Chapter 3

Hayward Fault Network

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1. Introduction

Historical seismicity rates, from various networks operating over the years, suggest that there is sufficient seismicity, perhaps an event per day at a detection threshold around magnitude 0.5 to 1.0 to allow high-resolution imaging of fault-zone processes. Such a detection sensitivity requires high-gain instrumentation and sophisticated noise mitigation techniques, possible in the East Bay Area only with borehole-installed seismometers. A network of borehole-installed wide dynamic range seismographic stations - the Hayward Fault Network (HFN) - is being developed cooperatively with the US Geological Survey with support from USGS, EPRI, Caltrans, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL, and LBNL (Figure 3.1 and Figure 3.2). The purpose of the network is to lower substantially the threshold of microearthquake detection for events along the fault and to record much higher frequency waveforms in order to increase the resolution of fault-zone structure and spatio-temporal characteristics in the seismicity. This new data base will improve working models for the Hayward fault, and provide enhanced data to the real-time monitoring and alert systems functioning at the Berkeley Seismological Laboratory.

2. Sensors, Recording, and Telemetry Systems

The basic concept for the HFN is that, in an urban environment swamped with cultural background noise (traffic and industry vibrations) orders of magnitude above average levels in remote sites, any individual station running on-site detection software has a high probability of being desensitized from the noise and thus will miss many of the small events that we need to record at all network stations for high-resolution study of Hayward Fault activity. It is impractical to telemeter all of the data at the necessarily high sample rates (500 sps, up to 4 components) to a central site for processing in real time. To circumvent this problem we employ two countermeasures: (1) the sensors are placed in boreholes as deep as possible (preferably 100 m or more) and in bedrock, for a significant reduction in surface noise, and (2) representative signals (a single 100 sps vertical component from each station) are processed centrally for the detection of legitimate microearthquakes, and recovery of the full data set for the event from the entire network is accomplished by command from the central site, in a fully automated system. The detector has been running for 18 months now in an offline processing mode successfully. The magnitude threshold is approximately 0.0 for small events along the Hayward Fault. With a false detection rate of about two-thirds, on average more than one event per day is recovered, satisfying the design goals of the network. As more stations in boreholes are added, the quantity and quality of the data will improve.

Six-component borehole sensor packages designed and fabricated at LBNL's Geophysical Measurement Facility by Don Lippert and Ray Solbau, with 3 channels of acceleration (Wilcoxin 731A) and 3 of velocity (OyO HS-1 4.5 Hz geophones) are being installed in the entire network. The 0.1-400 Hz accelerometers have lower self-noise than the geophones above about 25-30 Hz, and remain on scale and linear to 0.5 g. Sensors are installed at depths of 100-300 m and provide signals to the on-site Quanterra dataloggers (Q4120 and Q730 systems). Signals digitized at a variety of data rates (up to 500 Hz (Table 3.1) at 24-bit resolution. 7 of the HFN stations use digital frame relay telemetry to transmit continuous data at a reduced rate (100, 20, and 1 sps) to the central controller for event detection. The central controller declares valid network events, extracts appropriate data

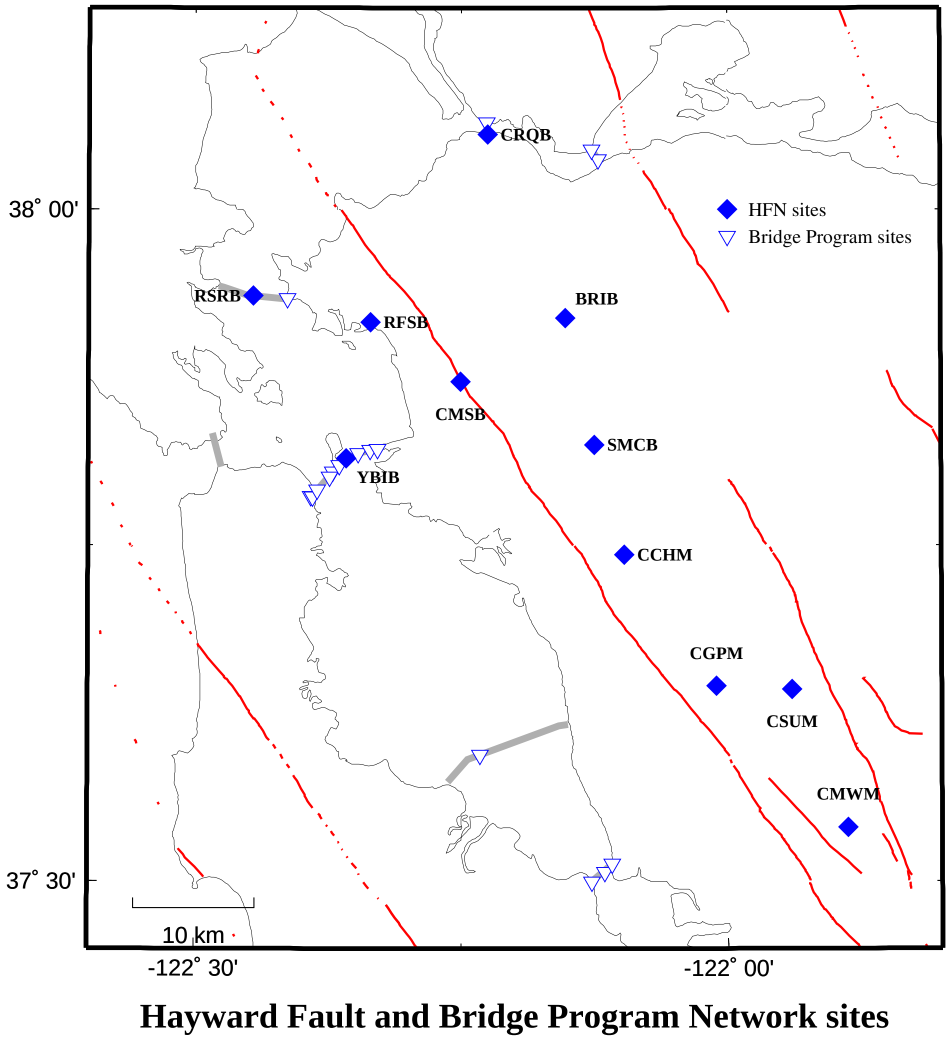


Figure 3.1: Map showing the locations of the Hayward fault stations and the Bridge Program stations. *Courtesy of L. Gee.*

