from over 1400 continuous and survey-mode monuments. There is no current further development planned for this project.

4. 2001-2004 DEFORMATION MONITORING

4.1 Data Analysis and Quality

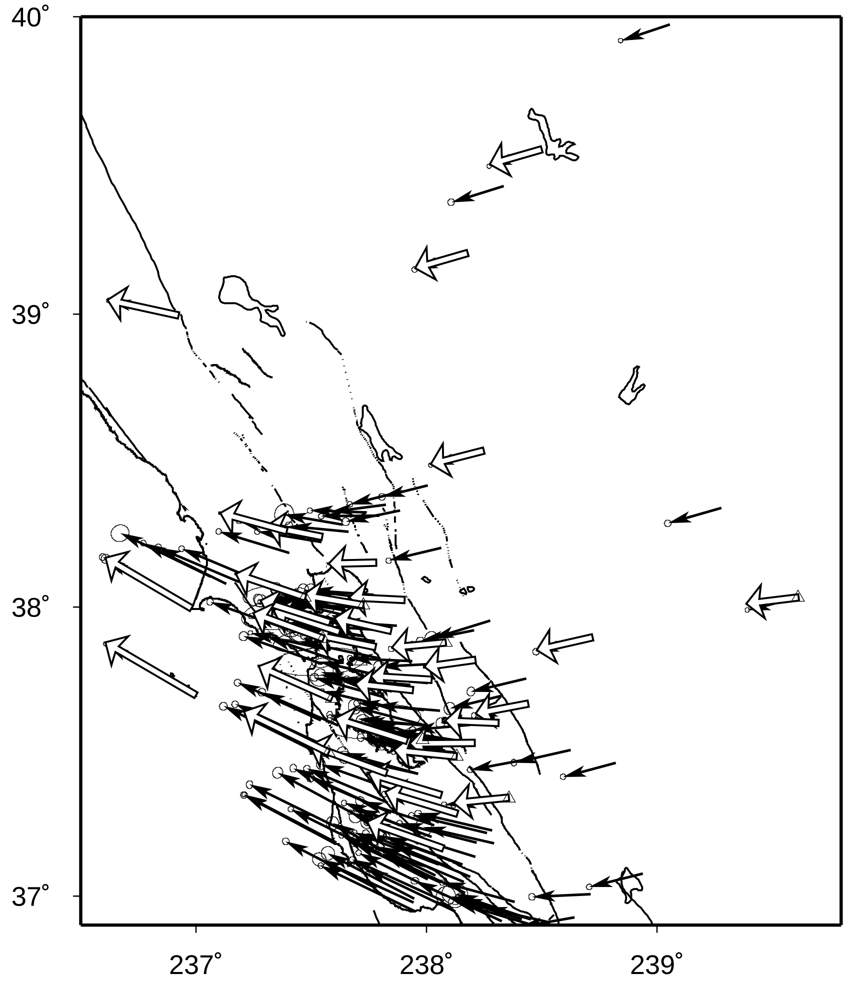


Figure 2: Comparison of the BARD solutions (white arrows) with the Bay Area Velocity Unification (BAVU, *d'Alessio et al.*, 2005) solutions (black arrows). All the data available at the BSL between 1994 and 2006 have been reprocessed (From *Houlié and Romanowicz,* 2006).BAVU website: http://seismo.berkeley.edu/ burgmann/RESEARCH/BAVU/

The data from the BARD sites generally are of high quality and measure relative horizontal positions at the 2–4 mm level. The 24-hour RINEX data files are processed daily with an automated system using high-precision IGS orbits. Final IGS orbits, available within 7–10 days of the end of a GPS week, are used for final solutions.

Preliminary solutions for network integrity checks and rapid fault monitoring are also estimated from Predicted IGS orbits (available on the same day) and from Rapid IGS orbits (available within 1 day). Data from 5 primary IGS fiducial sites located in North America and Hawaii are included in the solutions to help define a global reference frame. Average station coordinates are estimated from 24 hours of observations using the GAMIT software developed at MIT and SIO, and the solutions are output with weakly constrained station coordinates and satellite state vectors.

Processing of data from the BARD and other nearby networks is processed by GAMIT software. An additional solution including only the BARD site is also computed. The weakly constrained solutions are combined using the GLOBK software developed at MIT, which uses Kalman filter techniques and allows tight constraints to be imposed a posteriori. This helps to ensure a self-consistent reference frame for the final combined solution. These daily coordinate-only solutions are then combined with tight coordinate constraints to estimate day-to-day coordinate repeatabilities, temporal variations, and site velocities. The velocities are presented in Table 1.

