BSL Operations

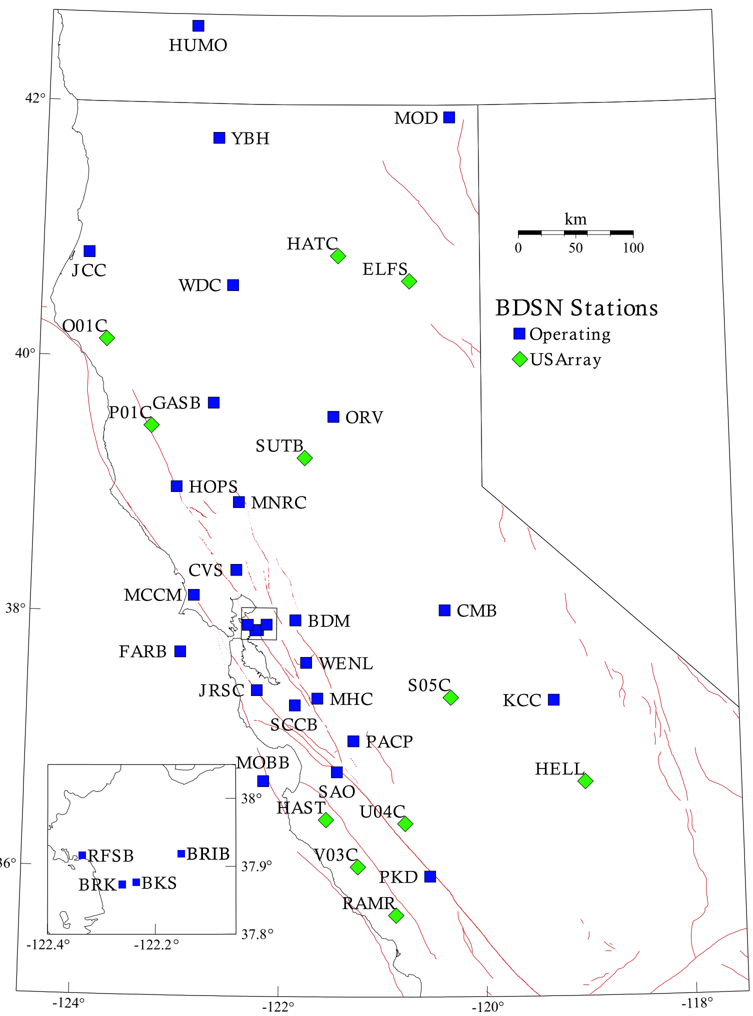

Figure 3.75: Map illustrating the distribution of BDSN stations (squares) in northern and central California. The diamonds indicate sites currently operated by USArray which we are monitoring as perspective future stations.

Chapter 4

Berkeley Digital Seismic Network

1. Introduction

The Berkeley Digital Seismic Network (BDSN) is a regional network of very broadband and strong motion seismic stations spanning northern California and linked to UC Berkeley through continuous telemetry (Figure 3.75 and Table 4.1). The network is designed to monitor regional seismic activity at the magnitude 3+ level as well as to provide high quality data for research projects in regional and global broadband seismology.

Since 1991 the BDSN has grown from the original 3 broadband stations installed in 1986-87 (BKS, SAO, MHC) to comprise 27 stations, including an autonomous ocean-bottom seismometer in Monterey Bay (MOBB). We take particular pride in high quality installations, which often involve lengthy searches for appropriate sites away from sources of low-frequency noise, as well as continuous improvements in installation procedures and careful monitoring of noise conditions and problems. Thus, although three new stations were completed, the focus of this year's technical efforts evolved to maintenance and repair, because of aging instruments, the desire for higher data rates, corrosion and outright equipment failure.

Further expansion of our network, one of BSL's long term goals, is contingent on the availability of funding and coordination with other institutions for the development of a denser state-of-the-art strong motion/broadband seismic network and joint earthquake notification system in this seismically hazardous region.

Equally important, data quality and the integrity of the established network must be preserved and remain assured despite expansion. The first generation of broadband seismometers installed by BSL have been operating for almost 25 years. At the same time, the first generation of broadband dataloggers are entering their 16th year of service. These will both require continued vigilance and greater time commitment to repairs in the future.

2. BDSN Overview

Twenty-four of the BDSN sites are equipped with 3 component broadband seismometers and strong-motion accelerometers, and a 24-bit digital data acquisition system or datalogger. Two additional sites (RFSB and SCCB) consist of a strong-motion accelerometer and a 24-bit digital datalogger. The ocean-bottom station MOBB is equipped with a 3 component broadband seismometer. Data from all BDSN stations, except MOBB, are transmitted to UC Berkeley using continuous telemetry. In order to insure against data loss during utility disruptions, each site has a 3-day supply of battery power and is accessible via a dialup phone line. The combination of high-dynamic range sensors and digital dataloggers ensures that the BDSN has the capability to record the full range of earthquake motion for source and structure studies. Table 4.2 lists the instrumentation at each site.

Most BDSN stations have Streckeisen STS-1 or STS-2 three-component broadband sensors (*Wielandt and Streckeisen*, 1982; *Wielandt and Steim*, 1986). A Guralp CMG-3T downhole broadband sensor contributed by LLNL is deployed in a post-hole installation at BRIB. A Guralp CMG1-T is deployed at MOBB. The strong-motion instruments are Kinematrics FBA-23 or FBA-ES-T with ± 2 g dynamic range. The recording systems at all sites are either Q330, Q680, Q730, or Q4120 Quanterra dataloggers, with 3, 6, 8, or 9 channel systems. The Quanterra dataloggers employ FIR filters to extract data streams at a variety of sampling rates. In general, the BDSN stations record continuous data at .01, 0.1, 1.0, 20.0 or 40.0, and 80 or 100 samples per second, although some sites send triggered data at the highest sampling rate using the Murdock, Hutt, and Halbert event detection algorithm (*Murdock and Hutt*, 1983) (Table 4.3). In addition to the 6-channels of seismic data, signals from thermometers and barometers are recorded at nearly every site (Figure 4.1).

In parallel with the upgrade of the broadband network, a grant from the CalREN Foundation (California Research and Education Network) in 1994 enabled

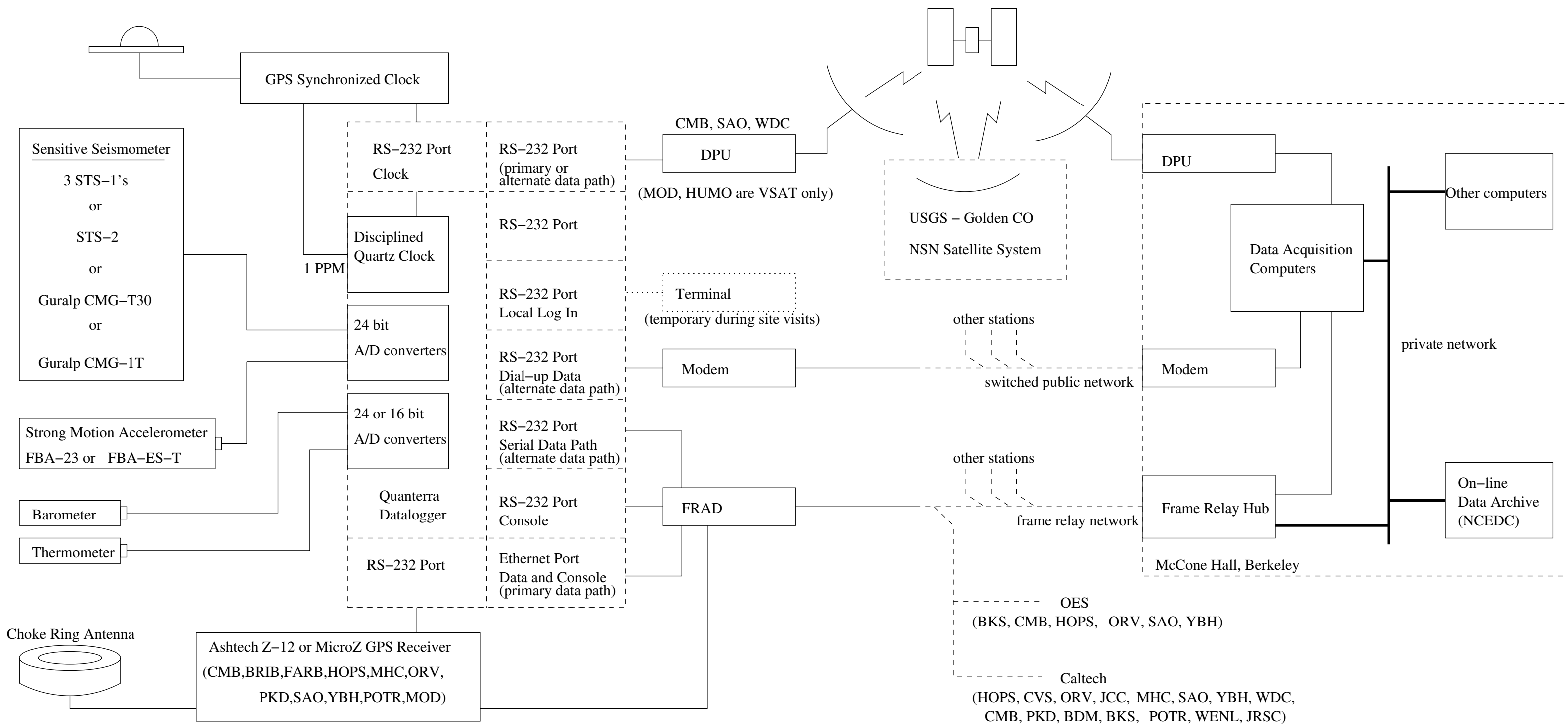

Figure 4.1: Schematic diagram showing the flow of data from the sensors through the dataloggers to the central acquisition facilities of the BSL.

the BSL to convert data telemetry from analog leased lines to digital frame-relay connections. The frame-relay network uses digital phone circuits that can support 56 Kbit/s to 1.5 Mbit/s throughput. Since frame-relay is a packet-switched network, a site may use a single physical circuit to communicate with multiple remote sites through the use of "permanent virtual circuits". Frame Relay Access Devices (FRADs), which replace modems in a frame-relay network, can simultaneously support multiple interfaces such as RS-232 async ports, synchronous V.35 ports, and ethernet connections. In practical terms, the upgrade to frame relay communication provides faster data telemetry between the remote sites and the BSL, remote console control of the dataloggers, additional services such as FTP and telnet to the dataloggers, data transmission to multiple sites, and the ability to communicate and transmit data from multiple instruments such as GPS receivers and/or multiple dataloggers at a single site. Today, 23 of the BDSN sites use frame-relay telemetry for all or part of their communications system.

As described in Chapter 10, data from the BDSN are acquired centrally at the BSL. These data are used for rapid earthquake reporting as well as for routine earthquake analysis (Chapters 5 and 11). As part of routine quality control (Chapter 10), power spectral density (PSD) analyses are performed weekly. Figure 4.2 shows a summary of the results for 2005-2006.

The occurrence of a significant teleseism also provides the opportunity to review station health and calibration. Figure 4.3 displays BDSN waveforms for a M_w 7.6 deep focus earthquake in the Banda Sea region on January 27, 2006.

BDSN data are archived at the Northern California Earthquake Data Center. This is described in detail in Chapter 9.

Sensor	Channel	Rate (sps)	Mode	FIR
Broadband	UH?	0.01	C	Ac
Broadband	VH?	0.1	C	Ac
Broadband	LH?	1	C	Ac
Broadband	BH?	20/40	C	Ac
Broadband	HH?	80/100	C	Ac/Ca
SM	LL?	1	C	Ac
SM	BL?	20/40	C	Ac
SM	HL?	80/100	C	Ac/Ca
Thermometer	LKS	1	C	Ac
Barometer	LDS	1	C	Ac

Table 4.3: Typical data streams acquired at BDSN stations, with channel name, sampling rate, sampling mode, and the FIR filter type. SM indicates strong-motion; C continuous; T triggered; Ac acausal; Ca causal. The LL and BL strong-motion channels are not transmitted over the continuous telemetry but are available on the Quanterra disk system if needed. The HH channels are recorded at two different rates, depending on the dataloger type. Q4120s provide 100 sps and causal filtering; Q680/980s provide 80 sps and acausal filtering.

2.1 Electromagnetic Observatories

In 1995, in collaboration with Dr. Frank Morrison, the BSL installed two well-characterized electric and magnetic field measuring systems at two sites along the San Andreas Fault which are part of the Berkeley Digital Seismic Network. Since then, magnetotelluric (MT) data have been continuously recorded at 40 Hz and 1 Hz and archived at the NCEDC (Table 4.4). At least one set of orthogonal electric dipoles measures the vector horizontal electric field, E, and three orthogonal magnetic sensors measure the vector magnetic field, B. These reference sites, now referred to as electromagnetic (EM) observatories, are co-located with seismographic sites so that the field data share the same time base, data acquisition, telemetry and archiving system as the seismometer outputs.

The MT observatories are located at Parkfield (PKD1, PKD) 300 km south of the San Francisco Bay Area, and Hollister (SAO), halfway between San Francisco and

Sensor	Channel	Rate (sps)	Mode	FIR
Magnetic	VT?	0.1	C	Ac
Magnetic	LT?	1	C	Ac
Magnetic	BT?	40	C	Ac
Electric	VQ?	0.1	C	Ac
Electric	LQ?	1	C	Ac
Electric	BQ?	40	C	Ac

Table 4.4: Typical MT data streams acquired at SAO and PKD, with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous; T triggered; Ac acausal.

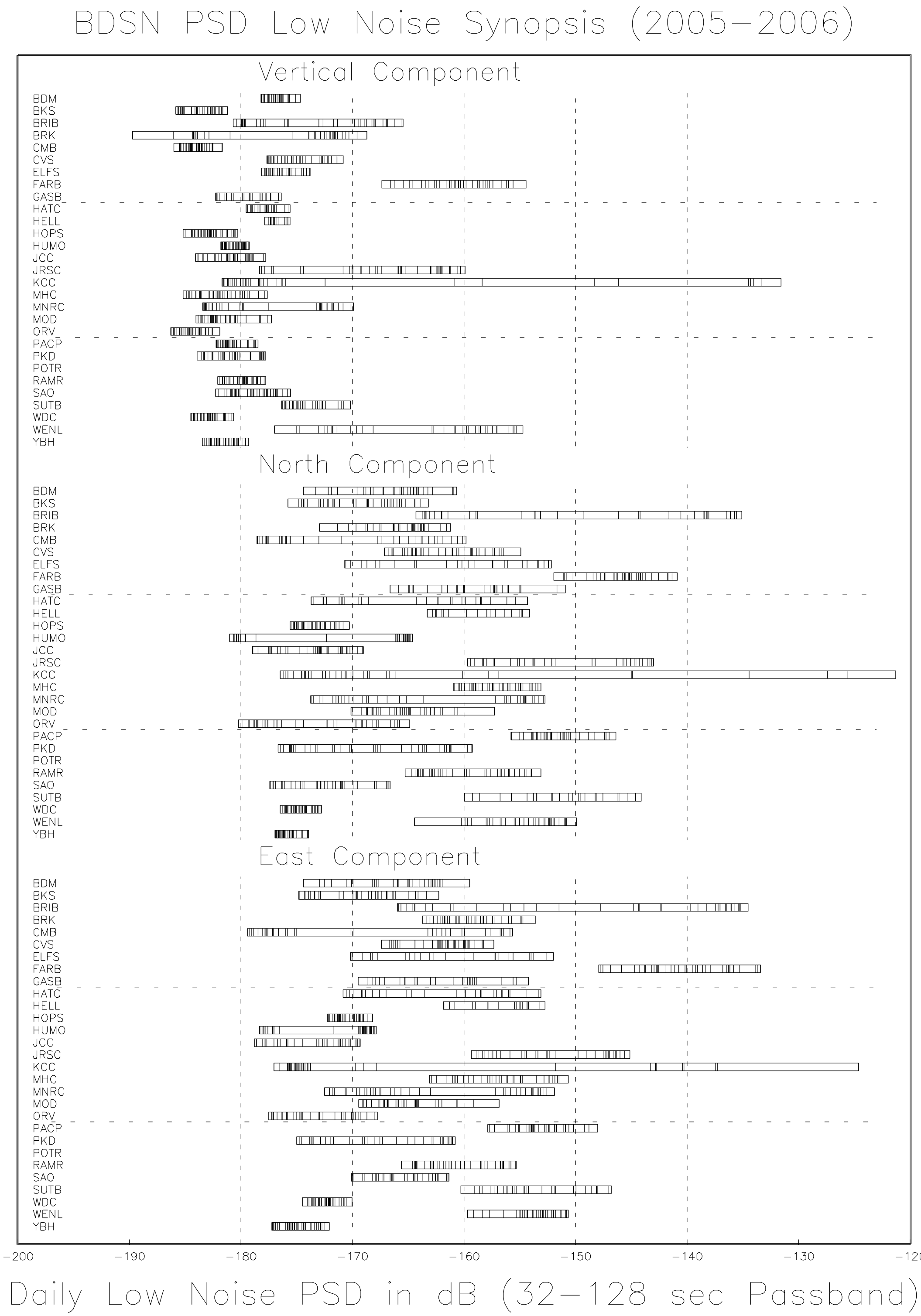

Figure 4.2: PSD noise analysis for BDSN stations, by channel, in the period range from 32-128 sec from 7/1/2005-6/30/2006. BRIB (situation in a shallow vault that is prone to tilting) and FARB (located on the Farallon Islands) stand out as sites with high noise levels. HUMO (located in an abandoned mine) stands out as an exceptionally quiet site.