Site	Location	Latitude	Longitude	Depth (m)	Sensors	Datalogger	Telemetry
BRIB	Briones Preserve	37.91894	-122.15062	108.8	Standard HFN Acc. Failed	Quanterra 4120 GPS clock	Frame-relay to BSL
CMSB	Memorial Stadium	37.87202	-122.25060	167.6	Standard HFN	Quanterra 4120 GPS clock	Frame-relay to BSL
RFSB	Richmond Field Station	37.91616	-122.33502	91.4	Standard HFN	Quanterra 4120 GPS clock	Frame-relay to BSL
SMCB	St. Mary's College	37.8387	-122.1116		Standard HFN Posthole	Quanterra 4120 GPS clock	Frame-relay to BSL
CCHM	Chabot	37.74339	-122.09550	118.5	Standard HFN	Nanometrics HRD24 Central Timing	Radio to USGS
CGPM	Garin Park	37.64552	-122.01021	120.6	Standard HFN	Nanometrics HRD24 Central Timing	Radio to USGS
CSUM	Sunol	37.64303	-121.93916	123.5	Standard HFN	Nanometrics HRD24 Central Timing	Radio to USGS
CMWM	Mill Creek	37.54033	-121.88653	155.3	Standard HFN	Nanometrics HRD24 Central Timing	Radio to USGS
CYDM	Coyote	37.56296	-122.09562	136.8	Standard HFN		
	Bay Bridge San Francisco Anchorage	37.7861	-122.3893	< 0.5	LLNL S-6000 Posthole	Reftek 72A-07	
	Bay Bridge Pier W2	37.79120	-122.38525		Standard HFN	Reftek 72A-02 GPS clock	
	Bay Bridge Pier W5	37.8010	-122.3737		Standard HFN	Reftek 72A-02 GPS clock	
	Bay Bridge Yerba Buena Anchorage	37.8094	-122.3645	3	Standard HFN	Reftek 72A-02 GPS clock	
YBIB	Bay Bridge Pier E2	37.81427	-122.35815	61.0	Standard HFN	Quanterra 4120 GPS clock	Radio to BSL
	Bay Bridge Pier E7	37.81847	-122.34688	134.0	Standard HFN	Reftek 72A-07 GPS clock	
	Bay Bridge Pier E17	37.82086	-122.33534	160.0	Standard HFN	Reftek 72A-07 GPS clock	
BBEB	Bay Bridge Pier E23	37.82167	-122.32867	182.9	Standard HFN Acc. Failed		
	Dumbarton Bridge Pier1	37.49947	-122.12755	1.5, 71.6, 228.0	Standard HFN Acc. Failed	Reftek 72A-02 GPS clock	
	Dumbarton Bridge Pier 27	37.50687	-122.11566	182.9	Standard HFN	Reftek 72A-02 GPS clock	
	Dumbarton Bridge Pier 44	37.51295	-122.10857	1.5, 62.5, 157.9	Standard HFN Acc. Failed	Reftek 72A-02 GPS clock	
RSRB	Richmond-San Rafael Bridge Pier 34	37.93583	-122.44540	109.0	Standard HFN	Quanterra 4120 GPS clock	Frame-relay to BSL
	Richmond-San Rafael Bridge Pier 58	37.93372	-122.41313	44.0	Standard HFN		
CRQB	Carquinez Bridge	38.05591	-122.22402		Standard HFN	Quanterra 4120 GPS clock	Frame-relay to BSL
	San Mateo Bridge Pier 343	37.59403	-122.23242	298.0	Standard HFN		

Figure 3.2: Station of the Hayward fault Network and Bridge Program.

segments at full resolution (up to 500 sps), and collects other associated information from the Southern Hayward Fault Network (SHFN).

Similar to BDSN sites, station processors are capable of continuous on-site recording and local storage at full resolution for more than one day and have batteries to provide backup power. On-site detectors can monitor critical conditions and preset changes in operating mode can be invoked. The new UltraSHEAR communication software devised for this network (and now widely used) allows control and change of parameters from the central site. MultiSHEAR provides for multi-station nodes using the Q730 satellite acquisition platforms around a Q4120, with a single 4-station telemetry link to the central site. Data are archived in the NCEDC archive established jointly at Berkeley by USGS and UCB.

As originally planned, the network will consist of of 24 to 30 stations, 12-15 each north and south of San Leandro, managed respectively by UCB and USGS. This is not happening quickly, although west of the fault we have several Caltrans bridge borehole sites. Caltrans plans to provide some holes of opportunity away from the bridges in the coming years, so we are planning two new borehole sites in data gaps east of the fault or near the Oakland Airport, bringing the geometry to a more effective state for imaging and real-time monitoring of the fault.

3. Station Maintenance

HFN sites have experienced the usual type of maintenance problems over the last year. Nearby lightning strikes affected telemetry at several stations. In spite of installed lightning and surge protection devices, storms damaged instruments at several locations, which required repair or replacement of equipment. At the Oakland-San Francisco Bay Bridge site of the HFN (YBIB), the electrical surge was sufficient to blow integrated circuits off of the printed circuit board within the data logger and completely destroy the digital radio modem.

4. Network Software

Central site triggering, one of the design goals of the Hayward Fault Network, is crucial to maximizing the performance of a modern borehole seismic network located in a noisy urban environment. Telemetry bandwidth limitations preclude the possibility of sending continuous 500 Hz or higher sampled data, and the high urban environment noise levels renders local detection of seismic events at each station unreliable. Single-station false triggers at the desired low detection threshold can easily amount to 99% of the recorded data. We have developed and tested a central site triggering algorithm that processes continuous 100 Hz EP1 (vertical geophone) data feeds from all telemetered HFN sites. Detection thresholds were adjusted until each station produced detections at a rate of about one detection per hour. The number of associated detections averages about 5 per day. Of these coincident detections, about one-third are local and regional earthquakes (and an occasional teleseism) and the rest are coincident noise associations. Subsequent analysis of the earthquakes identified by the prototype detector/associator indicates that:

- All events of magnitude 2 and larger within a 100 km radius of Berkeley located by the USGS Northern California Seismic Network (NCSN) were detected by the prototype detector.
- The number of earthquakes detected by the prototype detector and located within 30 km of Berkeley was three times as many as were detected by the NCSN in the same time interval.

The observed signal-to-noise ratios for a sample of the smallest detected events typically exceeds 10 dB at 20 Hz. The M_L threshold, calculated on the assumption that detector will trigger at two or more stations when the signal-to-noise ratio exceeds 10 dB at 20 Hz (STA/LTA ratio of 3.5), is somewhere between 0.0 and -0.6 for Berkeley local events (distances less than 10 km). Inferred from the observed magnitude distribution and rate of seismicity at the M_L 1.5 and larger level, the expected rate of seismicity within a 10 km radius of Berkeley, is 3 per month at the M_L 0.0 threshold and 10 per month at the M_L -0.6 threshold. Based upon the detected/associated number of local events, the detection threshold appears to be closer to M_L -0.6 than to M_L 0.0.

We are preparing to implement the final detection/association algorithm on the central site computer as we install the last of the Quanterra 4120 and 730 telemetered systems and complete the MultiSHEAR upgrade of the software on the remote dataloggers.

Sensor	Channel	Rate (sps)	Mode
Accelerometer	CL	500	T
Accelerometer	HL	100	C*
Accelerometer	BL	20	C
Accelerometer	LL	1	C
Geophone	DP	500	T
Geophone	EP	100	C*

Table 3.1: Typical data streams acquired at each HFN site, with channel name, sampling rate, and sampling mode. C indicates continuous; T triggered. The 100 sps channels (EP & HL) are only archived when the 500 sps channels are not available.

Chapter 4

Parkfield Borehole Network

T. V. McEvilly and R. W. Clymer

1. Introduction

As part of the U.S. Geological Survey initiative known as the Parkfield Prediction Experiment, the operation of the High Resolution Seismic Network (HRSN) at Parkfield, California, and the collection and analysis of its recordings began in 1987. Figure 4.1 shows the location of the network and its relationship to the seismicity along the San Andreas fault. The HRSN records exceptionally high-quality data, owing to its 10 closely spaced three-component borehole sensors, its very broad band recordings (0-125 Hz), and its sensitivity (recording events below magnitude -0.5) due to the extremely low attenuation and background noise levels at the 200-300 m sensor depths (*Karageorgi et al.*, 1992). Several aspects of the Parkfield region make it ideal for the study of small earthquakes and their relation to tectonic processes. These include the fact that the network spans the expected nucleation region of a repeating magnitude 6 event and the transition from locked to creeping behavior on the San Andreas fault, the availability of three-dimensional P and S velocity models, a very complete seismicity catalogue, a well-defined and simple fault segment, and a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip).