The estimated relative baseline determinations typically have 2–4 mm WRMS scatter about a linear fit to changes in north and east components and the 10–20 mm WRMS scatter in the vertical component. Average velocities for the longest running BARD stations during 1993–2006 are shown in Figure 2, with 95% confidence regions. We have allowed 1 mm $yr^{-1/2}$ random-walk variations in the site positions in order to more accurately characterize the long-term stability of the site monuments and day-to-day correlations in position. The velocities are defined in the ITRF2000 (*Altamimi et al.*, 2002).

The first preliminary results suggest that the Pacific Plate is strongly rigid and does not experience any deformation west of the San Andreas fault. This is indicated by small residual velocities of the sites located west of the San Andreas fault and supported by a small seismicity level in the same area. The rigidity state would thus induce a large deformation contrast on both sides of the San Andreas fault. This new discovery justifies modeling of the fault dislocation by using an algorithm allowing for asymetrical geometries.

4.2 Parkfield Earthquake

The Parkfield earthquake study is an ongoing project at BSL. The 12 sites (Figure 3) are daily computed with the BARD sites (including PKDB).

Regarding the 2004 seismic event, static GPS solutions have been released in the past (*Langbein et al., 2005*). A new solution including the closest stations to the fault MIDA and CARH was recently computed (Figure 3) and included in the finite fault motion model under development at BSL. Indeed, close to the fault, the broadband seismometers clipped, the GPS sensors which are less sensitive to the high-frequency content ($T \leq 5$ seconds) of the seismic energy, remain stable. The GPS network provides additional constraints that can be inverted jointly with strong-motion seismic data (*Dreger et al.*, 2005, *Kim and Dreger*, 2006).

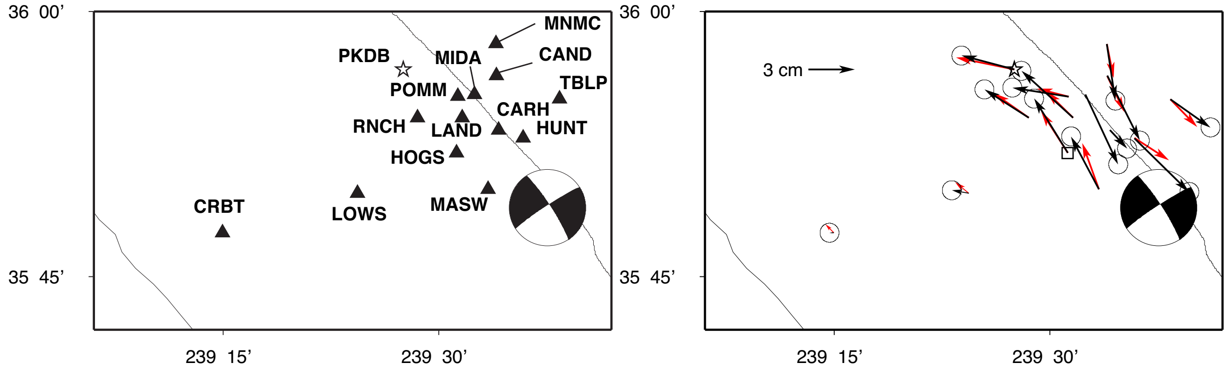
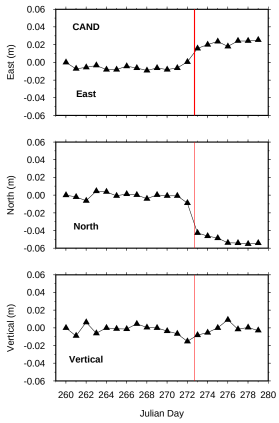


Figure 3: a) Map of the Parkfield GPS monitoring network. The location and the focal mechanism of the event is indicated. b) Coseismic displacement. We compare here the two BSL solutions together. Both solutions seem in agreement while the processing strategies are very different (static (black) versus rapid static(red)).

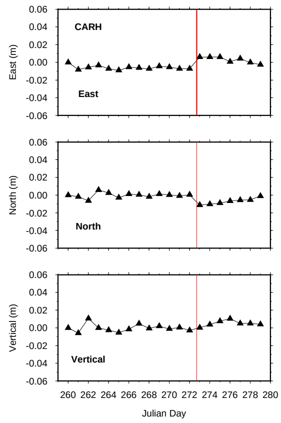
Daily coordinates time-series have been computed and allow to assess both coseismic displacements and changes of trends during the first hours following the mainshock. Time series are presented in Figures 4 to 9. The vertical displacements at the GPS sites during the seismic event are mostly close to zero and all of them are less than the half of the repeatability noise on the vertical component ($\sim 1cm$).