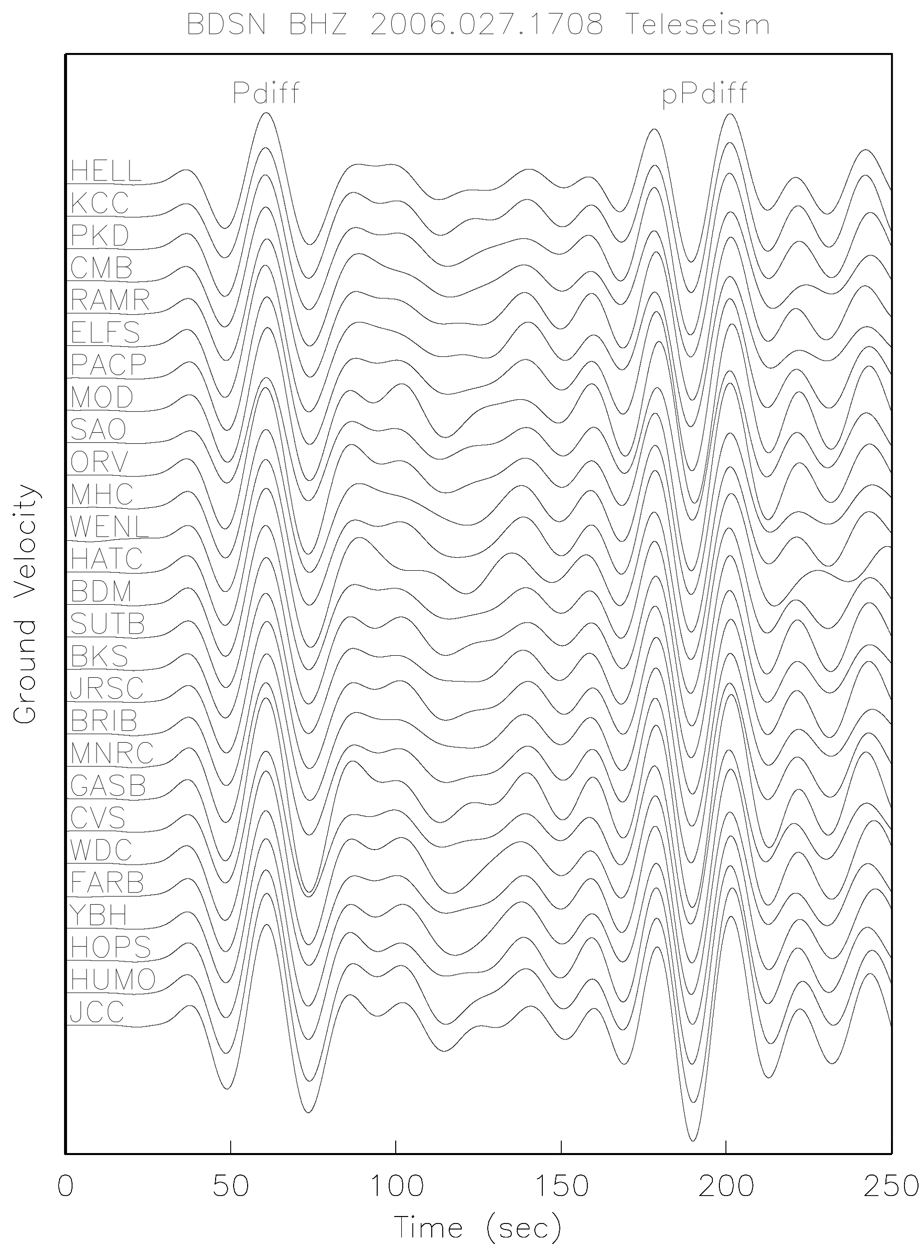

Figure 4.3: P_{diff} and pP_{diff} vertical component broadband waveforms recorded across BDSN from a deep focus (397 km) M_w 7.6 teleseism which occurred on January 27, 2006, in the Banda Sea at 5.482° S, 128.093° E, at a distance of 108.8° from Berkeley, and at an azimuth of N82W. The traces are deconvolved to ground motion, scaled absolutely, and ordered by distance from the epicenter. They are aligned on the first trough of P_{diff}. The pP_{diff} waveform, arriving 100 seconds later, is an inverted image of P_{diff} due to the polarity inversion that occurs when the P wave reflects from the free surface near the source. The highly similar waveforms recorded across the BDSN provide evidence that the broadband sensors are operating within their nominal specifications.

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
BDM	BK	37.9540	-121.8655	219.8	34.7	1998/11 -	Black Diamond Mines, Antioch
BKS	BK	37.8762	-122.2356	243.9	25.6	1988/01 -	Byerly Vault, Berkeley
BRIB	BK	37.9189	-122.1518	219.7	2.5	1995/06 -	Briones Reservation, Orinda
BRK	BK	37.8735	-122.2610	49.4	2.7	1994/03 -	Haviland Hall, Berkeley
CMB	BK	38.0346	-120.3865	697.0	2	1986/10 -	Columbia College, Columbia
CVS	BK	38.3453	-122.4584	295.1	23.2	1997/10 -	Carmenet Vineyard, Sonoma
FARB	BK	37.6978	-123.0011	-18.5	0	1997/03 -	Farallon Island
GASB	BK	39.6547	-122.716	1354.8	2	2005/09 -	Alder Springs
HOPS	BK	38.9935	-123.0723	299.1	3	1994/10 -	Hopland Field Stat., Hopland
HUMO	BK	42.6071	-122.9567	554.9	50	2002/06 -	Hull Mountain, Oregon
JCC	BK	40.8175	-124.0296	27.2	0	2001/04 -	Jacoby Creek
JRSC	BK	37.4037	-122.2387	70.5	0	1994/07 -	Jasper Ridge, Stanford
KCC	BK	37.3236	-119.3187	888.1	87.3	1995/11 -	Kaiser Creek
MCCM	BK	38.1448	-122.8802	-7.7	2	2006/02 -	Marconi Conference Center, Marshall
MHC	BK	37.3416	-121.6426	1250.4	0	1987/10 -	Lick Obs., Mt. Hamilton
MNRC	BK	38.8787	-122.4428	704.8	3	2003/06 -	McLaughlin Mine, Lower Lake
MOBB	BK	36.6907	-122.1660	-1036.5	1	2002/04 -	Monterey Bay
MOD	BK	41.9025	-120.3029	1554.5	5	1999/10 -	Modoc Plateau
ORV	BK	39.5545	-121.5004	334.7	0	1992/07 -	Oroville
PACP	BK	37.0080	-121.2870	844	0	2003/06 -	Pacheco Peak
PKD	BK	35.9452	-120.5416	583.0	3	1996/08 -	Bear Valley Ranch, Parkfield
RFSB	BK	37.9161	-122.3361	-26.7	0	2001/02 -	RFS, Richmond
SAO	BK	36.7640	-121.4472	317.2	3	1988/01 -	San Andreas Obs., Hollister
SCCB	BK	37.2874	-121.8642	98	0	2000/04 -	SCC Comm., Santa Clara
WDC	BK	40.5799	-122.5411	268.3	75	1992/07 -	Whiskeytown
WENL	BK	37.6221	-121.7570	138.9	30.3	1997/06 -	Wente Vineyards, Livermore
YBH	BK	41.7320	-122.7104	1059.7	60.4	1993/07 -	Yreka Blue Horn Mine, Yreka

Table 4.1: Currently operating stations of the Berkeley Digital Seismic Network. Each BDSN station is listed with its station code, network id, location, operational dates, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame and the elevation (in meters) is relative to the WGS84 reference ellipsoid. The elevation is either the elevation of the pier (for stations sited on the surface or in mining drifts) or the elevation of the well head (for stations sited in boreholes). The overburden is given in meters. The date indicates either the upgrade or installation time.

Parkfield (Figure 3.75). In 1995, initial sites were established at PKD1 and SAO, separated by a distance of 150 km, and equipped with three induction coils and two 100 m electric dipoles. PKD1 was established as a temporary seismic site, and when a permanent site (PKD) was found, a third MT observatory was installed in 1999 with three induction coils, two 100 m electric dipoles, and two 200 m electric dipoles. PKD and PKD1 ran in parallel for one month in 1999, and then the MT observatory at PKD1 was closed.

Data at the MT sites are fed to Quanterra dataloggers, shared with the collocated BDSN stations, synchronized in time by GPS and sent to the BSL via dedicated communication links.

3. 2005-2006 Activities

3.1 USArray

The BSL concluded an agreement with IRIS during 2003-2004 to contribute 19 stations of the BDSN to USArray while the experiment is deployed in California. This included 17 existing stations: CMB, CVS, FARB, HOPS, HUMO, JCC, JRSC, KCC, MNRC, MOD, ORV, PACP, PKD, POTR, WDC, WENL, and YBH as well as the two new sites: GASB and MCCM.

The 19 BDSN sites provided USArray with a running start in northern California. In June of 2004, the BSL set up the software necessary to exchange data with USArray and made modifications to the dataloggers to change the BH sampling rate from 20 Hz to 40 Hz. In this third year of USArray, the BDSN has continued to use the 40 Hz sampling rate for the BH channels.

During the station installation phase for northern and

Code	Broadband	Strong-motion	datalogger	T/B	GPS	Other	Telemetry	Dial-up
BDM	STS-2	FBA-23	Q4120	X			FR	
BKS	STS-1	FBA-23	Q980	X		Baseplates	FR	X
BRIB	CMG-3T	FBA-23	Q980		X	Vol. Strain	FR	X
BRK	STS-2	FBA-23	Q680				POTS	
CMB	STS-1	FBA-23	Q980	X	X	Baseplates	FR	X
CVS	STS-2	FBA-23	Q4120	X			FR	
FARB	CMG-3T	FBA-23	Q4120	X	X		R-FR/R	
GASB	STS-2	FBA-ES-T	Q4120	X			R-FR	
HOPS	STS-1	FBA-23	Q980	X	X	Baseplates	FR	X
HUMO	STS-2	FBA-ES-T	Q4120	X			VSAT	X
JCC	STS-2	FBA-23	Q980	X			FR	X
JRSC	STS-2	FBA-23	Q680				FR	X
KCC	STS-1	FBA-23	Q980	X		Baseplates	R-Mi-FR	X
MCCM	STS-2	FBA-ES-T	Q4120				VSAT	
MHC	STS-1	FBA-23	Q980	X	X		FR	X
MNRC	STS-2	FBA-ES-T	Q4120	X			None	X
MOBB	CMG-1T		GEOSense			Current meter, DPG	None	
MOD	STS-1	FBA-ES-T	Q980	X	X	Baseplates	VSAT	X
ORV	STS-1	FBA-23	Q980	X	X	Baseplates	FR	X
PACP	STS-2	FBA-ES-T	Q4120	X			Mi/FR	
PKD	STS-2	FBA-23	Q980	X	X	EM	R-FR	X
RFSB		FBA-ES-T	Q730				FR	
SAO	STS-1	FBA-23	Q980	X	X	Baseplates, EM	FR	X
SCCB		FBA-ES-T	Q730		X		FR	
WDC	STS-2	FBA-23	Q980	X			FR	X
WENL	STS-2	FBA-23	Q4120	X			FR	
YBH	STS-1 & STS-2	FBA-23	Q980	X	X	Baseplates	FR	X

Table 4.2: Instrumentation of the BDSN as of 06/30/2006. Except for PKD1, RFSB, SCCB and MOBB, each BDSN station consists of collocated broadband and strong-motion sensors, with a 24-bit Quanterra datalogger and GPS timing. The stations PKD1, RFSB and SCCB are strong-motion only, while MOBB has only a broadband sensor. Additional columns indicate the installation of a thermometer/barometer package (T/B), collocated GPS receiver as part of the BARD network (GPS), and additional equipment (Other) such as warpless baseplates or electromagnetic sensors (EM). The obs station MOBB also has a current meter and differential pressure gauge (DPG). The main and alternate telemetry paths are summarized for each station. FR - frame relay circuit, R - radio, Mi - microwave, POTS - plain old telephone line, VSAT - USGS ANSS satellite link, None - no telemetry at this time. An entry like R-Mi-FR indicates telemetry over several links, in this case, radio to microwave to frame relay.

central California, the BSL collaborated with USArray to identify and permit sites that might be suitable as BDSN stations, several at UC reserves and field stations. The stations currently operating at Sutter Buttes, Hat Creek Radio Observatory, Eagle Lake Biological Field Station, Kirkwood Ski Area, Ben Lomond Conservation Camp, and at the summer home of a BSL staff member (M. Hellweg) in the Sierra Nevada foothills were established with support from BSL staff. Data from these sites (Figure 3.75) are being sent directly to the BSL as well as to the Array Network Facility. In addition, the BSL is monitoring data from several other USArray stations to evaluate their performance as possible future BDSN stations when USArray moves on across the country. In particular, noise comparisons are being conducted in different frequency bands for all BDSN and USArray stations in northern California (see Chapter 10 for further details).

3.2 Station Upgrades, Maintenance and Repairs

Given the remoteness of the off-campus stations, BDSN data acquisition equipment and systems are designed, configured, and installed so that they are both cost effective and reliable. As a result, the need for regular station visits has been reduced. Most station visits are necessitated by some catastrophic failure. The 2005-2006 fiscal year was no exception.

NSN VSAT modifications

In a collaborative effort with USGS/NEIC (US-NSN program), satellite dishes (VSAT's) were installed 10 years ago at stations SAO, CMB and WDC. The satellite connections allow us to contribute data to the NSN, while at the same time providing a redundant telemetry path to BSL. A VSAT was also installed in 1999 at MOD, where this was the only available means of telemetry. In 2002, station HUMO was installed as a collaboration between BSL, NEIC and the IRIS/GSN and VSAT telemetry insalled as the only telecommunications link. A VSAT down-link is also provided at the BSL data center. Due to a change in satellite vendors, hardware at all installations was changed and the satellite dishes repointed in 03/04. This effort was coordinated to minimize the interruption to the data flow. In early 2006, a third site at the Marconi Center (MCCM) was added to the partnership with NEIC and the IRIS/GSN. The NEIC also provided VSAT equipment for MCCM and is described elsewhere in this report.

KCC Telemetry Upgrade

Since 1996, telemetry links for all the BSL stations have been upgraded to 56 kbaud digital circuits with the exception of KCC, which is located in a hydropower facility operated by Edison International within the Sierra Nevada range. Due to the remoteness of the site, access to the area is limited after the first snowfall. Planning for the upgrade of KCC began in early 2001, when BSL engineers began discussions with Edison engineers. The terrorist events of September 11, 2001 required Edison to re-evaluate their network and site security, relegating BSL's telemetry upgrade at the KCC site to the back burner until the summer of 2005.