2. Network Performance and Upgrade Plans

The system has recorded more than 10000 microearthquakes in the Parkfield region along with many times that number of regional and teleseismic events. More than 5000 good quality 3-D locations make up the catalog for the 40 km stretch of the fault zone centered at Middle Mountain. More than 50 controlled-source data sets from the Vibroseis monitoring program have also been gathered from mid-1987 until its termination in 1997. Waveforms and locations are accessible on the NCEDC archive (Table 4.1).

The original data acquisition system failed in 1998. It was a modified VSP system using a 1980-vintage LSI-11 cpu and a 5 MByte removable Bernoulli system disk with a 9-track tape drive, configured to record both triggered microearthquake and Vibroseis (discontinued in 1997) data. The system was remote and completely autonomous - it could not be monitored from Berkeley - so that reliability and hands-off operation was a crucial design feature.

Thanks to emergency funding from the USGS NEHRP, we have begun to replace the present system with a modern 24-bit acquisition system, and resources requested in this proposal will complete the upgrade of the 10 stations. The new system is compatible with the data flow and archiving common to all the elements of the Berkeley Digital Seismic network (BDSN) and the NCEDC. This will provide remote access and control of the system and produce data with better timing accuracy and longer records flowing seamlessly into NCEDC. We had a one-sample timing uncertainty, and a record length limitation because the time to do a tape write after event detection is longer than the length of the record, and we were off-line for the write time. The new system, based on the Quanterra Q730 datalogger, solves all three problems: timing resolution, dynamic range, and complete detection, in addition to the advantage in the conventional data flow. We hope to add three new borehole stations to the NW edge of the network as part of the fault-zone drilling (SAFOD) project, if that initiative is successful, to improve resolution at the planned drilling target on the fault.

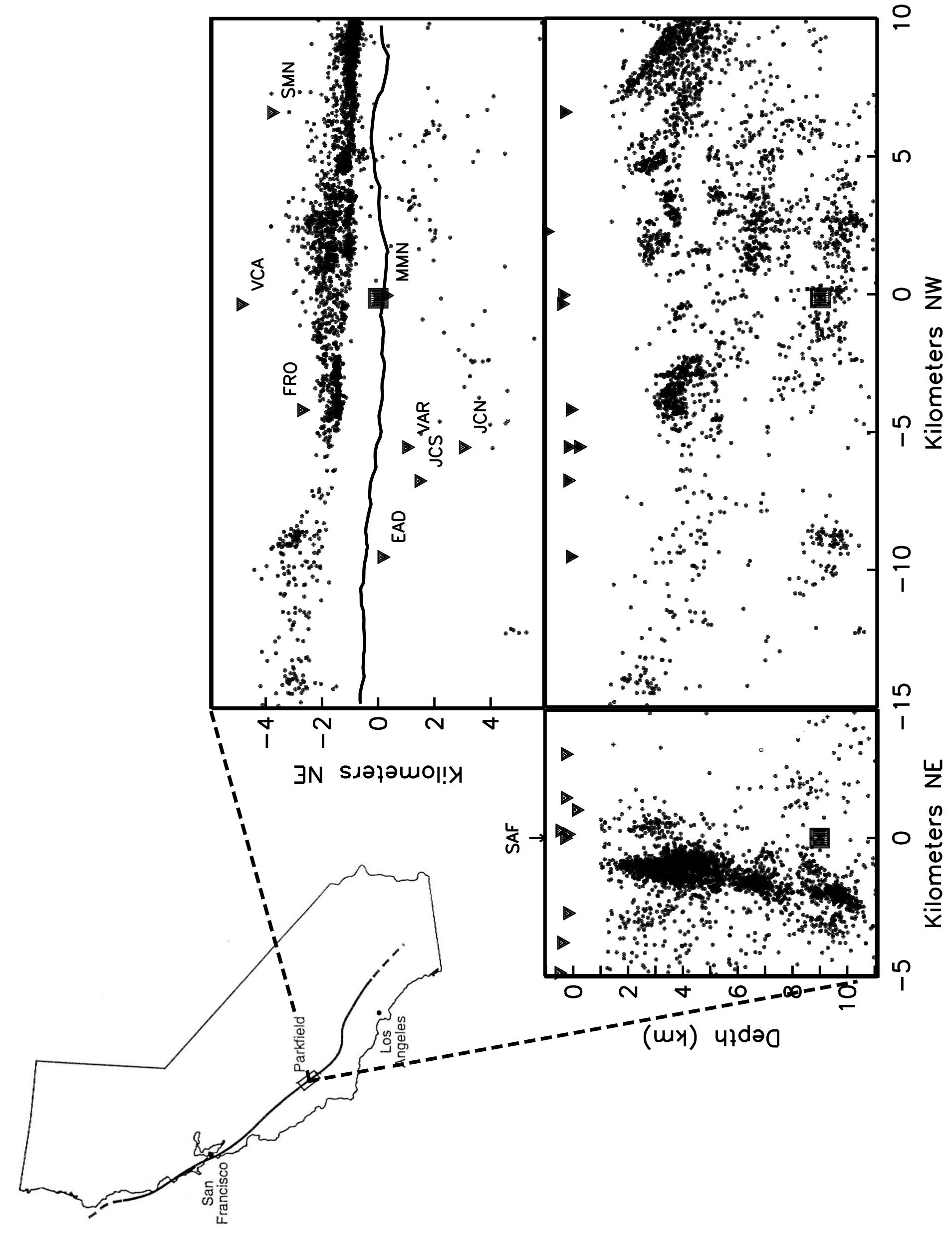


Figure 4.1: Parkfield HRSN Network and Seismicity.

Stat	Chan	Rate (sps)	Latitude	Longitude	elev (m)	depth (m)	Dip	Az
EAD	DPZ	500	35.89522	-120.42262	503	245	90	0
EAD	DP1	500	35.89522	-120.42262	503	245	0	170
EAD	DP2	500	35.89522	-120.42262	503	245	0	260
FRO	DPZ	500	35.91095	-120.48688	549	284	90	0
FRO	DP1	500	35.91095	-120.48688	549	284	0	338
FRO	DP2	500	35.91095	-120.48688	549	284	0	248
GHI	DPZ	500	35.83225	-120.34728	427	63	-90	0
GHI	DP1	500	35.83225	-120.34728	427	63	0	???
GHI	DP2	500	35.83225	-120.34728	427	63	0	???
JCN	DPZ	500	35.93897	-120.43112	567	224	90	0
JCN	DP1	500	35.93897	-120.43112	567	224	0	0
JCN	DP2	500	35.93897	-120.43112	567	224	0	270
JCZ	DPZ	500	35.92117	-120.43400	488	155	-90	0
JCZ	DP1	500	35.92117	-120.43400	488	155	0	300
JCZ	DP2	500	35.92117	-120.43400	488	155	0	210
MMN	DPZ	500	35.95650	-120.49600	735	221	90	0
MMN	DP1	500	35.95650	-120.49600	735	221	0	175
MMN	DP2	500	35.95650	-120.49600	735	221	0	265
RMN	DPZ	500	36.00087	-120.47772	1198	73	90	0
RMN	DP1	500	36.00087	-120.47772	1198	73	0	310
RMN	DP2	500	36.00087	-120.47772	1198	73	0	40
SMN	DPZ	500	35.97297	-120.57988	732	282	90	0
SMN	DP1	500	35.97297	-120.57988	732	282	0	120
SMN	DP2	500	35.97297	-120.57988	732	282	0	210
VAR	DPZ	500	35.92608	-120.44705	509	572	-90	0
VAR	DP1	500	35.92608	-120.44705	509	572	0	15
VAR	DP2	500	35.92608	-120.44705	509	572	0	285
VCA	DPZ	500	35.92162	-120.53392	789	200	90	0
VCA	DP1	500	35.92162	-120.53392	789	200	0	200
VCA	DP2	500	35.92162	-120.53392	789	200	0	290

Table 4.1: Stations of the Parkfield HRSN, with channel name, sampling rate, location (referenced to NAD84), surface elevation (in meters above mean sea level), sensor depth below the surface, and the dip and azimuth of the sensors.