Site	Lon.	Lat	Ve (mm/y)	Vn (mm/y)	σ_e (mm/y)	σ_n (mm/y)	Start
BAY1*	197.29	55.19	-6.3	-25.5	0.0000	0.0000	1996.08
BAY2	197.29	55.19	-5.6	-25.2	0.0400	0.0300	1996.08
BRIB	237.85	37.92	-24.8	5.6	0.0100	0.0100	1993.58
CMBB	239.61	38.03	-22.9	-2.8	0.0100	0.0100	1993.92
CNDR	238.72	37.90	-24.4	-5.5	0.0200	0.0200	1999.27
DIAB	238.08	37.88	-23.7	-2.2	0.0100	0.0100	1998.33
FARB	237.00	37.70	-39.8	23.3	0.0100	0.0100	1994.00
GOLD*	243.11	35.43	-18.2	-5.4	0.0000	0.0000	1989.95
HCRO	238.53	40.82	-18.0	-8.7	0.1400	0.1500	2003.50
HOPB	236.93	39.00	-31.1	6.8	0.0100	0.0100	1995.58
JPLM*	241.83	34.21	-36.6	11.8	0.0000	0.0000	1989.44
LUTZ	238.14	37.29	-31.7	9.5	0.0100	0.0100	1996.33
MHCB	238.36	37.34	-24.2	-2.4	0.0100	0.0100	1996.33
MODB	239.70	41.90	-16.9	-9.1	0.0200	0.0200	1999.83
MOLA	237.58	37.95	-30.5	9.7	0.0100	0.0100	1993.75-2002.22
MONB	238.13	37.49	-27.5	2.7	0.0100	0.0100	1998.50
MUSB	240.69	37.17	-22.3	-4.0	0.0100	0.0100	1997.83
OHLN	237.73	38.01	-26.4	4.4	0.0200	0.0200	2001.83
ORVB	238.50	39.56	-22.7	-6.6	0.0100	0.0100	1996.83
OXMT	237.58	37.50	-36.9	18.0	0.0600	0.0600	2004.12
P181(PBO)	237.62	37.92	-29.0	9.6	0.3800	0.4000	2005.09
P198 (PBO)	237.39	38.26	-29.2	7.9	0.0900	0.1000	2004.77
P200 (PBO)	237.55	38.24	-24.3	4.7	0.2000	0.2200	2005.73
P222 (PBO)	237.92	37.54	-31.5	10.0	0.1100	0.1200	2005.26
P224 (PBO)	237.78	37.86	-26.9	5.5	0.1000	0.1100	2005.25
P225 (PBO)	237.94	37.71	-25.2	2.7	0.0900	0.1000	2005.14
P227 (PBO)	238.21	37.53	-28.6	-0.4	0.5800	0.6300	2006.20
P228 (PBO)	238.31	37.60	-23.5	1.0	0.4300	0.4700	2005.93
P229 (PBO)	238.02	37.75	-26.8	1.6	0.1100	0.1200	2005.29
P230 (PBO)	238.21	37.82	-22.5	-3.1	0.1100	0.1200	2005.15
P261 (PBO)	237.78	38.15	-21.0	-0.5	0.0900	0.1000	2004.50
P262 (PBO)	237.90	38.03	-24.2	1.2	0.1100	0.1200	2005.32
PKDB	239.46	35.95	-43.0	18.7	0.0100	0.0100	1996.67
PPT1*	237.61	37.19	-40.7	22.1	0.0000	0.0000	1996.14
PTRB	236.98	38.00	-37.7	22.2	0.0100	0.0100	1998.58
S300	238.44	37.67	-22.9	-4.4	0.0200	0.0200	1998.48
SAOB	238.55	36.77	-41.4	22.0	0.0100	0.0100	1997.58
SBRN	237.59	37.69	-32.0	14.2	0.0300	0.0300	2003.18
SODA	26.39	67.42	18.7	34.1	0.1400	0.1600	1994.70
SODB	238.07	37.17	-33.1	11.7	0.0100	0.0100	1996.33
SUAA	237.83	37.43	-33.7	12.4	0.0100	0.0100	1994.30
SUTB	238.18	39.21	-23.1	-6.7	0.0100	0.0100	1997.33
SVIN	237.47	38.03	-30.5	10.3	0.0400	0.0400	2003.89
THAL	238.07	37.35	-32.0	9.5	0.2000	0.2200	2003.00
TIBB	237.55	37.89	-30.8	11.2	0.0100	0.0100	1994.42
UCD1	238.25	38.54	-23.1	-6.0	0.0100	0.0100	1996.38
VNDP*	239.38	34.56	-42.2	20.9	0.0000	0.0000	1992.48
YBHB	237.29	41.73	-15.8	-6.7	0.0100	0.0100	1996.75

Table 1: CALREF 2006 official velocities. All velocities and estimated errors (σ)are indicated in mm per year. As the formal errors provided by GAMIT are too small to be considered as realistic, these values give an estimate of the quality solutions after months of measurement. For each site, the start date is specified. The sites with a star are the sites for which the velocities have been used during the combination of the daily solutions.