BSL and Edison upgraded the data link from the site over a two day period in October of 2005. Ethernet connectivity over a continuous 56k baud circuit was achieved to the site.

Also at that time, BSL engineers reinstalled the external reference clock. At KCC, the datalogger is located nearly 400 meters inside a granite tunnel. Satellite clock reception at the datalogger is impossible. During the original installation in 1996, the clock was placed at the entrance of the tunnel and digital clock output signals relayed to the datalogger via solid state short haul modems. Periodically, clock quality would suffer under this arrangement.

This year, BSL engineers moved the external reference clock to the back of the tunnel (near the datalogger) and installed a high gain antenna outside the tunnel. The connection between the clock and the antenna is via a super low loss coaxial cable. The printed circuit board which provides internal/external clock functions within the Quanterra datalogger was also replaced due to age related failure.

Temporary Removal of Seismometers from WENL

The BSL broadband installation at Wente Brothers Vineyards (WENL) was initially installed in 1997 at the rear of an adit that is used for the aging and storage of wine. The winter of 2005-2006 brought record rainfall to northern California. During the rains, the output from both the STS-2 and FBA-EST strong motion instruments were observed to be peculiar. Engineers from BSL found that ground water had risen and was touching the bottom of the seismometers. The cooling effect of the water had altered their responses. In order to prevent damage to the instruments in the event that the water should continue to rise, the instruments were immediately removed and returned to Berkeley. After inspection and verification of their response, the instruments were reinstalled at WENL six weeks later when the water had subsided.

Vandalism at MNRC

By design, stations of the BDSN are located in remote locations. This remoteness assures minimization of the cultural noise while providing a measure of security. Occasionally, the remoteness provides opportunity for mischief. In early 2006, such mischief occurred at the MNRC site. Vandals broke the lock off the line power meter box and switched the power off. The system continued to operate off of battery back up power until battery voltage fell critically low. BSL engineers restored the site operation with a station visit in which they turned the line power back on and installed a new lock. These simple tasks however, required five hours of round trip driving from Berkeley.

Electromagnetic Instruments at JRSC

BSL has jointly operated and maintained seismic instruments with Stanford University at the Jasper Ridge site (JRSC) since June of 1994. During the past year, BSL engineers endeavored on several days to reduce offsets and long period noise at the site. Largely these efforts involved altering grounding schemes and changing power connections with varying success. Backup batteries at the site were also changed and the FBA-23 strong motion instrument was changed to accommodate 2G full scale. Concurrent to these efforts, BSL engineers worked several days at Stanford installing and troubleshooting to support a joint USGS, Stanford Bay Area ULF-EM monitoring project. BSL has a subcontract award grant for assistance in installation, telemetry and data archiving for this project. BSL engineers troubleshoot cabling, connection, power and polarity issues. Additionally, a method for injection EM and magnetic signals into the ground was developed in order to verify system operation.

Upgrade and Repair of Dataloggers

As a result of aging, a number of BDSN dataloggers required repairs in 2005-2006. The dataloggers at BKS, BRK, and KCC experienced large drifts in their internal clocks as the crystal oscillators aged. These instruments were initially purchased during the network upgrades in the early 1990's. Replacement oscillators were available from the manufacturer. In each case, a backup datalogger was rotated in to replace the original unit, which was sent for service.

Support for Earthscope Transportable Array at SUTB, RAMR and HAST

BSL has supported the Earthscope Transportable Array (TA) within northern California by helping to permit sites, visiting them to maintain equipment, and by providing telemetry.

During 2005-2006, the TA installed a temporary broadband station near Sutter Buttes. Located within the flat central valley of California, the Sutter Buttes are the remnant of an ancient volcano. They rise steeply 700 meters above the valley floor, and their highest point holds a cluster of commercial radio towers and support facilities. Due to the remoteness and topology of the area, the planned telemetry via the cell phone network was found to be unreliable, and no commercial telephone service is available.

Since 1997, BSL has operated a BARD GPS station by special arrangement with the radio site operator. For this station, BSL engineers installed a digital radio link to the BSL site at ORV approximately 30 kilometers away. There, the data are consolidated with that of the seismic and GPS installations at ORV, and fed via a single 56k telco circuit to Berkeley. To support the US Traveling Array, the radio hardware at Sutter Buttes was changed in 2005 to enable the radio there to act as both a repeater for the USArray seismic data and a radio transmitter for the BARD GPS data from Sutter Buttes. Correspondingly, the radio equipment at the ORV end was changed. At present, the single digital telco circuit between ORV and Berkeley thus carries data from the ORV seismic instruments and GPS, the GPS instruments at Sutter Buttes, and the USArray seismic installation.

BSL engineers made multiple site visits to both the Sutter Buttes radio installation and the US Array seismic site in order to achieve the desired network connectivity.

The Hasting Reservation is a research and natural history facility operated by the University of California system in Monterey County California. The BSL provided permitting and logistic support during placement of the USArray instrument as well a strong motion instrumentation for the site. BSL engineers visited the site to replace the failed accelerometer in early 2006.

3.3 New Installations

Two new BDSN stations, Alder Springs (GASB) and Marconi Conference Center (MCCM) were completed and brought on line in 2005/2006. Both stations provide broadband and strong motion data with continuous data telemetry. No existing buildings or structures were available at these locations. BSL engineers constructed the necessary infrastructure.

Alder Springs (GASB)

The Alder Springs (GASB) site is located approximately 35 kilometers west of the central valley town of Willows. Local geology is mostly serpentine and Franciscan. In the past, a short period observatory has been operated at the Alder Springs site by the California Department of Water Resources. The GASB site is being developed in cooperation with the CREST (Consolidated Reporting of EarthquakeS and Tsunamis) network, and closes a gap in the BDSN network between stations MNRC and WDC.

In June 2004, construction began on a steel and concrete seismographic vault similar to those at JCC, PKD, HOPS, and MNRC. On-site excavation was contracted. Inmates from the CDF Valley View Conservation Camp provided labor for the concrete pour and back filling of the excavation. BSL engineers built the forms and framing for the concrete, as well as all electrical wiring at the site. The permit for this site was provided by the US Forest Service, Mendocino National Forest.

Although, physical work at the site temporarily stopped in September 2004, a frame-relay circuit was installed at the CDF camp in early January of 2005. Local loop connectivity to the vault was achieved via wireless Ethernet bridge (radio). Installation of the seismic instruments at GASB was completed in September 2005, and broadband data acquisition began.

Marconi Conference Center (MCCM)

In November 2004, BSL and the University of California signed a License Agreement to construct a seismic vault and install instruments at the Marconi Conference Center near Marshall, CA. Located along the Tomales Bay, the surface trace of the San Andreas Fault, the conference center is part of the California State Park system. The site for the station was selected for its proximity to existing utilities and to minimize the disturbances to the historical and visual elements of the park. This site was constructed with combined funding from BSL, USGS/NEIC and the IRIS/GSN and is part of the ANSS backbone network.

Following the success of the seismic vaults at HOPS, PKD, and MNRC, the vault at MCCM was constructed using a recycled, ocean going, steel shipping container. The design is advantageous in locations where existing facilities or mine adits do not exist. Construction began in February 2005, with excavation and concrete pours. However, the installation of the instrumentation was delayed until after December 2005, when the electrical power was connected. Telemetry from the site is achieved via a NEIC VSAT. The satellite installation was completed by joint efforts of BSL and NEIC engineers in February 2006.

The station has been recording data since early February 2006, and VSAT telemetry has been operating since late February. The MCCM site features a Q4120 datalogger, a STS-2 seismometer, and a FBA ES-T strong motion instrument with 2 G limit. BSL engineers are presently pursuing a permit to augment the site telemetry via digital radio repeater. This permit is expected sometime in the next year.

3.4 The Monterey Bay Ocean Bottom Seismic Observatory (MOBB)

The Monterey Ocean Bottom Broadband observatory (MOBB) is a collaborative project between the Monterey Bay Aquarium Research Institute (MBARI) and the BSL. Supported by funds from the Packard Foundation to MBARI, NSF/OCE funds and UC Berkeley funds to BSL, its goal has been to install and operate a long-term seafloor broadband station as a first step towards extending the on-shore broadband seismic network in northern California, to the seaside of the North-America/Pacific plate boundary, providing better azimuthal coverage for regional earthquake and structure studies. It also serves the important goal of evaluating background noise in near-shore buried ocean floor seismic systems, such as may be installed as part of temporary deployments of "leap-frogging" arrays (e.g. Ocean Mantle Dynamics Workshop, September 2002).

BSL staff put significant effort in the development of procedures to minimize instrumental noise caused by air circulation inside the seismometer package casing (see 2001-2002 and 2002-2003 BSL Annual Reports). These procedures were later applied to the preparation of 3 similar packages destined for installation on the Juan de Fuca plate in the framework of University of Washington's Keck project.

This project follows the 1997 MOISE experiment, in which a three component broadband system was deployed for a period of 3 months, 40 km off shore in Monterey Bay, with the help of MBARI's "Point Lobos" ship and ROV "Ventana" (Figure 4.4). MOISE was a cooperative program sponsored by MBARI, UC Berkeley and the INSU, Paris, France (*Stakes et al.*, 1998; *Romanowicz et al.*, 1999; *Stutzmann et al.*, 2001). During the MOISE experiment, valuable experience was gained on the technological aspects of such deployments, which contributed to the success of the present MOBB installation.

The successful MOBB deployment took place April 9-11, 2002 and the station is currently recording data autonomously (e.g. *Romanowicz et al.*, 2003). It comprises a 3 component very broadband CMG-1T seismometer system, a diffential pressure gauge (DPG, *Cox et al.*, 1984) and a current meter. Data from the DPG are acquired with a sampling rate of 1 sps, and are crucial for the development and implementation of a posteriori noise deconvolution procedures to help counteract the large contribution of infragravity wave noise in the period range 20-200 sec. Procedures for removal of ingravity wave noise as well as signal generated noise have been developed (see chapter 10.).

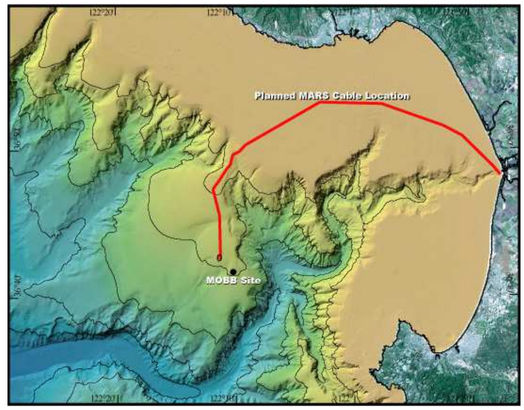

Figure 4.4: Location of the MOBB station in Monterey Bay, California, against seafloor and land topography. The projected path of the MARS cable is indicated by the solid line.

Seventeen "dives" involving the MBARI ship "Point Lobos" and ROV "Ventana" have so far taken place to exchange dataloggers and battery packages during the time period 04/10/02 to 06/15/06. In February 2004, the N/S component seismometer failed. It was temporarily replaced, from 05/19/04 to 07/09/04 by one of the Keck seismometer packages which was conveniently available at that time. The original seismometer was sent back to Guralp Inc. for repair and successfully reinstalled on 07/09/04.

The data collection from the broadband seismic system is fairly complete. However, there have been recurring DPG sensor as well as DPG data storage problems in the first two years of the MOBB operation. Well recorded DPG data are available since 03/18/2004.

The MOBB station is located close to the projected path of the MARS cable (Figure 4.4) which is scheduled to be deployed in the Fall of 2006. The connection of MOBB to the MARS cable will allow continuous, realtime data acquisition from this site. Developing the interface for the connection to MARS is the object of a proposal to NSF submitted in the summer of 2006.

4. Acknowledgements

Under Barbara Romanowicz's general supervision, Peggy Hellweg and Doug Neuhauser oversee the BDSN data acquisition operations and Bill Karavas heads the engineering team. John Friday, Jarrett Gardner, Rick Lellinger and Bob Uhrhammer contribute to the operation of the BDSN. Karl Kappler has been responsible for the operation of the EM observatories. Bill Karavas, Bob Uhrhammer, and Peggy Hellweg contributed to the preparation of this chapter.

The California Governor's Office of Emergency Services provided funding toward the development of sites MCCM and GASB as part of the CISN. The Incorporated Research Institutions in Seismology provided matching funds for the installation of MCCM. The CREST project provided a datalogger for GASB. Earthscope (USArray) provided funds towards telemetry of northern California TA stations through BSL and operation of joint BDSN/USArray stations.

MOBB is a collaboration between the BSL and MBARI, involving Barbara Romanowicz, Bob Uhrhammer, Doug Neuhauser and David Dolenc from the BSL, and Debra Stakes and Paul McGill from MBARI. The MBARI team also includes Steve Etchemendy (Director of Marine Operations), Jon Erickson, John Ferreira, Tony Ramirez and Craig Dawe. The MOBB effort at the BSL is supported by UC Berkeley funds. MBARI supports the dives and data recovery. The MOBB seismometer package was funded by NSF/OCE grant #9911392.

The Earthscope Transportable Array provides support for telemetry and maintenance of the 19 BDSN stations from which the BSL supplies data to the USArray efforts.

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Chapter 5

California Integrated Seismic Network

1. Introduction

Advances in technology have made it possible to integrate separate earthquake monitoring networks into a single seismic system as well as to unify earthquake monitoring instrumentation. In California, this effort began in the south with the TriNet Project. There Caltech, the California Division of Mines and Geology, now called the California Geological Survey (CGS), and the USGS combined their efforts to create a unified seismic system for southern California. With major funding provided by the Federal Emergency Management Agency (FEMA), the California Governor's Office of Emergency Services (OES), and the USGS, the TriNet project provided the opportunity to upgrade and expand the monitoring infrastructure, combining resources in a federal, state and university partnership. More recently, the integration effort has been expanded to the entire State in a cooperation between the California Geological Survey, Caltech, UC Berkeley, USGS Menlo Park, and the USGS Pasadena called the California Integrated Seismic Network (CISN).

The initial efforts to create this collaboration are described in the 2000-2001 Annual Report. The CISN is now in the sixth year of collaboration and its fifth year of funding from the OES.

2. CISN Background

2.1 Organization

The organizational goals, products, management, and responsibilities of the CISN member organizations are described in the founding MOU and in the strategic and implementation plans. To facilitate coordination of activities among institutions, the CISN has formed three management centers:

- Southern California Management Center: Caltech/USGS Pasadena
- Northern California Earthquake Management Center: UC Berkeley/USGS Menlo Park
- Engineering Strong Motion Data Center: California Geological Survey/USGS National Strong Motion Program

One important goal of the CISN is for the Northern and Southern California Management Centers to operate as twin statewide earthquake processing centers while the Engineering Strong Motion Data Center has the responsibility for producing engineering data products and distributing them to the engineering community.

The Steering Committee oversees CISN projects and comprises two representatives from each core institution and a representative from OES. The position of chair rotates among the institutions; Woody Savage is currently the chair of the Steering Committee.

An external Advisory Committee, representing the interests of structural engineers, seismologists, emergency managers, industry, government, and utilities, has been formed for review and oversight. The Advisory Committee is chaired by Stu Nishenko of Pacific Gas and Electric Company. The Advisory Committee last met in October 2005. The agendas from previous meetings and the resulting reports may be accessed through the CISN Web site (`http://www.cisn.org/advisory`). The next meeting is planned for August 2006.

The Steering Committee has formed other committees, including a Program Management Group to address planning and coordination, a Strong Motion Working Group to focus on issues related to strong-motion data, and a Standards Committee to resolve technical design and implementation issues.

In addition to the core members, several organizations contribute data that enhances the capabilities of the CISN. Contributing members of the CISN include: University of California, Santa Barbara; University of California, San Diego; University of Nevada, Reno; University of Washington; California Department of Water Resources; Lawrence Livermore National Lab; and Pacific Gas and Electric.

2.2 CISN and ANSS

The USGS Advanced National Seismic System (ANSS) is being developed along a regionalized model. Eight regions have been organized, with the CISN representing California. David Oppenheimer of the USGS serves as the CISN representative to the ANSS National Implementation Committee (NIC).