3. References

Karageorgi, E., R. Clymer and T.V. McEvilly, Seismological studies at Parkfield. II. Search for temporal variations in wave propagation using Vibroseis, *Bull. Seism. Soc. Am., 82*, 1388-1415, 1992.

Chapter 5

Bay Area Regional Deformation Network

Mark Murray, Ray Baxter, Bill Karavas, Roland Bürgmann

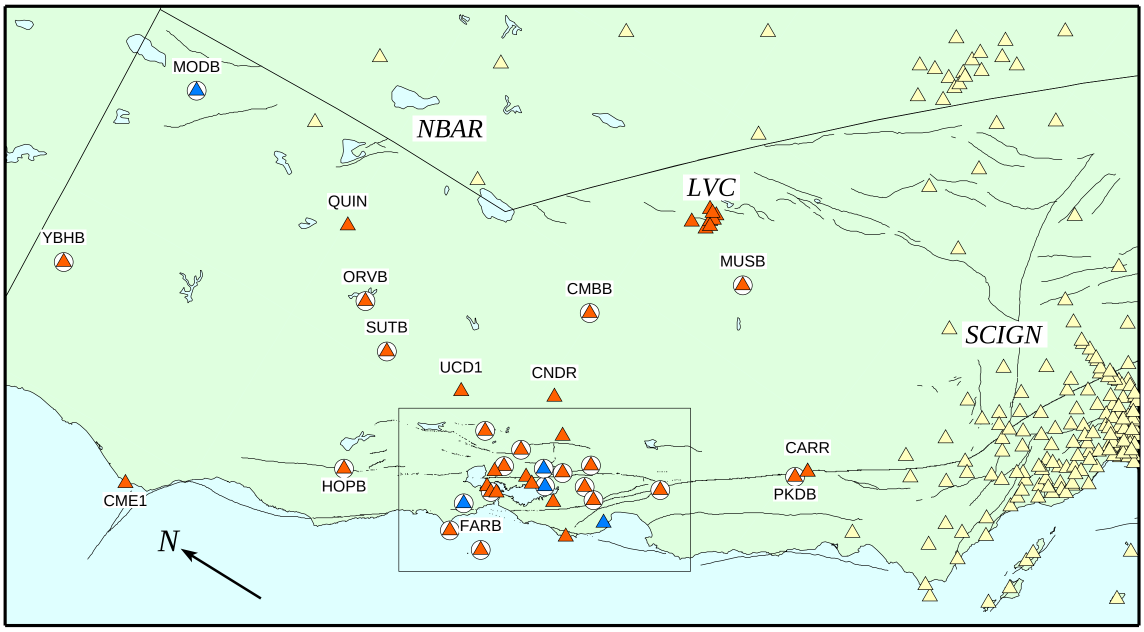
1. Introduction

The Bay Area Regional Deformation (BARD) network of permanent, continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.,* 1998a). It is a cooperative effort of the Berkeley Seismological Laboratory at UC Berkeley (BSL), the US Geological Survey (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), BARD now includes 40 permanent stations and will expand to about 50 stations in 2000 (Figure 5.1). The principal goals of the BARD network are: 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 San Andreas fault (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 infrastructure for geodetic data management and processing in northern California in support of related efforts within the BARD Consortium and with surveying, meteorological, and other interested communities.

BARD presently includes 40 permanent, continuously operating stations, 8 of which monitor the Long Valley caldera near Mammoth. The remaining 32 stations (Table 5.1) include 18 maintained by the BSL (including two with equipment provided by Lawrence Livermore National Laboratory (LLNL), and the Satloc Corporation), 2 each by the USGS and Trimble Navigation, and one each by LLNL, Stanford University, and UC Davis. Other stations are maintained by institutions outside of northern California, such as the National Geodetic Survey, the Jet Propulsion Laboratory, and the Scripps Institution of Oceanography, as part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation.

Between 1993 and 1996, the BSL acquired 5 Ashtech Z-12 receivers from UC Berkeley and private (EPRI) funding, which together with 2 USGS receivers, formed the nucleus of the initial BARD network. Since 1996, the BSL has acquired additional Ashtech Z-12 receivers with Dorne-Margolin design choke ring antennas: 13 in 1996 from a combination of federal (NSF), state (CLC), and private (EPRI) funding, and 4 in the last year from federal (USGS) funding. All but 6 of these receivers have been permanently installed to enhance continuous strain measurements in the Bay Area and to consolidate the regional geodetic network. The network includes several profiles between the Farallon Islands and the Sierra Nevada in order to better characterize the larger scale deformation field in northern California (Figure 5.1). Four more of the BSL receivers and a receiver owned by UC Santa Cruz will be installed during the next year.

In 1996, researchers from the BSL, the USGS, Stanford University, LLNL, UC Davis, and UC Santa Cruz formed a consortium of institutions involved in studies of the tectonic deformation in the San Francisco Bay area and northern California. Members of the BARD consortium agreed to pool existing resources and coordinate development of new ones in order to advance an integrated strategy for improving the temporal and spatial resolution of the strain field. They agreed in principle to the continued development of the network of permanently deployed GPS receivers, to the development and maintenance of a pool of GPS receivers for survey-mode operations that may be deployed in semi-permanent mode in the Bay Area when not otherwise in use, to archiving of all data at the NCEDC, and to the development