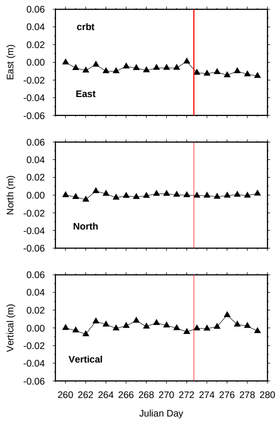


(a) CAND

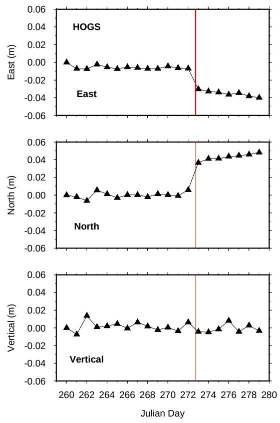


(b) CARH

Figure 4: CAND and CARH time-series

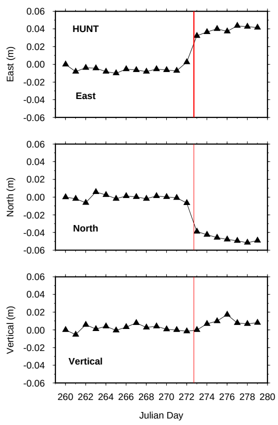


(a) CRBT

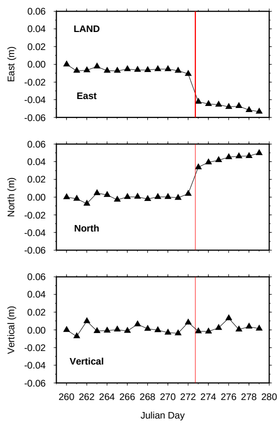


(b) HOGS

Figure 5: CRBT and HOGS time-series

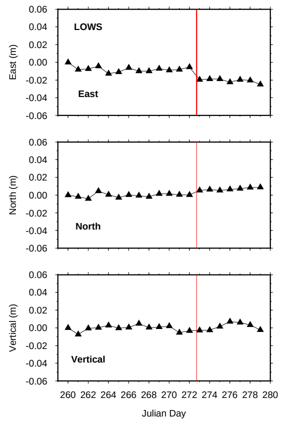


(a) HUNT

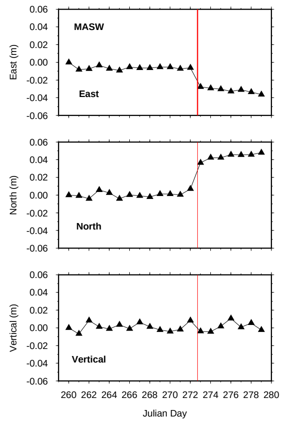


(b) LAND

Figure 6: HUNT and LAND time-series

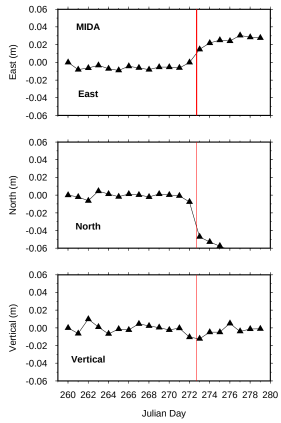


(a) LOWS

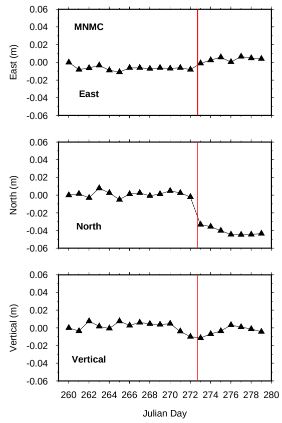


(b) MASW

Figure 7: LOWS and MASW time-series

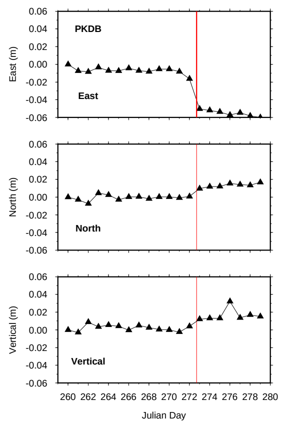


(a) MIDA

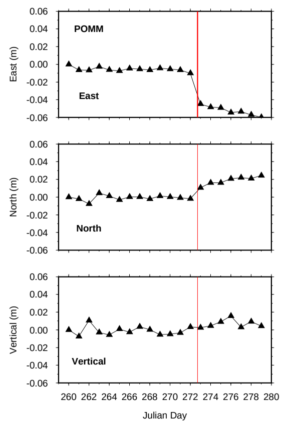


(b) MNMC

Figure 8: MIDA and MNM time-series



(a) PKDB



(b) POMM

Figure 9: PKDB and POMM time-series

4.3 Real-Time Processing

We are also developing real-time analysis techniques that will enable rapid determinations ($\sim$minutes) of deformation following major earthquakes to complement seismological information and aid determinations of earthquake location, magnitude, geometry, and strong motion (*Murray et al.*, 1998c). In northern California, rapid earthquake notification is a collaborative effort of the USGS Menlo Park and the UC Berkeley Seismological Laboratory (BSL). Notification is performed in stages as data and results become available. The USGS use data from their short-period vertical seismic network to provide preliminary locations within seconds, and final locations and preliminary coda magnitudes within 2-4 minutes. This information is used by BSL to drive the Rapid Earthquake Data Integration (REDI) processing system (*Gee et al.*, 1996; 2002). If the coda magnitude is 3.0 or greater, waveforms from the BSL broadband seismic network are analyzed to estimate local magnitude, and peak ground motions and moment tensors are estimated at higher magnitudes.

Because the point source approximation made in the moment tensor codes may break down at regional distances for $M > 7.5$ events, we have extended the seismic methodologies to estimate finite fault parameters. However, seismic data alone have difficulty determining the geometry of finite faults. Geodetic networks provide a complementary data source that can be used to independently estimate rupture parameters of $M > 6$ events, particularly for shallow events located near stations in the network. Geodetic measurements of coseismic displacements provide important constraints on earthquake faulting, including the location and extent of the rupture plane, unambiguous resolution of the nodal plane, and the distribution of slip on the fault unbiased by rupture velocity assumptions (e.g., *Murray et al.*, 1996).