Over the past 7 years, ANSS funding in California has been directed primarily to the USGS Menlo Park to expand the strong-motion instrumentation in the San Francisco Bay Area. As a result, more than 100 sites have been installed or upgraded, significantly improving the data available for ShakeMaps.

As the ANSS moves forward, committees and working groups are being established to address issues of interest. BSL faculty and staff have been involved in several working groups of the Technical Integration Committee, including Doug Dreger, Pete Lombard, Doug Neuhauser, Bob Uhrhammer, and Stephane Zuzlewski.

2.3 CISN and OES

The California Governor's Office of Emergency Services has had a long-term interest in coordinated earthquake monitoring. The historical separation between northern and southern California and between strong-motion and weak-motion networks resulted in a complicated situation for earthquake response.

OES has been an advocate of increased coordination and collaboration in California earthquake monitoring and encouraged the development of the CISN Strategic and Implementation Plans. In FY01/02, Governor Gray Davis requested support for the CISN, to be administered through OES. Funding for the California Geological Survey, Caltech and UC Berkeley was made available in spring 2002, officially launching the statewide coordination efforts.

Following the first year of funding, OES support led to the establishment of 3-year contracts to the UC Berkeley, Caltech, and the California Geological Survey for CISN activities. The first multi-year award covered activities in 2002-2005. The first year of the current, three-year contract has just been completed.

2.4 Statewide Communications

One of the major accomplishments in FY01/02 was the design and initial implementation of a CISN "backbone" communications infrastructure. Doug Neuhauser of the BSL took the lead in investigating options and the CISN partners decided to establish a "ring" of T1 communication links (Figure 5.1) with redundant routers at each site. The CISN backbone will gracefully revert to routing traffic through encrypted tunnels over the Internet should the T1 circuits fail at a site.

The CISN backbone has been operating since FY03/04. It is being used to transmit seismic waveform data and parametric data, including strong motion parameters, between the management centers and to distribute ShakeMaps to OES. It is also used to support mirroring of the CISN Web server.

All of the routers, with the exception of those at OES, have Internet connections for backup tunnels over the Internet if the T1 circuits fail. However, if the CISN T1 circuits were to go down at OES, OES would be completely isolated from the CISN network and all CISN partners. This continues to be an issue of major concern.

3. 2005-2006 Activities

The CISN funding from OES facilitated a number of activities at the BSL during the past year.

3.1 FEMA Hazard Grant Mitigation Program Funds

The San Simeon and Parkfield earthquakes highlighted the sparseness of high quality instrumentation in northern California, outside of the Bay Area. In both cases, the initial ShakeMaps were not well constrained, due to the lack of digital instrumentation with real-time communications. One major difference between these two events is that the Parkfield area is very densely instrumented, particularly with accelerometers deployed by the California Geological Survey. However, since these instruments were primarily analog, the data were not available until several days after the event.

As a result of the San Simeon earthquake and other disasters, FEMA has made funds available to OES under the Hazard Grant Mitigation Program (HGMP). The BSL, Caltech, and CGS submitted joint applications for funds to two of the HGMP programs, which were funded in August 2005 and May 2006. Funds to BSL from the first grant have been used to purchase equipment for one broadband station, and to relocate the data acquisition and processing systems from McCone Hall to 2195 Hearst (described in Chapter 10). The seismic equipment will be installed at the USArray station RAMR near the epicenter of the San Simeon event. The second grant will be used to purchase equipment for three further broadband stations, which will be installed in sparsely instrumented areas. One will also be in central California at HAST. The two other new stations will be located along the northern California coast, another seismically active region with few stations.

3.2 Expanded Instrumentation

In the past year, the BSL completed the installation broadband stations at two sites, Alder Springs, California, and the Marconi Conference Center, near Pt. Reyes, California (GASB and MCCM, Figure 3.75). The station at GASB has been under discussion for a number of years, initially as part of the National Tsunami Hazards Program. It has been transmitting data since November, 2005. MCCM has been partially funded by IRIS, as a permanent component of USArray, and by USGS and OES. The first data were recorded in early February, 2006, with the installation of power, and telemetry commenced later in the month, when the ANSS VSAT system was installed.

With the completion of GASB and MCCM, the BSL has installed 4 of the 5 sets of site equipment purchased in the first year of the CISN. The efforts at GASB and MCCM are more fully described in Chapter 4.

3.3 Network Operations

With funding from the CISN project, the BSL purchased upgrade kits for 23 Q4120 data loggers to improve remote diagnostic capabilities. Three types of kits were purchased – power board only, calibration board only, and combined power and calibration boards – so that each Q4120 has a power board and that each 8-channel Q4120 also has a calibration board. The power boards allow battery voltage to be monitored, so staff can discriminate between power and telemetry problems remotely. The calibration boards provide the capability to monitor mass position and allow remote calibration of the seismic sensors. Both boards also record data logger temperature. To upgrade the dataloggers they must be returned to the lab, where the boards are installed and the lattices on the CPU board replaced. New cables must be prepared to transmit the mass position signals. When the upgrade is complete, the datalogger is redeployed to the field. The 3 remaing upgrades were completed this year, with cables or lattices being replaced where necessary.

3.4 Collaboration with USArray

In late 2003, the CISN concluded a memorandum of agreement with the Incorporated Research Institutions in Seismology (IRIS) covering the duration of the USArray project in California. As a result 19 stations operated by the BSL and 41 stations operated by Caltech are part of USArray during its California deployment. Both Caltech and the BSL modified some station operations in order to meet the USArray specifications. In particular, USArray requires BH data to be sampled at 40 sps, rather than the 20 sps as was standard in California. The surface broadband stations of BDSN were converted to 40 sps over June 15-16th, 2004. The BSL has also provided accelerometers for use at USArray sites which may be of interest as future BDSN stations. We continue to monitor the data from these stations in real time, and use the data in ShakeMaps and moment tensors. The collaboration between the BSL and USArray is discussed more fully in Chapters 4 and 10, including the telemetry the BSL provides for the two USArray stations RAMR and SUTB.

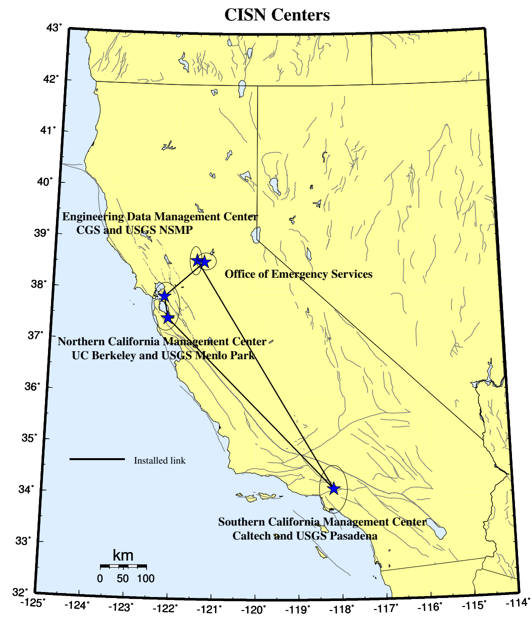

Figure 5.1: Map showing the geographical distribution of the CISN partners and centers. The communications “ring” is shown schematically with installed links (solid lines).

3.5 Northern California Earthquake Management Center

As part of their effort within the CISN, the BSL and the USGS Menlo Park have begun to implement the next generation of the northern California joint notification system. Chapter 11 describes the operations of the existing Management Center and reports on design discussions.

Communications Infrastructure

In order to move ahead with plans for restructuring the northern California earthquake monitoring system, the USGS Menlo Park and BSL have been working to improve their communications infrastructure.

At present, the BSL and the USGS Menlo Park are connected by two dedicated T1 circuits. One circuit is a component of the CISN ring, while the second circuit was installed in 2004-2005 (Figure 5.3) to support dedicated traffic between Berkeley and Menlo Park above and beyond that associated with the CISN.

The installation of the second dedicated T1 between Berkeley and Menlo Park freed up a frame-relay connection deployed by the BSL as part of the CalREN project

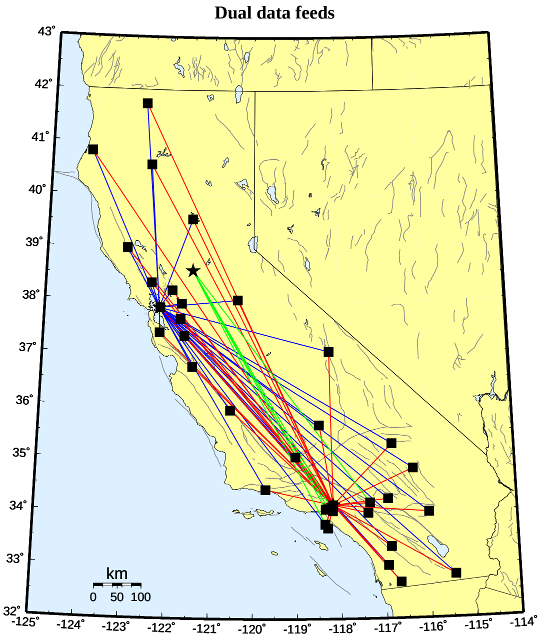

Figure 5.2: Map showing the 30 stations selected to send data directly to the Northern and Southern California processing centers, and the 5 stations that send data directly to the Engineering Data Center and the Southern California processing center.

in mid-1990s. The BSL has reconfigured this frame-relay circuit to serve as a second data acquisition link. The plan is to distribute the BDSN data acquisition between the two frame-relay T1 circuits, eliminating what had been a single point of failure. A second component of the plan is to establish an additional Permanent Virtual Circuit (PVC) at each BDSN site so that each station has connections to both T1s.

The acquisition of seismic data is now distributed between the two T1s and a second PVC is established at each frame-relay site. This effort has improved the robustness of data acquisition at the BSL by providing redundancy in the incoming circuit.

In the long term, the BSL and USGS Menlo Park hope to be connected by high-bandwidth microwave or satellite service. Unfortunately, we have not been able to obtain funding for this additional communication link at this time.

4. Statewide Integration

BSL staff are involved in many elements of the statewide integration effort. The Standards Committee continues to define and prioritize projects necessary to develop a prototype system and establish working groups to address them (see minutes from meetings and conference calls at `http://www.cisn.org/standards/meetings.html`).

Dual Station Feeds

One of the major accomplishments in the first few years has been the establishment of "dual station feeds" at 30 stations (15 in northern California and 15 in southern California) (Figure 5.2). To achieve this, the BSL and Caltech both ordered the DLCIs (data link connection identifier) that allow the 2nd center to establish a PVC to each station using the frame-relay network.

The Northern California Earthquake Management Center (NCEMC) is using data from the Southern California stations to estimate magnitudes on a routine basis. A subset of these stations are being used for the moment tensor inversions, a computation that is sensitive to the background noise level.

Data Exchange

Pick exchange was initiated between the NCEMC and its Southern California counterpart in 2001-2002. The software CISN has developed to produce and exchange the reduced amplitude timeseries has been completed. Currently, these timeseries are being exchanged at the NCEMC, but not yet statewide.

Using a common format, the CISN partners continue to exchange observations of peak ground motion with one another following an event or a trigger. This step increases the robustness of generating products such as ShakeMap, since all CISN partners now exchange data directly with one another. This also improves the quality of ShakeMaps for events on the boundary between northern and southern California, such as the San Simeon earthquake, by allowing all data to be combined in a single map. Finally, this is a necessary step toward the goal of generating statewide ShakeMaps.

Software Calibration & Standardization

The CISN partners are working together on the problem of software calibration, particularly as it pertains to automated earthquake processing. Currently, the software implemented in the NCEMC and in Southern California Management Center is very different. Initially, the CISN focused on the issue of calibration although the last year has seen an increased focus on standardization.

In 2002-2003, effort was focused on phase pickers (`pick-ew`), the association algorithm (`binder`), the location algorithm (`hypoinverse`), and magnitude estimation (various). Since then, magnitude estimation continues to be a significant area of focus, as well as ShakeMap configuration, metadata exchange, and database standardization.

At this point, the issues of a statewide detection and location system are largely addressed. Configuration files have been standardized and a statewide system has been running in Menlo Park for more than a year. It performed well during the December 2003 San Simeon sequence and

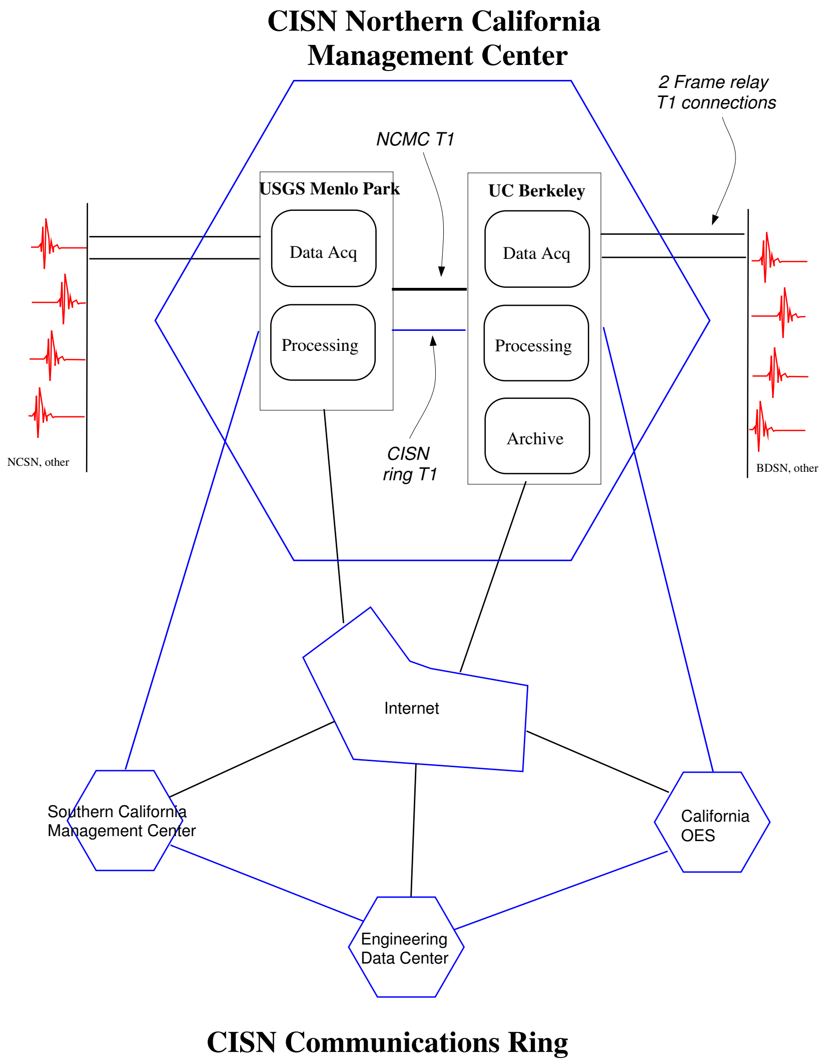

Figure 5.3: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley, forming the northern California Management Center, and with other elements of the CISN.

the 2004 Parkfield earthquake. A number of outstanding issues still remain to be addressed.

Magnitude: Calibrating magnitude estimates has proven to be more difficult than the CISN originally anticipated. As described in 2003-2004, three lines of evidence indicate that there is a bias between the northern and southern California magnitude estimates. First, a comparison of nearly 500 earthquakes over a 20 year period in central California recorded by both networks shows a bias of 0.14 magnitude units, with NC magnitudes higher than SC magnitudes. Second, efforts to invert Wood Anderson amplitudes using a differential approach, a constraint that the BKS and PAS adjustments sum to zero, and fixing the attenuation relationship to one determined by *Kanamori* (1993), indicates a bias of 0.14. Finally, an independent inversion of a different dataset (absolute approach, a different set of station constraints, and simultaneous inversion for attenuation) suggests a bias of 0.20.

Efforts to understand this issue have been hampered by the lack of a good statewide dataset. In 2005-2006, Bob Uhrhammer selected data from 180 earthquakes distributed throughout the state and comprising recordings from 976 horizontal components from the AZ, BK, CI and NC networks. He has begun to assess station-specific corrections for M_L by determining the difference for each station-component pair. State-wide, the average difference is -0.039. The primary advantage of using this differencing method is that the results are independent of a reference station.