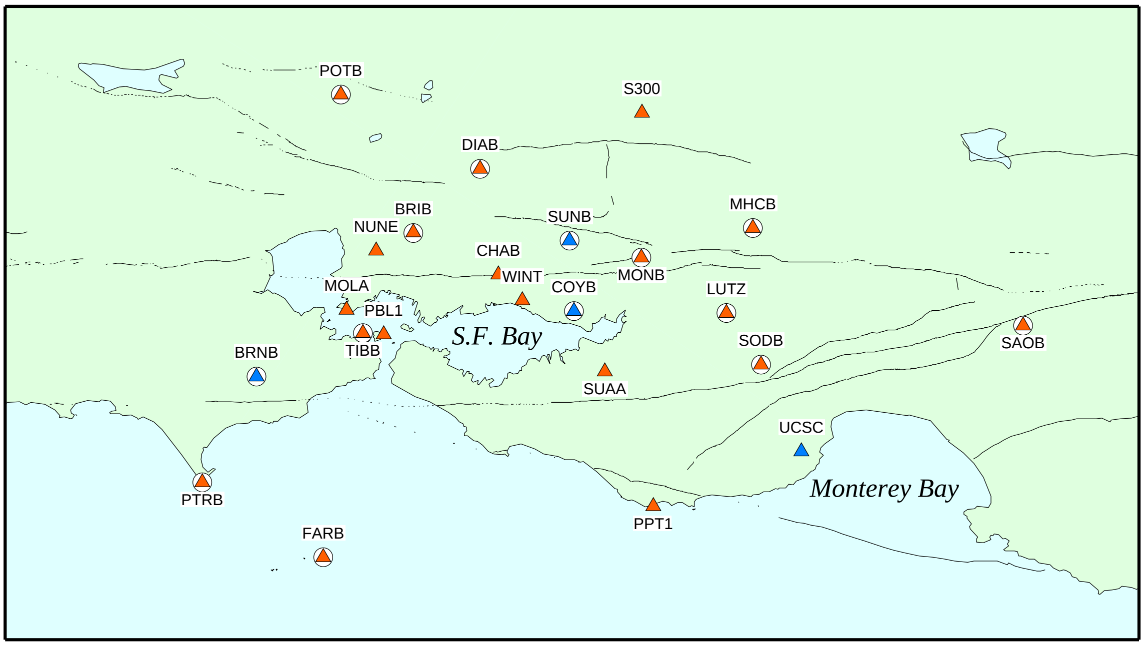


Figure 5.1: Operational (red triangles) and planned (blue triangles) BARD stations in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations (will) use continuous telemetry. The eight station Long Valley Caldera (LVC) network is shown with red triangles. Other nearby networks (yellow triangles) include: Northern Basin and Range (NBAR), and Southern California Integrated GPS Network (SCIGN). *Courtesy of M. Murray.*

Table 5.1: Operational and Planned BARD Stations

ID	Name	Instit.[a]	Start	Receiver	Comments[b]
		Operational BSL Stations			
BRIB	Briones	BSL/LLNL	8/93	Ashtech Z-12	CT,BB
CMBB	Columbia	BSL	12/93	Ashtech Z-12	CT,BB
FARB	Farallon	BSL	1/94	Ashtech Z-12	CT,BB
TIBB	Tiburon	BSL	6/94	Ashtech Z-12	CT
HOPB	Hopland	BSL	8/95	Ashtech Z-12	CT,BB
MHCB	Mt Hamilton	BSL	6/96	Ashtech Z-12	CT,BB
PKDB	Parkfield	BSL	9/96	Ashtech Z-12	CT,BB
YBHB	Yreka	BSL	10/96	Ashtech Z-12	CT,BB
ORVB	Oroville	BSL/SL	11/96	Ashtech Z-12	CT,BB
SUTB	Sutter Buttes	BSL	3/97	Ashtech Z-12	CT
SAOB	SAGO Hollister	BSL	7/97	Ashtech Z-12	CT,BB
MUSB	Musick Mtn	BSL	11/97	Ashtech Z-12	CT
DIAB	Mt Diablo	BSL	5/98	Ashtech Z-12	CT
MONB	Monument Peak	BSL	7/98	Ashtech Z-12	CT
PTRB	Pt Reyes	BSL	8/98	Ashtech Z-12	CT
POTB	Potrero Hills	BSL	12/98	Ashtech Z-12	CT,BB
LUTZ	Lutz	BSL	5/99	Ashtech Z-12	CT
SODB	SODB	BSL	5/99	Ashtech Z-12	CT
		Operational BARD Consortium Stations[c]			
CHAB	Chabot	USGS	9/91	Ashtech Z-12	
WINT	Winton	USGS	9/91	Ashtech Z-12	
MOLA	Molate	TN	10/93	Trimble SSE	
NUNE	Nunes	TN	10/93	Trimble SSE	
SUAA	Stanford	SU	4/94	Trimble SSE	HT
UCD1	UC Davis	UCD	5/96	Trimble SSE	CT,SP
S300	Site 300, LLNL	LLNL	4/99	Trimble SSI	HT
		Other Operational Stations			
QUIN	Quincy	JPL	9/92	Rogue	HT
CARR	Carr Hill, Parkfield	JPL	5/94	Rogue	
PBL1	Pt Blunt	NGS	7/95	Ashtech Z-12	HT
PPT1	Pigeon Pt	NGS	1/96	Ashtech Z-12	HT
CME1	Cape Mendocino	NGS	4/96	Ashtech Z-12	HT
EBMD	Oakland	EBMUD	2/99	Trimble SSE	
CNDR	Stockton	NGS	5/99	Ashtech Z-12	HT
		Planned Stations			
MODB	Modoc	BSL		Ashtech Z-12	CT,BB
BRNB	Barnabe Peak	BSL		Ashtech Z-12	CT
SUNB	Sunol	BSL		Ashtech Z-12	CT,BS
COYB	Coyote Hills	BSL		Ashtech Z-12	CT,BS
UCSC	UC Santa Cruz	UCSC		Trimble SSE	SP

[a]Institutions: BSL = UC Berkeley, USGS = US Geological Survey, UCD = UC Davis, SU = Stanford Univ., UCSC = UC Santa Cruz, TN = Trimble Navigation, LLNL = Lawrence Livermore Nat. Lab., SL = Satloc Corp., NGS = Nat. Geodetic Surv., SIO = Scripps Instit. of Ocean., EBMUD = East Bay Mun. Util. Dist., JPL = Jet Propulsion Lab.
[b]Comments: CT = continuous telemetry (frame relay and/or radio circuit), HT = Hourly telemetry, BB = collocated broadband seismometer, BS = collocated borehole strainmeter, SP = semi-permanent operation
[c]Excluding 8 stations monitoring the Long Valley caldera near Mammoth.

of a coordinated data analysis facility that will process permanent, semi-permanent, and survey data.

In the remainder of this section, we describe BARD-related activities the BSL has performed over the last year, including the installation of 3 new stations, converting 2 other stations to continuous operational mode, performing significant upgrades on all existing stations, testing an experimental single-frequency receiver, improving data archive and processing methods, and analyzing deformation signals detected by the network.

2. Site Installations

During fiscal year 1998–99 three new BARD stations (MONB, PTRB, and POTB) were permitted, designed, constructed and equipped with Ashtech Z-12 receivers by the BSL staff. The BSL staff also performed significant modifications to two stations (LUTZ and SODB) to convert them to continuous operations, collaborated with LLNL to install a station (S300) at their Site 300 facility, and prepared an additional station (MODB) in the Modoc Plateau in the northeastern corner of California in July–October 1999, which will become operational in the near future.

Station MONB is located on Monument Peak in the Mission Hills, east of San Jose, in a tectonically complicated region near the intersection of the Calaveras and southern Hayward faults where the seismicity appears to step over along the Mission fault. The site is under permit from the East Bay Regional Parks. The GPS receiver, telemetry, and power subsystems are located within a radio/microwave structure under permit by Kaiser Hospitals. The monument is drilled, anchored, and cemented into a hard rock outcrop. Skyview is excellent in all directions.

Station PTRB is located near the historic lighthouse in the Point Reyes National Seashore, at the westernmost point of land in the north Bay Area. Midway between the San Andreas fault (SAF) and the Farallon Islands, it will provide valuable constraints on deformation west of the SAF. The GPS receiver, telemetry, and power subsystems are located within a structure under permit by the National Park Service. Due to the remoteness of the site, telemetry via commercial phone service is not reliable, so we established a digital spread spectrum radio link to Mt. Tamalpias to the southeast. At Mt. Tamalpias, data from the Point Reyes station is combined with both BDSN and BARD data from the Farallon Islands (FARB) onto a single 56 kBaud digital frame-relay circuit.

Station POTB is located at the Potrero Hills-OEA Aerospace Inc. facility near Fairfield, just west of the Central Valley. The site is collocated with BDSN seismic instruments, allowing both instruments to share the same power and telemetry subsystems. The GPS monument is anchored in a massive concrete bunker that formerly housed Nike missiles. The concrete structure sits atop competent sandstone, providing a uniquely stable base within the Sacramento River delta area.