We currently process data available within 2 hours of measurement from the 20 continuous telemetered BSL stations, and several other stations that make their data available on an hourly basis. The data are binned into 2 hour files and processed simultaneously by pairs across major faults. Prior to the earthquake, the station locations can be constrained at the cm-level to well-known locations, which improves resolution of carrier phase integer ambiguities. The scatter of these hourly solutions is similar to the 24-hour solutions: 2-4 mm in the horizontal and 10 mm in the vertical. After an earthquake, the station locations cannot be assumed as precisely, so the uncertainties become much larger. Using 30 minutes of data, our simulations suggest that displacements at the 10 cm-level should be reliably detected, and that the current network should be able to resolve the finite dimensions and slip magnitude of a $M = 7$ earthquake on the Hayward fault.

We are currently investigating other analysis techniques that should improve both the rapidity and precision of the postseismic position estimates. Three mainshocks are available to complete the study on th rapid displacement signal at a BARD GPS receivers: 1998 San Juan Bautista (*Uhrhammer et al.*, 1999), 2003 San Simeon (*Rolandone et al.*, 2006) , 2004 Parkfield (*Langbein et al.*, 2005).

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8. DATA AVAILABILITY

Data and results from the BARD project are available at the Northern California Earthquake Data Center (*//www.quake.geo.berkeley.edu*) For additional information on the BARD network, contact Nicolas Houlié at 510-642-2601 or houlie@seismo.berkeley.edu.

FINAL TECHNICAL REPORT

AWARD NUMBER: 04HQAG0112

THE BARD CONTINUOUS GPS NETWORK:
MONITORING ACTIVE DEFORMATION AND STRAIN ACCUMULATION IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA:
Collaborative research with UC Berkeley,
and U.S. Geological Survey, Menlo Park

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PROGRAM ELEMENTS: I & II

KEY WORDS: GPS-Continuous, Surface Deformation, Fault Stress Interactions

NON-TECHNICAL ABSTRACT

We maintain 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 3-year project period, we performed enhancements to the existing network and operation procedures, installed several new stations, included new broadband deformation stations equipped with GPS and borehole strainmeters and seismometers and measured deformation due to the 2004 Parkfield.