A final component of the magnitude efforts is the designation of a magnitude reporting hierarchy. After many discussions, there is general agreement that, at least for the near future, each region will continue to use its own preferences for magnitude reporting.

ShakeMap: In addition to the efforts in standardizing earthquake locations and magnitudes, a CISN working group has been addressing issues related to ShakeMaps. At present, ShakeMaps are generated on 5 systems within the CISN. Two systems in Pasadena generate "SoCal" Shakemaps; 2 systems in the Bay area generate "NoCal" Shakemaps; and 1 system in Sacramento generates ShakeMaps for all of California. The Sacramento system uses QDDS to provide the authoritative event information for northern and southern California.

During the past year, the Working Group has continued to address standardization issues for ShakeMap. Initially efforts focused on the look and feel of the maps (topography, geology, faults, road, lake outlines, cities, and fonts). The Working Group reviewed a comprehensive compilation of the differences in configuration among the 3 implementations. Efforts continue to address the remaining differences between the centers, which range from the small (URL used in the "addon" message) to the significant (use of regressions, linear versus log amplitude weighting). Resolving these differences will move the CISN forward toward having fully standardized ShakeMaps.

The lack of stations in the near source region of the 2003 San Simeon earthquake raised the issues of how to measure the quality of a ShakeMap and to quantify the uncertainty. A subset of the Working Group has been working on this issue, based on the work of *Hok and Wald* (2003). *Lin et al* (2006) presented progress toward quantifying ShakeMap uncertainty. When the method is validated, we can use this information to determine a grade.

Toward the goal of improving access to ShakeMap, the working group has put together an outline of how to create a unified set of Web pages. With general agreement about what to do, small progress has been made on actual implementation. The primary difficulty has been time, since creating unified Web pages requires a separation between product generation and Web page generation.

A second goal of this effort was to improve the robustness of ShakeMap generation and delivery by taking advantage of the fact that ShakeMaps are generated in the Bay Area, Pasadena, and Sacramento. Renewed efforts in this direction will likely be based on the new USGS ShakeMap webpages at the National Earthquake Information Center. Work in this direction continues in the coming year.

Location Codes: The CISN adopted a standard for the use of "location" codes (part of the Standard for the Exchange of Earthquake Data (SEED) nomenclature to describe a timeseries based on network-station-channel-location) in the late fall of 2003. USGS and UC Berkeley developers have modified the Earthworm software to support the use of location codes. The migration to their use is awaiting the transition at USGS Menlo Park away from the CUSP analysis system.

Metadata Exchange: The availablity and exchange of metadata is vital to CISN activities, as correct metadata are required to insure valid interpretation of data. CISN is also working on issues related to the reliable and timely exchange of these data.

Several years ago, the Metadata Working Group compiled a list of metadata necessary for data processing and developed a model for exchanging metadata. In this model, each CISN member is responsible for the metadata for its stations and for other stations that enter into CISN processing through it. For example, Menlo Park is responsible for the NSMP, Tremor, and PG&E stations, while Caltech is responsible for the Anza data.

Initially, the exchange of metadata was to be accomplished through database replication. In the past two years, individual developments at the various CISN partners have made this an unwieldy solution. At the present time, dataless SEED volumes are being used to exchange metadata between the NCEMC and the SCMC, while the Metadata Working Group develops a better and more robust means of exchange. In the long term, it will be important to develop a vehicle for the exchange of a more comprehensive set of metadata than is permitted in dataless SEED volumes. They cannot encompass, for example, all the parameters which must be included in V0 formatted data.

In parallel, the Working Group has developed a plan for importing metadata from CGS. Their metadata is not currently stored in a database and is maintained in simple files. Their policy is to distribute the metadata as part of a waveform package using the especially developed V0 format. The Working Group developed the concept of a "dataless" V0 format (analogous to the dataless SEED files) which is used to distribute the metadata. The CGS now provides dataless V0 files containing current metadata for ShakeMap quality stations (i.e., with channels meeting CISN Reference Station or better standards) in the CGS network. They are being distributed and are also placed at the CGS FTP site. As agreed, the comment field in the V0 header defines the valid time period for the metadata. Each dataless V0 file contains the 3 channels of the reference sensor at the site. The Working Group plan includes the ability to handle corrections, as well as updates as stations are serviced.

In order to make use of the dataless V0 file, tools have been developed to parse the file and write an XML file containing the information (an expansion of capabilities of the v02ms program). The NCEMC has taken advantage of previously existing tools to create a system where the XML is converted into a spreadsheet format and then imported into the database. This plan will be further tested as CGS generates more dataless V0 files and the database is populated.

As part of this process, the issue of mapping the sensor orientation into the SEED channel nomenclature has come up. The v02ms program now uses the same algorithm for generating channel names as used by CGS.

Standardization The CISN's focus on standardization, rather then calibration of software continues. For example, the BSL and the USGS Menlo Park are adapting the software running at the SCMC for use at the NCEMC and are currently testing its various elements. Examples of collaboration include the development of the CISN Messaging Service - software designed to replace the commercial `SmartSockets` package used in the initial development of TriNet, implementation of the `RequestCardGenerator` and `Jiggle` in northern California, and ongoing efforts to develop specifications for a magnitude coordinator.

4.1 CISN Display

CISN Display is an integrated Web enabled earthquake notification system, designed to provide earthquake information for emergency response at 24/7 operations centers. First-responders, organizations with critical lifelines and infrastructure, and emergency responders are invited to register for an account at `http://www.cisn.org/software/cisndisplay.htm`.

The application provides users with maps of real-time seismicity, and automatically provides access to Web-related earthquake products such as ShakeMaps. CISN Display also offers an open source GIS mapping tool that allows users to plot freely available layers of public highways, roads and bridges, as well as private layers of organizational-specific infrastructure and facilities information. The current version of CISN Display is 1.31.

4.2 Earthquake Information Distribution

The USGS hosted a workshop in October 2004 to develop plans for the installation and use of the EIDS software. Doug Neuhauser and Pete Lombard participated in this workshop, which resulted in a document outlining the steps necessary for the installation and migration of the earthquake notification system from the current Quake Data Distribution Servies (QDDS) to EIDS.

4.3 Outreach

There has been progress at `www.cisn.org` in FY05/06. The CISN Web site is now supported by two servers located at Berkeley and Caltech. The Web servers are set up so that the load can be distributed between them, providing improved access during times of high demand. With the increased robustness provided by the new servers, the CISN has begun to provide access to certain earthquake products directly from `www.cisn.org`. For example, ShakeMaps are now served directly from the CISN Web site, in addition to being available from several USGS Web servers and the CGS.

The design and content of `http://www.cisn.org` continues to evolve. The Web site is an important tool for CISN outreach as well as for communication and documentation among the CISN partners.

The CISN continues to support the dedicated Web site for emergency managers. Following a suggestion from the Advisory Committee, we have designed a Web site to provide personalized access to earthquake information. Known as "myCISN," the Web site is available at `eoc.cisn.org`. Access to the Web site is limited to registered users in order to provide highly reliable access. At present, "myCISN" is a single Web server located at UC Berkeley. However, modifications to the database are underway to allow for multiple servers in the future. A second computer, already purchased, will either be installed in Sacramento or in southern California.

As part of the CISN, the BSL also contributed to efforts to raise awareness during 1906 centennial activities. In particular, we co-hosted the *1906 Earthquake Conference* contributed to the preparation of the CISN booth at the meeting (see Chapter **??**

5. Acknowledgements

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Barbara Romanowicz and Peggy Hellweg are members of the CISN Steering Committee. Peggy Hellweg is a member of the CISN Program Management Group and she leads the CISN project at the BSL, with support from Doug Neuhauser during the transition. . Doug Neuhauser is chair of the CISN Standards Committee, which includes Peggy Hellweg and Pete Lombard as members.

Because of the breadth of the CISN project, many BSL staff have been involved including: John Friday, Peggy Hellweg, Bill Karavas, Pete Lombard, Doug Neuhauser, Charley Paffenbarger, Bob Uhrhammer and Stephane Zuzlewski. Peggy Hellweg contributed to this chapter. Additional information about the CISN is available through reports from the Program Management Committee.

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Chapter 6

Northern Hayward Fault Network

1. Introduction

Complementary to the regional broadband network, a deployment of borehole-installed, wide-dynamic range seismographic stations is being established along the Hayward Fault and throughout the San Francisco Bay toll bridges network. This network is a cooperative development of the BSL and the USGS, with support from USGS, Caltrans, EPRI, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL, and LBNL (Figure 6.1 and Table 6.1). Efforts at ongoing development of the network have also recently been enhanced through coordinated efforts with the Mini-PBO project which is partially funded by NSF and by the member institutions of that project.

The purpose of the network is threefold: 1) to lower substantially the threshold of microearthquake detection, 2) to increase the recorded bandwidth for events along the Hayward fault, and 3) to obtain bedrock ground motion signals at the bridges from small earthquakes for investigating bridge responses to stronger ground motions. A lower detection threshold increases the resolution of the fault-zone seismic structure; allows seismologists to monitor the spatial and temporal evolution of seismicity at magnitudes down to $M \sim> -1.0$, where earthquake rates are many times higher than those captured by surface sites; allows researchers to look for pathologies in seismicity patterns that may be indicative of the nucleation of large damaging earthquakes; and allows scientists to investigate fault and earthquake scaling, physics and processes in the San Francisco Bay Area. This new data collection will also contribute to improved working models for the Hayward fault. The bedrock ground motion recordings are also being used to provide input for estimating the likely responses of the bridges to large, potentially damaging earthquakes. Combined with the improved Hayward fault models, source-specific response calculations can be made as well.

The Hayward Fault Network (HFN) consists of two parts. The Northern Hayward Fault Network (NHFN) is operated by the BSL and currently consists of 28 stations with various operational status, including those located on Bay Area bridges and at borehole sites of the Mini-PBO (MPBO) project. This network is considered part of the BDSN and uses the network code BK. The Southern Hayward Fault Network (SHFN) is operated by the USGS and currently consists of 5 stations. This network is considered part of the NCSN and uses the network code NC. This chapter is primarily focused on the NHFN and activities associated with the BSL operations.

2. NHFN Overview

The five MPBO sites have 3-component borehole geophone packages. All the remaining HFN sites have six-component borehole sensor packages. The packages were designed and fabricated at LBNL's Geophysical Measurement Facility by Don Lippert and Ray Solbau, with the exception of site SFAB. For the HFN sites, three channels of acceleration are provided by Wilcoxon 731A piezoelectric accelerometers, and three channels of velocity are provided by Oyo HS-1 4.5 Hz geophones. Velocity measurements for the MPBO sites are provided by Mark Products L-22 2 Hz geophones (Table 6.2). The 0.1-400 Hz Wilcoxon accelerometers have lower self-noise than the geophones above about 25-30 Hz, and remain on scale and linear to 0.5 g. In tests performed in the Byerly vault at UC Berkeley, the Wilcoxon is considerably quieter than the FBA-23 at all periods, and is almost as quiet as the STS-2 between 1 and 50 Hz.

Sensors are generally installed at depths of about 100 m, but several sites have sensors emplaced at depths of over 200 m, and the Dumbarton bridge sites have sensors at multiple depths (Table 6.1). During initial stages of the project, the NHFN sensors provided signals to on-site Quanterra Q730 and RefTek 72A-07 dataloggers.

Today, 14 of the NHFN sites have Quanterra dataloggers with continuous telemetry to the BSL. Similar to BDSN sites, these stations are capable of on-site recording and local storage of all data for more than one day and have batteries to provide backup power. Signals from these stations are digitized at a variety of data rates up to 500 Hz at 24-bit resolution (Table 6.3).

The NHFN dataloggers employ casual FIR filters at

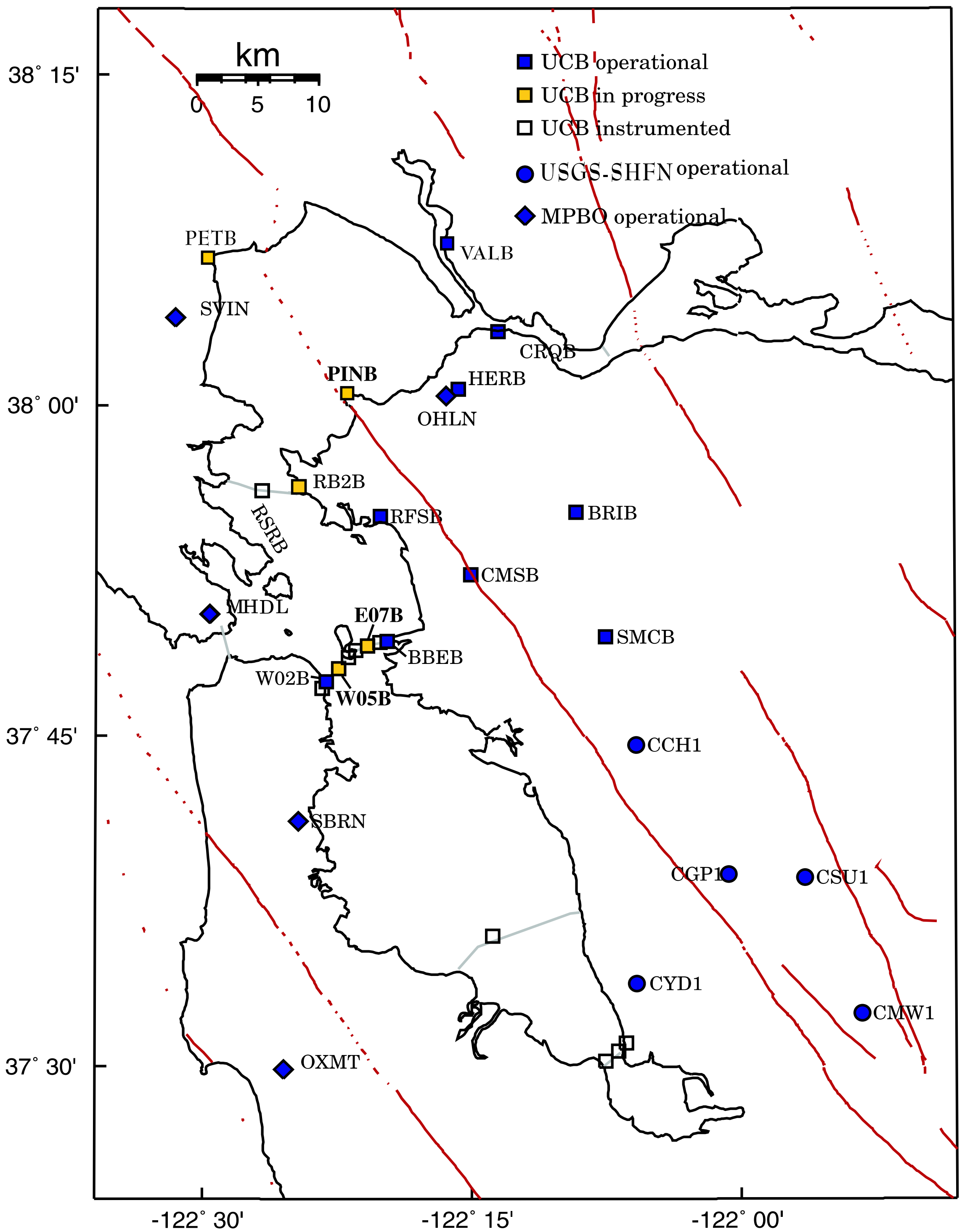

Figure 6.1: Map showing the locations of the HFN stations operated by the BSL (NHFN - squares) and the USGS (SHFN - circles) and Mini-PBO stations (diamonds) in the San Francisco Bay Area. Operational sites are filled blue/black, while sites in progress are yellow/grey. Other instrumented boreholes are indicated as open symbols.

high data rates and acausal FIR filters at lower data rates. Because of limitations in telemetry bandwidth and disk storage, 9 of these sites transmit one channel of 500 sps continuous data and 90 sec., 500 sps triggered data snippets for the remaining channels. The Murdock, Hutt, and Halbert (MHH) event detection algorithm (*Murdock and Hutt*, 1983) is operated independently at each station on 500 sps data for trigger determinations. Continuous data for all channels at reduced rates (20 and 1 sps) are also transmitted to and archived at the BSL. The five MPBO sites transmit continuous 100, 20 and 1 sps 3 component data streams that are also archived at BSL.