Each of these new stations conforms as much as possible to the standard station configuration developed by the BSL, which has been described in previous Annual Reports. They use a low-multipath choke-ring antenna, typically mounted to a reinforced concrete pillar approximately 0.5–1.0 meter above local ground level. If possible, the reinforcing steel bars of the pillar are drilled and cemented into rock outcrop to improve long-term monument stability. Low-loss antenna cables are used to minimize signal degradation on the longer cable setups that normally would require signal amplification. Continuous telemetry is provided by a combination of radio modem or frame-relay technologies. Low-voltage cutoff devices are installed to improve receiver performance following power outages. The Ashtech Z-12 receivers are programmed to record data once every 30 seconds, observing up to 12 satellites simultaneously at elevations down to the horizon.

Stations LUTZ and SODB, both in Santa Clara county in the south Bay Area, formerly used Trimble receivers operated intermittently by UC Davis depending on their availability. In early 1999, the BSL assumed responsibility for these 2 stations, installed Ashtech Z-12 receivers, and made the power and telemetry systems consistent with the standard BSL station configuration. Station LUTZ is located on a small hill at the Santa Clara County communications facility, which also houses the emergency response (911) operators and dispatchers. Station SODB is located in the Santa Cruz mountains southwest of the Santa Clara valley, near Loma Prieta Peak. Data from SODB is relayed to LUTZ via digital spread spectrum. A single 56 kBaud digital frame-relay circuit transmits data collected by both stations from the communications facility to the UC Berkeley hub. Both sites are located in a tectonically complex region between the SAF and Calaveras fault where transient deformation has been observed in the past, particularly in the aftermath of the 1989 Loma Prieta earthquake (*Bürgmann et al.,* 1997).

During 1997–99 BSL staff installed a reinforced concrete monument at the Site 300 explosion testing facility (station S300) of the Lawrence Livermore National Laboratory, and worked closely with LLNL and Trimble representatives to design a multi-purpose system, maintained by LLNL, that became fully operational in April 1999. This system provides real-time kinematic surveying capability for precise (cm-level) mapping of archaeological sites and other features at Site 300, publicly available differential corrections for real-time meter-level navigation and positioning capability in the general vicinity of the site, and near real-time telemetry of the raw data stream for the fault monitoring activities at the BSL. The site was chosen for its good sky visibility, for its availability of rock outcrop for monument stability, and for its proximity to the Central Valley. Because it is located at one of the easternmost sites in the Diablo Range, it will provide valuable constraints on the total deformation accommodated between the Sierra Nevada range and the San Andreas fault system.

Installations are also currently being permitted and prepared at several other sites, including Barnabe Peak (BRNB), just east of the SAF in the north Bay Area, in the Modoc plateau (MODB) in the northeast corner of California, and two stations (COYB and SUNB) that will be collocated with USGS borehole strainmeters along the southern Hayward fault. The remaining two GPS receivers owned by the BSL will be used to support other surveying activities, such as measuring ties with existing benchmarks, or will reside in temporary installations to improve the spatial density of the network.

3. Site Upgrades

The BSL staff performed significant modifications to nearly all the other BSL stations. The firmware on every Ashtech receiver was upgraded to a version compatible with both 4-digit year numbers, in anticipation of the year 2000 (Y2K), and with the GPS Week Rollover. The GPS satellites keep time in weeks and seconds of week, beginning on Sunday, January 6, 1980. On August 22, 1999, the week number changed from 1023 to 0000 internally on the satellites due to memory bit limitations. The receiver firmware was modified to maintain continuity of week number after the rollover. None of the BSL receivers were adversely affected by this problem.

The BSL staff also installed antenna domes at many of the stations. We purchased SCIGN-designed hemispherical domes using federal (USGS) funding. Domes cover the antennas to provide security and protection from the weather and other natural phenomenon. Previously the BSL stations had a mixture of dome types or none at all, adding a potential non-uniformity to signal delays and antenna phase patterns. The new SCIGN dome is designed for the Dorne-Margolin antennas and minimizes differential radio propagation delays by being hemispherical about the phase center and uniform in thickness at the 0.1 mm level. It is also very resistant to damage and, in its long form in combination with the SCIGN-designed antenna adapter, can completely cover the dome and cable connections for added protection. Adding the dome does cause a slight degradation in the signal-to-noise ratio (SNR) of the radio signals. We compared the receiver SNR values at both L1 and L2 frequencies, and found this degradation to be minimal (Figure 5.2). Observations collected below 15 degrees are not typically used in GPS processing due to the higher scatter induced by signal multipath. Tall domes and adapters were installed at 5 stations that require the most security due to public accessibility: DIAB, MUSB, PTRB, SAOB, and YBHB. Short domes were installed at 7 less accessible stations: HOPB, LUTZ, MHCB, MONB, PKDB, POTB, and SODB.

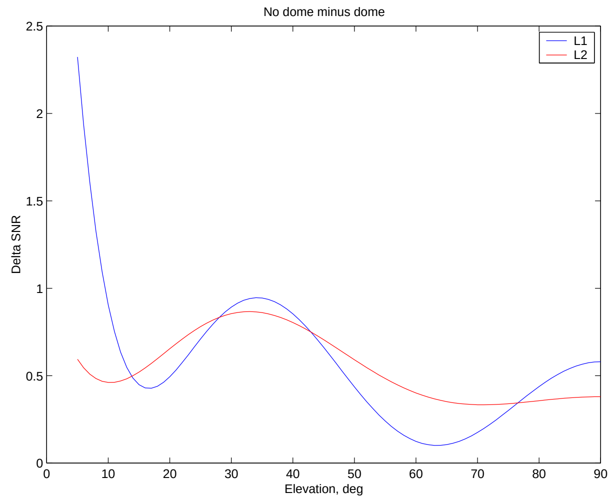


Figure 5.2: Signal-to-noise ratio (SNR) degradation caused by the SCIGN-designed antenna dome at L1 (blue) and L2 (red) frequencies versus satellite elevation above the horizon. SNR values for the Ashtech receivers are typically in the 150–200 range. Signals at all elevations are slightly degraded, with the greatest effect at low elevations in the L1 band. *Courtesy of M. Murray.*

Additional modifications were made to a number of the existing stations to make them consistent with the standard BSL station configuration. Low-voltage cutoff devices, described in previous reports, were installed at 6 stations: BRIB, MHCB, PKDB, SAOB, SUTB, and TIBB. Ashtech-to-Quanterra serial cables were installed at 6 stations in anticipation of a new telemetry method being developed by our staff (see below): FARB, HOPB, MHCB, PKDB, SAOB, and YBHB. Lightning protectors were installed on short-haul modem cables at CMBB and SAOB, which will be used for the Ashtech-to-Quanterra telemetry path. The BSL staff also helped to install a new low-latency telemetry path at the UCD1 station maintained by UC Davis. This station uses a Trimble receiver with a direct serial connection to a UNIX workstation. The new telemetry path allows automated ftp retrieval of the data in near-realtime, dramatically improving on the previous intermittent manual download method.

Significant station upgrades planned for the coming year include the conversion to choke-ring antennas at 2 remaining original stations (TIBB and BRIB), conversion to continuous telemetry of the 2 Trimble stations (MOLA and NUNE), and new monumentation at BRIB and CMBB to raise the antennas at least 0.5 meters above the ground to minimize multipath/troposphere modeling trade-offs that degrade the vertical position repeatability at these sites.

4. Continuous Telemetry

The BSL currently maintains and retrieves data from 18 Ashtech Z-12 receivers. Data from all stations are collected at 30-second intervals, transmitted continuously over serial connections, collected into 24-hour raw serial files and processed daily. The serial connections to 12 sites use frame relay technology, one site (TIBB) has a direct radio link to Berkeley and several sites (FARB, MUSB, PTRB, SODB, and SUTB) use a combination of radio and frame-relay technologies. We have developed software to interpret and collect the raw serial output into hourly files, which is then converted to the standard interchange RINEX format using the teqc software developed by UNAVCO.

Ten current GPS stations are collocated with broadband seismometers and Quanterra data collectors. With the support of IRIS we have developed software that will allow continuous GPS data to be stored on and retrieved from the Quanterra dataloggers (*Perin et al.,* 1998). This approach preserves GPS data during telemetry outages, and will be used at all the collocated stations after a new version of the Quanterra system software is installed this Fall. In anticipation, we have established and tested serial connections between the GPS receivers and dataloggers at six sites: FARB, HOPB, MHCB, PKDB, POTB, and YBHB.

5. Data Archival and Distribution

Raw and Rinex data files from the 18 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 by 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.

In the past year the BARD Project and the NCEDC have collaborated with UNAVCO and other members of the GPS community to define database schema and file formats for the GPS Seamless Archive Centers (GSAC) project. When completed this project will allow a user to access the most current version of GPS data and metadata from distributed GSAC locations. The NCEDC will participate at several levels in the GSAC project: as a primary provider of data collected from BSL-maintained stations, 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 produced monumentation files describing the data sets that are produced by the BARD project or archived at the NCEDC, and are working to implement programs that create incremental files describing changes to the holdings of the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings.

6. L1 System

The BSL staff is evaluating the performance of the UNAVCO-designed L1 system in an urban setting. This single-frequency receiver is relatively inexpensive but is less accurate than dual-frequency receiver that can completely eliminate first-order ionospheric effects. Hence we expect the L1 system to be most useful for short baseline measurements where ionospheric effects would tend to cancel due to similar propagation paths. We plan to deploy this self-contained system, which uses solar polar and an integrated radio modem, in the vicinity of the Hayward fault to improve the spatial density of our monitoring effort. The BSL borrowed 2 receivers and a master radio from UNAVCO to perform the evaluation. Considerable hardware and software development was required before the system became operation in June 1999. Baseline lengths estimated using the GAMIT software have cm-level precision out to 10-km lengths if ambiguity resolution is not attempted, but are several times worse if it is attempted, and are not improved by processing more than 2 stations simultaneously (Figure 5.3). These results are contrary to those typically obtained using dual-frequency data. We are currently working with MIT to assess how to improve the ambiguity resolution algorithms and with UNAVCO to investigate other analysis packages, such as Bernese, that may be better suited to this data type.

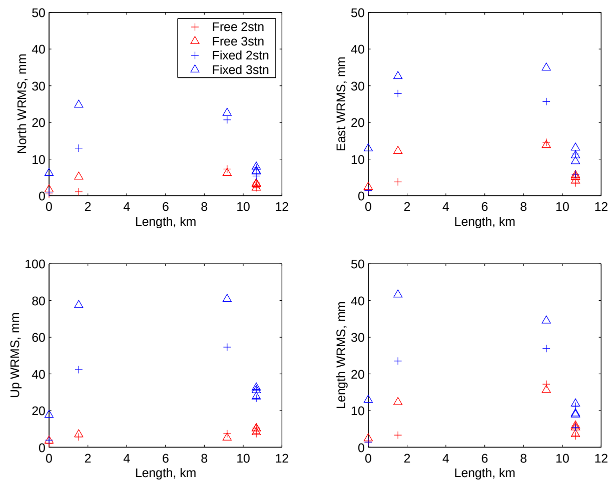


Figure 5.3: Weighted RMS scatter of L1-system baseline components and length versus baseline length. Red symbols are phase ambiguity unresolved (free) solutions. Blue symbols are phase ambiguity resolved (fixed) solutions. Triangles are 3-station network solutions. Crosses are 2-station baseline solutions. *Courtesy of M. Murray.*

7. Data Analysis

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 split into 6 geographical subregions: the Bay Area, northern California, Long Valley caldera, southern and northern Pacific Northwest, and the Basin and Range Province. Each subnet includes the 5 IGS stations and 3 stations in common with another subnet to help tie the subnets together. 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. The subnet solutions for each day are combined assuming a common orbit to estimate weakly constrained coordinate-only solutions. 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 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 1998–1999 are shown in Figure 5.4, with 95% confidence regions. The velocities are relative to stable North America, as defined by the five IGS fiducial stations. Most of the Sierra Nevada sites (CMBB, QUIN, and ORVB), as well as SUTB in the Central Valley, show little relative motion, indicating that the northern Sierra Nevada–Central Valley is tectonically stable. The motion of these