The remaining 14 sites of the NHFN have in the past recorded data using RefTek dataloggers. These sites do not have continuous telemetry for acquisition and in the past required visits from BSL staff for data recovery. Collection of data from these sites has been discontinued, but efforts are underway to upgrade them with Quanterra Q4120, Q730 or Q330 dataloggers and continuous telemetry.

Signals from the 5 SHFN stations are digitized by Nanometrics data loggers at 100 sps and transmit continuous data to Menlo Park by radio. These digital data streams are processed by the Earthworm system with the NCSN data and waveforms are saved when the Earthworm detects an event.

Data from both the NHFN and SHFN are archived at the NCEDC (Northern California Earthquake Data Center). At this time, the tools are not in place to archive the Hayward fault data together. The NHFN data are archived with the BDSN data, while the SHFN are archived with the NCSN data.

2.1 Station Maintenance

Ongoing network maintenance involves regular inspection of the collected seismic waveform data and spectra for nearby seismic events, and also from noise samples. Other common problems include changes to background noise levels due to ground loops, failing preamps, as well as power and telemetry issues. Troubleshooting and remediation of problems often require a coordinated effort with a technician at the BSL to examine seismic waveforms and spectra as the field technicians are still on site. BSL technicians regularly review data and assist in troubleshooting.

NHFN Station Maintenance Synopsis

The NHFN station hardware has proven to be relatively reliable. Nonetheless, numerous maintenance and performance enhancement measures are still required. Below is a synopsis of maintenance efforts performed recently for several NHFN stations that serves to illustrate some of the ongoing maintenance and enhancement measures that are typically performed.

BBEB: Ran radio tests on Wilan link to Space Sciences Lab at 18 dBm and at maximum power (23 dBm) to ascertain effect on dropped packets. At 24 dBm power, the throughput was 6 times higher than at 18 dBm power and the number of dropped packets reduced from 4.6

BRIB: Numerous frame relay telemetry problems were encountered during August and September, and the station was visited several times to troubleshoot and correct the problem.

CMSB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up.

CRQB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up and was functioning normally.

HERB: Velocity channel was found in September to not be responsive to events. The problem was traced to a blown fuse in the power system, although it is unclear as to how that problem effected the responsiveness of the velocity channel.

RFSB: Visited station several times to repair frame relay and power supply problems.

SMCB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up.

W02B: Telemetry link went down in October and again in December due to an antenna problem.

Quality Control

A commonly used check on the calibration of the borehole installed network, is to compare the bandpass filtered (0.3-2 Hz) ground velocity data recorded at NHFN and MPBO stations for large teleseismic earthquakes. As an example, a M 7.5 intermediate focus teleseism that occurred in Peru at a depth of 115 km is shown in Figure 6.3.

Another practise for quality control is the assessment of power spectral density (PSD) distributions for the network stations. Shown in Figure 6.2 are power spectral density distributions of background noise for a sample of 13 NHFN land and bridge site stations. In general, background noise levels of the borehole HFN stations is more variable and generally higher than that of the Parkfield HRSN borehole stations (see Parkfield Borehole Network chapter). This is due in large part to the significantly greater level of cultural noise in the Bay Area, and to the fact that noise reduction efforts on the much more recently installed NHFN stations are still underway. For example the two noisiest stations (i.e. BBEB and W02B) are located on the Bay Bridge, which is currently undergoing earthquake retrofit and east span reconstruction. These stations have also only recently come back on-line with upgraded infrastructure and instrumentation, so the full complement of noise reduction modifications have not yet been implemented.

On average the MPBO component of the NHFN sites is more consistent and somewhat quieter. This is due in

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
VALB	BK	38.1215	-122.2753	-24	155.8	2005/11 - current	Napa River Bridge
PETB	BK	38.1189	-122.5011	-30	113	in progress	Petaluma River Bridge
CRQB	BK	38.05578	-122.22487	-25	38.4	1996/07 - current	CB
HERB	BK	38.01250	-122.26222	-25	217.9	2000/05 - current	Hercules
PINB*	BK	38.0113	-122.3653	tbd	tbd	in progress	Point Pinole
BRIB	BK	37.91886	-122.15179	219.7	108.8	1995/06 - current	BR, Orinda
RFSB	BK	37.91608	-122.33610	-27.3	91.4	1996/01 - current	RFS, Richmond
CMSB	BK	37.87195	-122.25168	94.7	167.6	1994/12 - current	CMS, Berkeley
SMCB	BK	37.83881	-122.11159	180.9	151	1997/12 - current	SMC, Moraga
SVIN	BK	38.03325	-122.52638	-21	158.7	2003/08 - current	MPBO, St. Vincent's school
OHLN	BK	38.00742	-122.27371	-0	196.7	2001/07 - current	MPBO, Ohlone Park
MHDL	BK	37.84227	-122.49374	94	160.6	2006/05 - current	MPBO, Marin Headlands
SBRN	BK	37.68562	-122.41127	4	157.5	2001/08 - current	MPBO, San Bruno Mtn.
OXMT	BK	37.4994	-122.4243	209	194.2	2003/12 - current	MPBO, Ox Mtn.
BBEB	BK	37.82167	-122.32867	-31	150.0	2002/05 - current	BB, Pier E23
E17B	BK	37.82086	-122.33534		160.0	1995/08 - current *	BB, Pier E17
E07B	BK	37.81847	-122.34688	tbd	134.0	1996/02 - current *	BB, Pier E7
YBIB	BK	37.81420	-122.35923	-27.0	61.0	1997/12 - current *	BB, Pier E2
YBAB	BK	37.80940	-122.36450		3.0	1998/06 - current *	BB, YB Anchorage
W05B	BK	37.80100	-122.37370	tbd	36.3	1997/10 - current *	BB, Pier W5
W02B	BK	37.79120	-122.38525	-45	57.6	2003/06 - current	BB, Pier W2
SFAB	BK	37.78610	-122.3893		0.0	1998/06 - current *	BB, SF Anchorage
RSRB	BK	37.93575	-122.44648	-48.0	109.0	1997/06 - current *	RSRB, Pier 34
RB2B	BK	37.93	-122.41	tbd	133.8	2003/07 - current *	RSRB, Pier 58
SM1B	BK	37.59403	-122.23242		298.0	not recorded	SMB, Pier 343
DB3B	BK	37.51295	-122.10857		1.5	1994/09 - 1994/11	DB, Pier 44
					62.5	1994/09 - 1994/09	
					157.9	1994/07 - current *	
DB2B	BK	37.50687	-122.11566			1994/07 - current *	DB, Pier 27
					189.2	1992/07 - 1992/11	
DB1B	BK	37.49947	-122.12755		0.0	1994/07 - 1994/09	DB, Pier 1
					1.5	1994/09 - 1994/09	
					71.6	1994/09 - 1994/09	
					228.0	1993/08 - current *	
CCH1	NC	37.7432	-122.0967	226		1995/05 - current	Chabot
CGP1	NC	37.6454	-122.0114	340		1995/03 - current	Garin Park
CSU1	NC	37.6430	-121.9402	499		1995/10 - current	Sunol
CYD1	NC	37.5629	-122.0967	-23		2002/09 - current	Coyote
CMW1	NC	37.5403	-121.8876	343		1995/06 - current	Mill Creek

Table 6.1: Stations of the Hayward Fault Network. Each HFN station is listed with its station code, network id, location, operational dates, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame. The elevation of the well head (in meters) is relative to the WGS84 reference ellipsoid. The overburden is given in meters. The start dates indicate either the upgrade or installation time. The abbreviations are: BB - Bay Bridge; BR - Briones Reserve; CMS - Cal Memorial Stadium; CB - Carquinez Bridge; DB - Dumbarton Bridge; MPBO - mini-Plate Boundary Observatory; RFS - Richmond Field Station; RSRB - Richmond-San Rafael Bridge; SF - San Francisco; SMB - San Mateo Bridge; SMC - St. Mary's College; and, YB - Yerba Buena. The * for station PINB indicates that this station name has been requested but has not yet been approved and may change. The * in the Date column indicates that the stations have recorded data from an earlier period of manually retrieved tapes, but that are currently off-line.

large part to the greater depth of the MPBO sensors, the locations of MPBO stations in regions of generally less industrial and other cultural noise sources, and possibly to the absence of powered sensors (i.e. accelerometers)

Site	Geophone	Accelerometer	Z	H1	h2	datalogger	Notes	Telem.
VALB	Oyo HS-1	Wilcoxon 731A	TBD	TBD	TBD	Q330		FR
PETB	Oyo HS-1	Wilcoxon 731A	TBD	TBD	TBD	TBD		TBD
CRQB	Oyo HS-1	Wilcoxon 731A	-90	251	341	Q4120		FR
HERB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Q4120		FR
PINB	Oyo HS-1	Wilcoxon 731A	TBD	TBD	TBD	TBD		TBD
BRIB	Oyo HS-1	Wilcoxon 731A	-90	79	349	Q4120	Acc. failed, Dilat.	FR
RFSB	Oyo HS-1	Wilcoxon 731A	-90	256	346	Q4120		FR
CMSB	Oyo HS-1	Wilcoxon 731A	-90	19	109	Q4120		FR
SMCB	Oyo HS-1	Wilcoxon 731A	-90	76	166	Q4120	Initially Posthole	FR
SVIN	Mark L-22		-90	298	28	Q4120	Tensor.	FR/Rad.
OHLN	Mark L-22		-90	313	43	Q4120	Tensor.	FR
MHDL	Mark L-22		-90	TBD	TBD	Q4120	Tensor.	FR
SBRN	Mark L-22		-90	347	77	Q4120	Tensor.	FR
OXMT	Mark L-22		-90	163	253	Q4120	Tensor.	FR
BBEB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Q4120	Acc. failed	Radio
E17B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
E07B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
YBIB	Oyo HS-1	Wilcoxon 731A	-90	257	347	None at present	Z geop. failed	FR/Rad.
YBAB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
W05B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
W02B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Q4120		Radio
SFAB	None	LLNL S-6000	TBD	TBD	TBD	None at present	Posthole	
RSRB	Oyo HS-1	Wilcoxon 731A	-90	50	140	None at present	2 acc. failed	FR
RB2B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present	1 acc. failed	
SM1B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
DB3B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present	Acc. failed	
DB2B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
DB1B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present	Acc. failed	
CCH1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio
CGP1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio
CSU1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio
CYD1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio
CMW1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio

Table 6.2: Instrumentation of the HFN as of 06/30/2006. Every HFN downhole package consists of co-located 3-component geophones and accelerometers, with the exception of MPBO sites which have only 3-component geophones and are also collecting tensor strainmeter data. Six HFN sites (5 of the SHFN and 1 of the NHFN) also have dilatometers (Dilat.). Currently, 14 NHFN sites have Quanterra dataloggers with continuous telemetry to the BSL. The remaining sites are either still being developed with support from Caltrans or are being upgraded to Quanterra dataloggers. The 5 SHFN sites have Nanometrics dataloggers with radio telemetry to the USGS. The orientation of the sensors (vertical - Z, horizontals - H1 and H2) are indicated where known or identified as "to be determined" (TBD).

in their borehole sensor packages.

One of the most pervasive problems at NHFN stations equipped with the Q4120 dataloggers is power line noise (60 Hz and its harmonics at 120, 180, and 240 Hz). This noise reduces the sensitivity of the MHH detectors. Whenever a NHFN station is visited, the engineer at the site and a seismologist at the BSL work together to expedite the testing process, especially when attempting to identify and correct ground-loop faults which generally induce significant 60, 120, 180, and 240 Hz seismic signal contamination due to stray power line signal pickup, generally inductively coupled and aggravated by the presence of ground loops.

Geophone Calibration Test Equipment

Comparisons of the inferred ground accelerations generated by local earthquakes from co-sited NHFN geophone and accelerometer pairs show that the waveforms

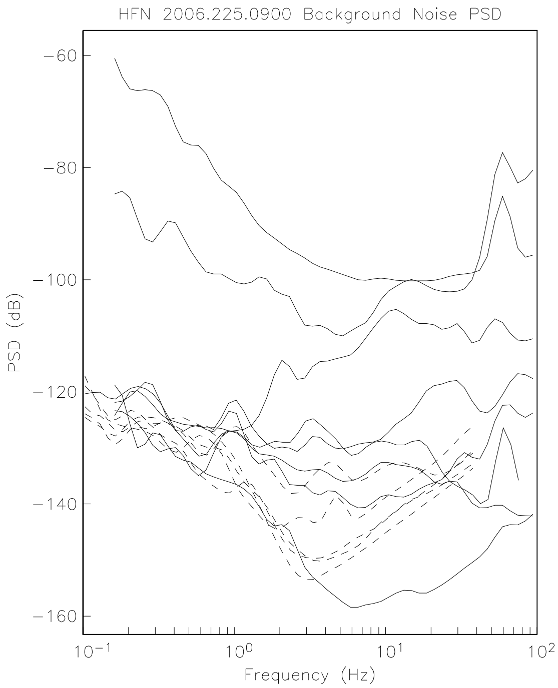

Figure 6.2: Plot showing typically observed background noise PSD for the NHFN borehole stations (including the MPBO in dashed lines) as a function of frequency. The data are from 2 am Local time on a Sunday morning. Note that there is considerable variation in the general level and structure of the individual station background noise PSD estimates. Of all the HFN stations, BRIB, the quietest borehole emplanted station, is also the farthest from local cultural noise sources. The signals from three of the stations (BBEB, SMCB and W02B) have 60 Hz noise, which is due to the presence of ground loops. The four noisiest stations (BBEB, CRQB, VALB and W02B) are near bridge anchorages. The PSD ranking of the stations of the stations at 4.6 Hz (near minimum PSD for most of the stations) is:
BRIB.BK.DP1 -156.46204
CMSB.BK.DP1 -151.96701
OXMT.BK.EP1 -151.28152
MHDL.BK.EP1 -149.33257
SVIN.BK.EP1 -148.51234
SBRN.BK.EP1 -138.45128
RFSB.BK.DP1 -137.71815
OHLN.BK.EP1 -132.80258
SMCB.BK.DP1 -131.35008
VALB.BK.EP1 -128.44617
CRQB.BK.DP1 -114.13147
BBEB.BK.DP1 -109.71306
W02B.BK.DP1 -98.61494

generally are quite coherent in frequency and phase response, but that their inferred ground accelerations differ significantly. At times, the amplitudes differ by up to a factor of 2 while the times of the peak amplitudes are identical. This implies that the free period and damping of the geophones are well characterized. However, it also indicates that the generator constant is not accurate (assuming that the corresponding ground accelerations inferred from the accelerometers are accurate).

Generally speaking, the accelerometers, being an active device, are more accurate and also more stable than the geophones, so it is reasonable to assume that the most likely reason for the difference is that the assumed generator constants for the geophones are inaccurate. *Rodgers et al.* (1995) describe a way to absolutely calibrate the geophones in situ and to determine their generator constant, free period and fraction of critical damping. The only external parameter that is required is the value of the geophones inertial mass.

We have built a calibration test box which allows us to routinely perform the testing described by *Rodgers et al.* whenever site visits are made. The box drives the signal coil with a known current step and rapidly switches the signal coil between the current source and the datalogger input. From this information, expected and actual sensor response characteristics can be compared and corrections applied. Also, changes in the sensor response over time can be evaluated so that adjustments can be made, and pathologies arising in the sensors due to age can be identified. Once a geophone is absolutely calibrated, we can also check the response of the corresponding accelerometer.

We are still performing the initial calibration tests and response adjustments for all NHFN stations as sites are visited for routine maintenance. We also plan to schedule routine re-tests of all sites to monitor for sensor responses changes through time.

3. 2005-2006 Activities

In addition to routine maintenance, operations and data collection, activities of the NHFN project over the past year have also included numerous efforts at network expansion, quality control and data analysis.