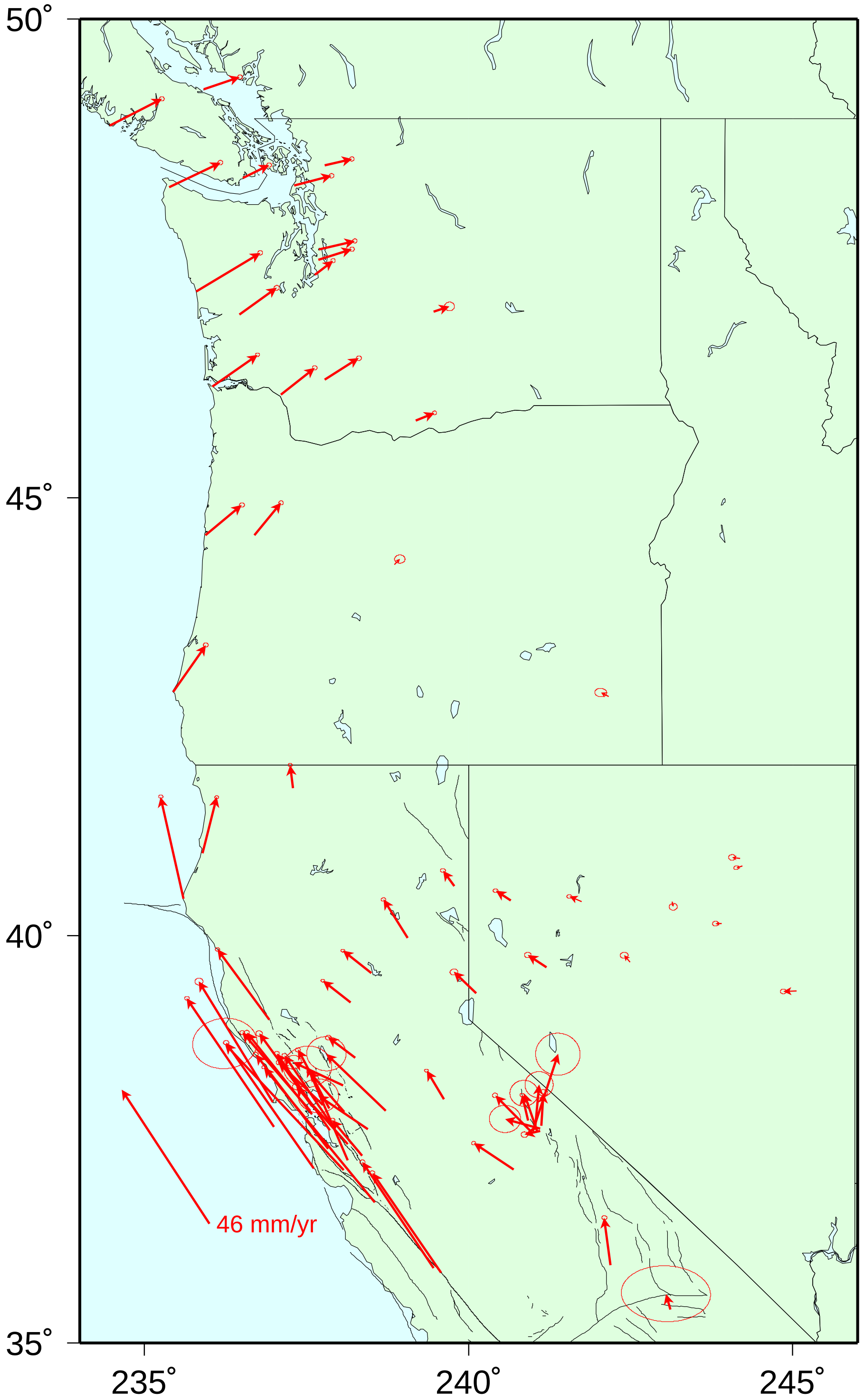


Figure 5.4: Velocities relative to stable North America for the BARD stations and other stations operated in nearby networks. Data from January 1998 to September 1999 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, with the predicted Pacific–North America relative plate motion in central California shown for scale. *Courtesy of M. Murray.*

sites relative to North America is consistent with spreading in the Basin and Range Province, which appears to be localized in western Nevada (*Bennett et al.,* 1998). The sites near Long Valley caldera show anomalously high radial motions away from the center of the caldera, consistent with inflation of magmatic sources at depth. Deformation in the Pacific Northwest is generally consistent with interseismic strain accumulation along the Cascadia megathrust, the interface between the Juan de Fuca and North America plates, particularly in Washington where the velocity vectors are nearly parallel to the oblique convergence direction. Greater arc-parallel motion in Oregon and northern California may be due to the influence of the SAF system to the south and spreading in the Basin and Range Province to the east.

Deformation along the coast in central California is dominated by the active SAF system, which accommodates about 35 mm/yr of right-lateral shear. The velocities parallel and perpendicular to the SAF system of stations located in a profile from the San Francisco Bay area to eastern Nevada are shown in Figure 5.5. The Farallon Island site (FARB) off the coast of San Francisco is moving at nearly the rate predicted by the NUVEL-1A Pacific–North America Euler pole. Most of the 46 mm/yr of relative motion is accommodated within a 100-wide zone centered on the SAF system and a broader zone in the Basin and Range Province in Nevada.

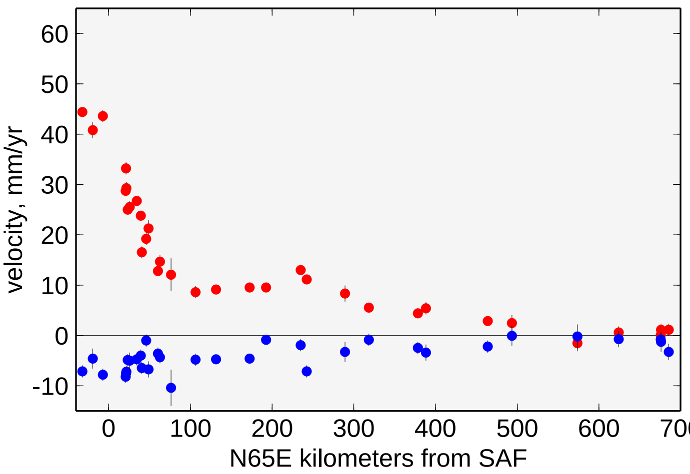


Figure 5.5: Velocities relative to stable North America of stations located in a profile from the Bay Area to eastern Nevada. Velocities, with one standard deviation error bars, are parallel (red) and perpendicular (blue) to the average azimuth of the SAF system, and distance is from the SAF near Pt. Reyes. *Courtesy of M. Murray.*

These BARD results are being combined with older VLBI and spatially dense Geodolite EDM and survey GPS measurements collected by the USGS, Stanford University, and UC Berkeley (*Murray et al.,* 1998b). The combined velocity map will provide significantly improved constraints on three-dimensional locking depth and deep-slip models of strain accumulation, which will be used for seismic hazard assessment along the SAF system. This effort is discussed in greater detail in a later chapter, entitled "Interseismic Crustal Deformation in Northern California".

We are also developing real-time analysis techniques that will enable rapid determinations (∼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). We currently process data available within 1 hour of measurement from the 18 continuous telemetry BSL stations, and several other stations that make their data available on an hourly basis. The data are binned into 1 hour files and processed simultaneously. The scatter of these hourly solutions is much higher than the 24-hour solutions: 10 mm in the horizontal and 30–50 mm in the vertical. Our simulations suggest that displacements 3–5 times these levels 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 upon these results, such as using a Kalman filter that can combine the most recent data with previous data in near real-time.

8. Transient Deformation of the 1998 San Juan Bautista Earthquake

The August 1998 M=5.1 San Juan Bautista earthquake produced a detectable displacement signal at the nearby SAOB GPS receiver (*Uhrhammer et al.,* 1999). The observed transient deformation, which appears to have both coseismic and postseismic components, is similar to nearby creep and strainmeter observations. No significant vertical offset was detected and no other BARD sites were measurably displaced. Relative to the PKDB station (Figure 5.6), SAOB moved north 2.6±0.5 mm and west 4.3±0.6 mm. This GPS-derived displacement, which represents an average over the six-week interval following the earthquake, is more than double that inferred from the more instantaneous accelerometer measurements at the collocated seismic station SAO. Continued aseismic slip on the fault following the earthquake is one possible explanation for this difference. Measurements at the nearby SJS borehole tensor strainmeter, which show an instantaneous 0.5 microstrain coseismic offset followed by an additional 0.5 microstrain increase over the next 12 days, are consistent with this interpretation (Figure 5.6).

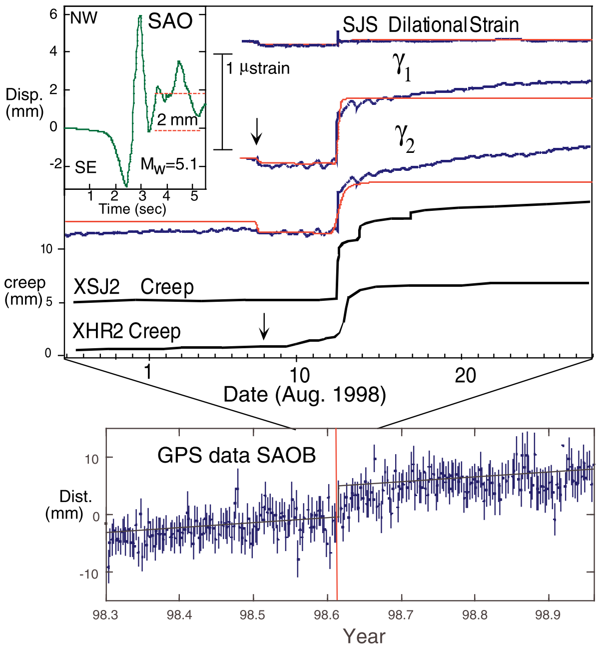


Figure 5.6: Transient deformation following the 1998 San Juan Bautista earthquake, as observed on strain dilatometers (top right), accelerometers (top left), surface creepmeters (middle), and GPS (bottom). Modified from (*Uhrhammer et al.,* 1999). *Courtesy of R. Bürgmann.*

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