3.1 New Installations

As originally conceived, the Hayward Fault Network was to consist of 24 to 30 stations, 12-15 each north and south of San Leandro, managed respectively by UCB and USGS. Due to funding limitations, however, progress has been slow and the original plan has been significantly modified. Fortunately and with additional Caltrans support continued development of the NHFN component of the project has been possible and is ongoing. This important contribution to the Hayward Fault Network has

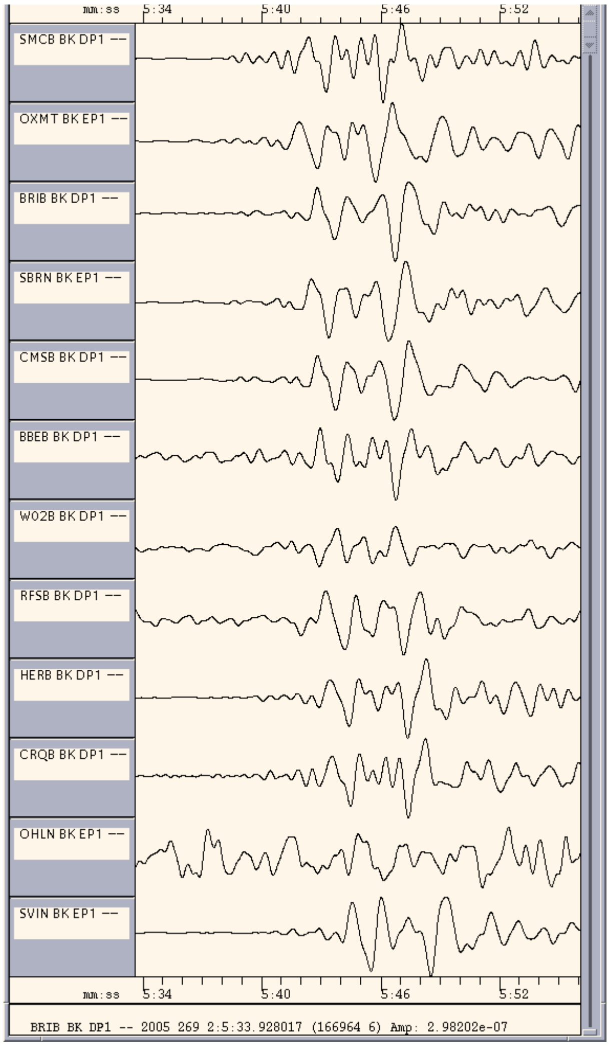

Figure 6.3: Plot of P-wave seismograms, recorded by 12 NHFN/MPBO borehole stations operating at the time of a major intermediate focus earthquake occurring this past year (2005/09/26; 01:55:38 UT; 115 km deep; M_w 7.5; 60.8 deg. S55E of Berkeley, CA). Here vertical component geophone data have been deconvolved to ground acceleration, 0.3-2 Hz 6-pole, BP filtered and ordered by increasing distance (top to bottom). Of the 12 HFN, BB and MPBO vertical geophones that recorded the event, all the P waveforms are highly similar except for OHLN, which is noisy and not responding nominally to ground motion, and W02B, which has a low amplitude and distorted signal.

more than doubled the number of sites with instrumentation that would otherwise not have existed. Caltrans continues to provide holes of opportunity (e.g., recently SMCB, PETB, VALB), so we have plans for additional stations that will bring the network geometry to a more effective state for imaging and real-time monitoring of the

Sensor	Channel	Rate (sps)	Mode	FIR
Accelerometer	CL?	500.0	T	Ca
Accelerometer	BL?	20.0	C	Ac
Accelerometer	LL?	1.0	C	Ac
Geophone	DP?	500.0	T,C	Ca
Geophone	EP?	200.0	C	Ca
Geophone	BP?	20.0	C	Ac
Geophone	LP?	1.0	C	Ac

Table 6.3: Typical data streams acquired at each NHFN site, with channel name, sampling rate, sampling mode and FIR filter type. C indicates continuous, T triggered, Ca causal, and Ac acausal. Typically the DP1 continuous channel is archived and the remaining high sample rate data (i.e., CL and DP channels) are archived as triggered snippets. Prior to Sept. 2004, however, only triggered data was archived for all high sample rate channels.

Hayward fault. Below are short summaries of activities over the past year related to the preparation, installation and activation of new NHFN stations.

San Francisco Bay and Richmond-San Rafael Bridges

Current support is allowing 4 Bay-Bridge stations to be included in the compliment of NHFN stations and two of these stations are already on-line (i.e., BBEB and W02B). Telemetry issues dictate that these two site also serve as rely sites for data coming from the remaining two sites (i.e., W05B and E07B). Because of their critical roles as data relay sites, robust telemetry from these sites is needed. This year various adjustments have been made to optimize telemetry performance of these two stations including their upgrade to Wilan radio telemetry. The infrastructure of the W05B and E07B sites has been upgraded with the installation of weatherproof boxes, power, and telemetry in anticipation of installing Q4120 dataloggers and telemetering their data back to Berkeley.

These and continuing efforts to bring W05B and E07B on-line have been significantly hampered by ongoing Bay-Bridge retrofit work. As a particularly poignant example of this occurred in the Spring of 2006 when retrofit work crews severed the sensor cable to the mid-western span station W05B, losing the cabling into deep bay waters. Fortunately, with Caltrans assistance, a deep diving crew was dispatched and the sensor cable was recovered in good condition.

On the Richmond-San Rafael Bridge, similar problems associated with Bridge retrofit work have been encountered. In addition to the complete loss of mid-span station RSRB a few years ago, our toll plaza site RB2B has had to be relocated. Drilling and installation of the sensors down hole for the site was finished last year and this year installation of the new site infrastructure and electronics has been largely completed. Coordination with Caltrans for power and telephone hook-ups are currently underway.

Land Sites

Agreements with Caltrans and St. Mary's College have been made to replace the post hole installation at St. Mary's College (SMCB) with a deep borehole installation. This year the hole was drilled by Caltrans as a hole of opportunity (i.e., when the schedule of a Caltrans drilling crew had an opening). The site has been reviewed by UCB, Caltrans and St. Mary's College personnel, and with assistance from Caltrans and St. Mary's College grounds crew personnel, the site infrastructure is nearly complete, and data acquisition and telemetry to UCB is expected to begin shortly.

Caltrans has also provided funding and support for drilling and sensor installation at 2 other land sites (VALB and PETB). The Napa River Bridge site in Vallejo, CA (VALB) is now operating and has been online since November of 2005. The PETB (Petaluma River Bridge) site has been drilled and instrumented. Infrastructure construction on the site continues and should be completed within weeks. Routine data flow and archival at the NCEDC is expected after telemetry and power hook-ups are completed.

Currently we are also considering three other sites (in Pt. Pinole regional Park, Mt. Diablo Regional Park and at Wildcat Mtn.) as candidates for two additional holes-of-opportunity in the North//East Bay. We are in the process of obtaining permission from the East Bay Regional Park District (EBRPD) to site the Pt. Pinole station at the Point Isabel Regional Shoreline and have completed field inspection of the two other sites which appear to be suitable.

Mini-PBO

The stations of the Mini-PBO project are equipped with 3-component borehole seismometers and tensor strainmeters. As these stations have become operational, they augment well the HFN's coverage of the Bay Area (Figure 6.1). In the last year, MHDL (Marine Headlands) has come on-line and is now adding much needed coverage on the west side of the Bay.

3.2 Quality control and Data Analysis

In order to monitor and capture the source spectrum of moderate down to micro-scale earthquakes, it is essential that the NHFN instruments operate at high precision and in an extremely low noise environment. Therefore, the stations record at high sample rate and their sensors are emplaced in deep boreholes to reduce noise contamination originating in the near surface weathered zone and from cultural noise sources. In addition, the reduction of noise at these stations through vigilant monitoring of actual seismic events plays a central part of our quality control effort.

The Aug. 3, 2006 Glen Ellen Earthquake

In Figure 6.4, we show a profile of the NHFN stations for the recent (August 3, 2006) M_L 4.6 earthquake located at Glen Ellen, California, about 60 km NW of Berkeley. Figures such as this are helpful for evaluating network health, and analysis of the waveforms and spectra assist in troubleshooting problems. As Figure 6.4 shows the network is performing very well, but there are some stations exhibiting problems. For example, the Bay Bridge site W02B shows high frequency noise, and OLNH and OXMT show sensitivity and dropout problems.

Microseismicity

As mentioned, a key aspect of quality control of the NHFN data is the analysis of actual seismic events. Seismic events of larger magnitude are relatively rare and generally provide more energy at lower frequencies. Hence in order to provide more frequent real events and quality control in the higher frequency band of the NHFN stations, analysis of recordings from the much more frequent microearthquakes are needed. Because real event analyses are relatively labor intensive and because of inadequate insufficient funding, traditional methods of event analysis have proven financially infeasible. To help circumvent these problems, efforts to develop new and improved analysis techniques are ongoing. We have developed and are currently testing some promising techniques that are particularly well suited to the analysis of similar and repeating microearthquakes. The advantages of similar and repeating event analyses for both quality control and scientific purposes are numerous, and the nature of the seismograms from these types of events make automated, rapid and robust analysis possible.

Towards this end, we are currently testing three new algorithms which we have developed: 1) a phase onset time detector with sub-sample timing resolution for improved absolute pick time accuracy, 2) a pattern scanning recognition scheme to detect, pick, locate and determine magnitudes for small and very small similar events recorded either continuously or from among large volumes of noisy triggered data snippets, and 3) a phase coherency method for identification of characteristically repeating events sequences from among groups of similar event multiplets.

Phase Onset Time Detection: The phase onset time detector makes use of the concept that the complex spectral phase data over the bandwidth of interest (i.e., where the SNR is sufficiently high) will sum to a minimum at the onset of an impulsive P-wave. The algorithm searches for the minimum phase time via phase shifting in the complex frequency domain over the bandwidth where the SNR is above 30 dB to identify the onset time of the seismic phase. The algorithm requires that the recorded waveforms be deconvolved to absolute ground displacement. This implicitly requires that any acausality in the anti-aliasing filtration chain, such as the FIR filters used in the BDSN Quanterra dataloggers, be removed. The algorithm typically resolves P-wave onset times to one-fiftieth of the sample interval or better.

Pattern Scanning Recognition: The Murdock-Hutt detection algorithms used by MultiSHEAR, which basically flags an event whenever the short-term average exceeds a longer-term average by some threshold ratio, is neither appropriate for nor capable of detecting the smallest seismic events where signal to noise levels approach those of spurious cultural and earth noise signals. This is because the increased sensitivity parameters needed for small event detection also result in a large fraction of false event triggers. The use of multiple station association filters to reduce the false trigger rates are also of limited value since many of the smaller events are only recorded with enough signal to noise to trigger at a few stations and noise triggers at high sensitivity also often appear to associate temporally at several stations. Added to this is this the exponential increase in the frequency of events with decreasing magnitude, which quickly makes analyst time requirements for comprehensive review and processing of the smallest events financially infeasible.

The approach we have been working on this year to help overcome these problems has been to enhance the effective signal to noise and to focus on identification and processing of some of the more scientifically significant events through the use of a cross-correlation based scanning approach, which scans known waveform patterns through either continuous or collections triggered event snippets (regardless of the triggered event noise levels). With this approach continuous or triggered waveform data that does not match selected patterns are ignored while waveforms that approximately match selected reference event patterns are flagged as newly identified earthquakes.

This approach is less comprehensive in that it only detects events that are somewhat similar in waveform character to the reference patterns. However, it can be generalized significantly by increasing the number of event patterns scanned or by using fairly low maximum cross-correlation thresholds for event flagging. Preliminary tests of our scanning code show that scans of 100 distinct event patterns can be scanned through a days worth of waveform data in 75 minutes on one 900Mhz SPARC cpu when continuous seismic data is used. Scanning through collections of all triggered snippets is substantially faster, in proportion to the inverse fraction of total time spanned by the snippet data.

The approach also provides automated cross-correlation pick alignments that can be used for high precision relative locations and for automated low-frequency spectral ratio determinations for magnitude estimates. Clearly the method has potential for automatically cataloging a large fraction of the more numerous microearthquakes, and in conjunction with the special attributes of similar event groups, updates of the catalogs in an automated monitoring mode can provide near-real-time microearthquake information that can be a powerful tool for monitoring network performance of real event data. Future plans include development and implementation of an automated similar event scanning and cataloging scheme that will provide real-event data from similar small magnitude events for assessment of network health on a much more frequent basis (every few days).

Perhaps more significantly, the approach can also capture and rapidly catalog some of the most scientifically relevant events (e.g. repeats of characteristically repeating microearthquakes used for deep slip rate monitoring and swarms of similar events typically associated with foreshocks and aftershocks). The approach is also surprisingly good at detecting events over a wide magnitude range. Hence there is clear potential for using patterns from larger aftershocks (e.g. flagged by REDI) to rapidly and automatically develop a high-resolution picture of foreshock and aftershock activity associated with large mainshocks. Tests so far using waveform patterns from an aftershock from the Parkfield magnitude 6 event (2.2Ml) have been able to detected and fully process similar events as low as Ml - 1.2 (a range of 3.4 magnitude units). Testing in this regard is continuing, but clearly the 3.4 magnitude range is a lower bound on the potential magnitude range attainable.

Phase Coherency: A spectral phase coherency algorithm was developed to facilitate high resolution quantification of the similarities and differences between highly similar Hayward fault events that occur months to years apart. The resolution of the complex spectral phase coherency methodology is an order of magnitude better than the cross correlation method, which is commonly used to identify highly similar events with resolution of order of a few 10's of meters. This method, originally developed using NHFN borehole data, is now also being tested and refined using data from another borehole network (the HRSN). The goal of the testing and refinement is ultimately to develop a scheme for rapid and objective discrimination and identification of characteristically repeating microearthquakes sequences down to the lowest magnitude possible (where recurrence times are short and hence temporal resolutions are higher) at both Parkfield,

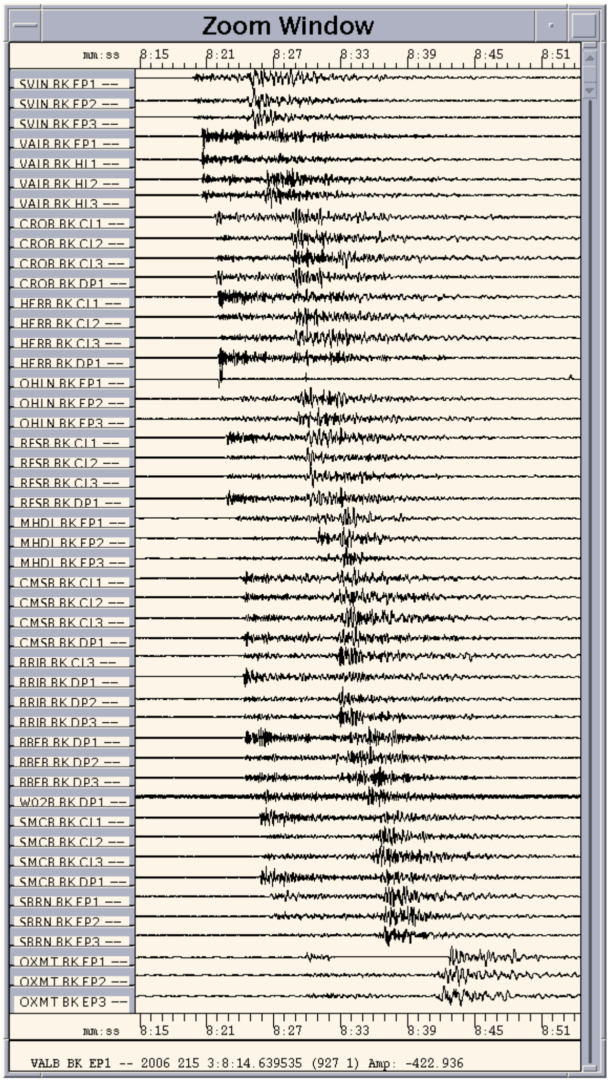

Figure 6.4: Record section of NHFN data for the 03 August 2006, Ml 4.6 Glen Ellen, California earthquake located about 60 km northwest of Berkeley. These raw waveform data are ordered by epicentral distance and are relatively scaled.

and in the Bay Area of California.

4. Acknowledgments

Thomas V. McEvilly, who passed away in February 2002, was instrumental in developing the Hayward Fault Network, and without his dedication and hard work the creation and continued operation of the NHFN would not have been possible.

Under Bob Nadeau's, Bob Uhrhammer's and Doug Dreger's general supervision, Rich Clymer, Doug Neuhauser, Bill Karavas, John Friday, and Rick Lellinger all contribute to the operation of the NHFN. Bob Nadeau and Bob Uhrhammer contributed to the preparation of this chapter.

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Chapter 7

Parkfield Borehole Network (HRSN)

1. Introduction

The operation of the High Resolution Seismic Network (HRSN) at Parkfield, California began in 1987, as part of the United States Geological Survey (USGS) initiative known as the Parkfield Prediction Experiment (PPE) (*Bakun and Lindh*, 1985).

Figure 7.1 shows the location of the network, its relationship to the San Andreas fault, sites of significance from previous and ongoing research using the HRSN, double-difference relocated earthquake locations from 1987-1998, routine locations of seismicity from August 2002 to July 2003, nonvolcanic tremor locations from January 2001 through April 2005, and the epicenter of the 1966 and 2004 M6 earthquakes that motivated much of the research. The HRSN records exceptionally high-quality data, owing to its 13 closely spaced three-component borehole sensors (generally emplaced in the extremely low attenuation and background noise environment at 200 to 300 m depth (Table 7.1), its high-frequency wide bandwidth recordings (0-100 Hz; 250 sps), and its low magnitude detection threshold (below magnitude 0.0 Ml).

Several aspects of the Parkfield region make it ideal for the study of small earthquakes and nonvolcanic tremors and their relationship to tectonic processes and large earthquakes. These include the fact that the network spans the SAFOD (San Andreas Fault Observatory at Depth) experimental zone, the nucleation region of earlier repeating magnitude 6 events and a significant portion of the transition from locked to creeping behavior on the San Andreas fault, the availability of three-dimensional P and S velocity models (*Michelini and McEvilly*, 1991), the existing long-term HRSN seismicity catalogue that is complete to very low magnitudes and that includes at least half of the M6 seismic cycle, a well-defined and simple fault segment, the existence of deep nonvolcanic tremor (NVT) activity, and a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip).

In a series of journal articles and Ph.D. theses, we have presented the cumulative, often unexpected, results of UC Berkeley's HRSN research efforts (see: `http://www.seismo.berkeley.edu/seismo/faq/parkfield_bib.html`). They trace the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate-boundary loading, and they are forcing new thinking on the dynamic processes and conditions within the fault zone at the sites of recurring small earthquakes and deep nonvolcanic tremors (*Nadeau and Dolenc, 2005*).

The Parkfield area has also become an area of focus of the EarthScope Project (`http://www.earthscope.org`) through the SAFOD experiment (`http://www.icdp-online.de/sites/sanandreas/news/news1.html`), and the HRSN is playing a vital role in this endeavor. SAFOD is a comprehensive project to drill into the hypocentral zone of repeating M $\sim$ 2 earthquakes on the San Andreas Fault at a depth of about 3 km. The goals of SAFOD are to establish a multi-stage geophysical observatory in close proximity to these repeating earthquakes, to carry out a comprehensive suite of down-hole measurements in order to study the physical and chemical conditions under which earthquakes occur, and to monitor and exhume rock, fluid, and gas samples for extensive laboratory studies (*Hickman et al.*, 2004).

2. HRSN Overview

2.1 1986 - 1998

Installation of the HRSN deep (200-300m) borehole sensors initiated in 1986, and recording of triggered 500 sps earthquake data began in 1987. The HRSN sensors are 3-component geophones in a mutually orthogonal gimbaled package. This ensures that the sensor corresponding to channel DP1 is aligned vertically and that the others are aligned horizontally. In November 1987, the Varian well vertical array was installed and the first VSP survey was conducted, revealing clear S-wave anisotropy in the fault zone (*Daley and McEvilly*, 1990). During 1988, the original 10 station network was completed, which included a deep (572 m) sensor from the Varian well string. Data from network stations was

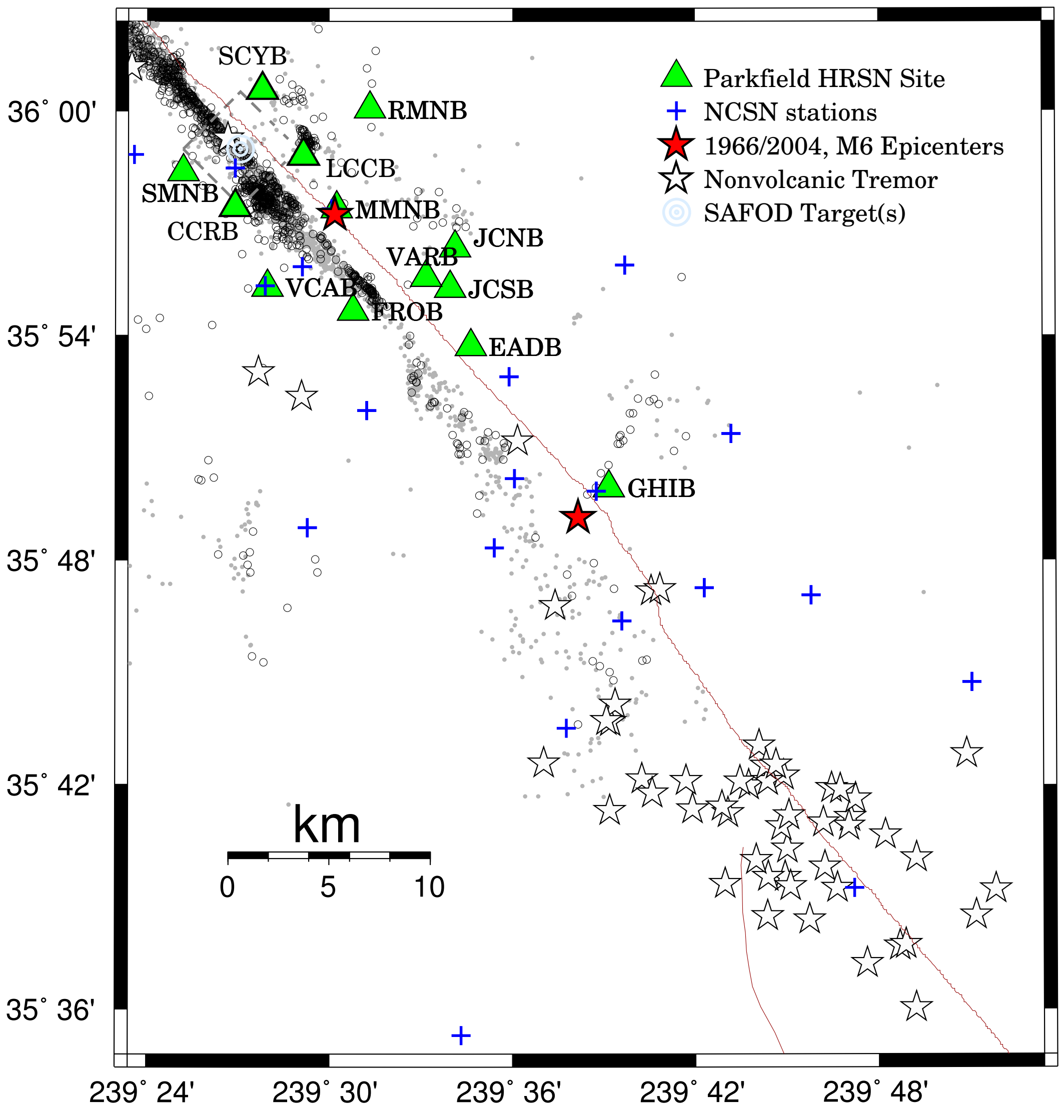


Figure 7.1: Map showing the San Andreas Fault trace and locations of the 13 Parkfield HRSN stations, the repeating M2 SAFOD targets (a 4 km by 4 km dashed box surrounds the SAFOD zone), and the epicenters of the 1966 and 2004 M6 Parkfield main shocks. Also shown are locations of the recently discovered nonvolcanic tremors, routine locations of earthquakes recorded by the expanded and upgraded 13 station HRSN (small open circles) and locations of events recorded by the earlier vintage 10 station HRSN relocated using an advanced 3-D double-differencing algorithm (gray points) applied to a cubic splines interpolated 3-D velocity model (*Michelini and McEvilly*, 1991).

telemetered into a central detection/recording system operating in triggered mode. Also in 1988, the Varian string system was slaved for about two years to the Vibroseis control signals, allowing simultaneous recording of vibrator signals on both systems. For several years beginning in 1991, low-gain event recorders (from PASSCAL) were installed at several of the sites to extend the dynamic range upward from about M_L 1.5 to about M_L 4.5.

The data acquisition system operated quite reliably until late 1996, when periods of unacceptably high down time developed. During this period, as many as 7 of the remote, solar-powered telemetered stations were occasionally down simultaneously due to marginal solar generation capacity and old batteries, and recording system outages of a week or more were not uncommon. In July 1998, the original data acquisition system failed permanently. This system was a modified VSP recorder acquired from LBNL, based on 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 data (Vibroseis discontinued in 1994, *Karageorgi et al.*, 1997). The system was remote and completely autonomous, and data tapes were mailed about once a month to Berkeley for processing and analysis. The old system also had a one-sample timing uncertainty and a record length limitation because the tape write system recovery after event detection was longer than the length of the record, leaving the system off-line after record termination and until write recovery was completed.

2.2 1998 - 1999

In December 1998, the original HRSN acquisition system was replaced by 10 stand-alone PASSCAL RefTek systems with continuous recording. To process these data, development of a major data handling procedure will be required in order to identify the microearthquakes below Ml = 0.0, since continuous telemetry to the Berkeley Seismological Laboratory (BSL) and application of a central site detection scheme was not an option at that time.

In July 1999, the network was reduced, due to limited instrument availability, to four RefTeks at critical sites that would ensure continuity in monitoring at low magnitudes and the archive of characteristic events for studying the evolution of their recurrence intervals. Properties of the 10 original sites are summarized in Table 7.2.

2.3 2001 Upgrade and SAFOD Expansion

Thanks to emergency funding from the USGS NEHRP, we replaced the original 10-station system with a modern 24-bit acquisition system (Quanterra 730 4-channel digitizers, advanced software using flash disk technology, spread-spectrum telemetry, Sun Ultra 10/440 central processor at the in-field collection point, with 56K frame-relay connectivity to Berkeley) in 2001. The new system is now online and recording data continuously at a central site located on California Department of Forestry (CDF) fire station property in Parkfield.

Sensor	Channel	Rate (sps)	Mode	FIR
Geophone	DP?	250.0	T and C	Ca
Geophone	BP?	20.0	C	Ac

Table 7.3: Data streams currently being acquired at each HRSN site. Sensor type, channel name, sampling rate, sampling mode, and type of FIR filter are given. C indicates continuous; T triggered; Ac acausal; Ca causal. "?" indicates orthogonal vertical and 2 horizontal components.

We have also added three new borehole stations, with NSF support, at the NW end of the network as part of the SAFOD project to improve resolution of the structure, kinematics and monitoring capabilities in the SAFOD drill-path and target zones. Figure 7.1 illustrates the location of the drill site, the new borehole sites, and locations of earthquakes recorded by the initial and upgraded/expanded HRSN.

The three new SAFOD stations have a similar configuration as the original upgraded 10 station network and include an additional channel for electrical signals. Station descriptions and instrument properties are summarized in Tables 7.1 and 7.2. All HRSN Q730 dataloggers employ FIR filters to extract data at 250 and 20 Hz (Table 7.3).

The remoteness of the drill site and new stations required an installation of an intermediate data collection point at Gastro Peak, with a microwave link to the CDF facility. The HRSN stations use SLIP to transmit TCP and UDP data packets over bidirectional spread-spectrum radio links between the on-site data acquisition systems and the central recording system at the CDF. Six of the sites transmit directly to a router at the central recording site. The other seven sites transmit to a router at Gastro Peak, where the data are aggregated and transmitted to the central site over a 4 MBit/second digital 5.4 GHz microwave link. All HRSN data are recorded to disk at the CDF site.

The upgraded and expanded system is compatible with the data flow and archiving common to all the elements of the BDSN/NHFN and the NCEDC (Northern California Earthquake Data Center), and is providing remote access and control of the system. It has also provided triggered data with better timing accuracy and longer records, which are to eventually flow seamlessly into NCEDC. The new system also helps minimize the problems of timing resolution, dynamic range, and missed detections, in ad-

Site	Net	Latitude	Longitude	Surf. (m)	Depth (m)	Date	Location
EADB	BP	35.89525	-120.42286	466	245	01/1988 -	Eade Ranch
FROB	BP	35.91078	-120.48722	509	284	01/1988 -	Froelich Ranch
GHIB	BP	35.83236	-120.34774	400	63	01/1988 -	Gold Hill
JCNB	BP	35.93911	-120.43083	527	224	01/1988 -	Joaquin Canyon North
JCSB	BP	35.92120	-120.43408	455	155	01/1988 -	Joaquin Canyon South
MMNB	BP	35.95654	-120.49586	698	221	01/1988 -	Middle Mountain
RMNB	BP	36.00086	-120.47772	1165	73	01/1988 -	Gastro Peak
SMNB	BP	35.97292	-120.58009	699	282	01/1988 -	Stockdale Mountain
VARB	BP	35.92614	-120.44707	478	572	01/1988 - 08/19/2003	Varian Well
VARB	BP	35.92614	-120.44707	478	298	08/25/2003 -	Varian Well
VCAB	BP	35.92177	-120.53424	758	200	01/1988 -	Vineyard Canyon
CCRB	BP	35.95718	-120.55158	595	251	05/2001 -	Cholame Creek
LCCB	BP	35.98005	-120.51424	640	252	08/2001 -	Little Cholame Creek
SCYB	BP	36.00938	-120.53660	945	252	08/2001 -	Stone Canyon

Table 7.1: Stations of the Parkfield HRSN. Each HRSN station is listed with its station code, network id, location, date of initial operation, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame, the surface elevation (in meters) is relative to mean sea level, and the depth to the sensor (in meters) below the surface. Coordinates and station names for the 3 new SAFOD sites are given at the bottom.

Site	Sensor	Z	H1	H2	RefTek 24	RefTek 72-06	Quanterra 730
EADB	Mark Products L22	-90	170	260	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
FROB	Mark Products L22	-90	338	248	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
GHIB	Mark Products L22	90	failed	unk	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
JCNB	Mark Products L22	-90	0	270	01/1988 - 12/1998	12/1998 - 06/2001	03/2001 -
JCSB	Geospace HS1	90	300	210	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
MMNB	Mark Products L22	-90	175	265	01/1988 - 12/1998	12/1998 - 06/2001	03/2001 -
RMNB	Mark Products L22	-90	310	40	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
SMNB	Mark Products L22	-90	120	210	01/1988 - 12/1998	12/1998 - 06/2001	03/2001 -
VARB	Litton 1023	90	15	285	01/1988 - 12/1998	12/1998 - 07/1999	03/2001 -
VCAB	Mark Products L22	-90	200	290	01/1988 - 12/1998	12/1998 - 06/2001	03/2001 -
CCRB	Mark Products L22	-90	N45W	N45E	-	-	05/2001 -
LCCB	Mark Products L22	-90	N45W	N45E	-	-	08/2001 -
SCYB	Mark Products L22	-90	N45W	N45E	-	-	08/2001 -

Table 7.2: Instrumentation of the Parkfield HRSN. Most HRSN sites have L22 sensors and were originally digitized with a RefTek 24 system. After the failure of the WESCOMP recording system, PASSCAL RefTek recorders were installed. In July of 1999, 6 of the PASSCAL systems were returned to IRIS and 4 were left at critical sites. The upgraded network uses a Quanterra 730 4-channel system. For the three new stations (bottom) horizontal orientations are approximate (N45W and N45E) and will be determined more accurately as available field time permits.

dition to providing the added advantage of conventional data flow (the old system recorded SEGY format).

2.4 Present Status

Because of limitations in telemetry bandwidth, however, not all continuous waveform data are currently transmitted to BSL. Instead, all continuous data are archived on DLT tapes which are brought to BSL every several weeks and uploaded to the NCEDC. A modified version of the REDI system (this report) was used to detect events in the HRSN data, extract waveform triggers, and transmit the waveform segments to the BSL in near-real-time. The December 22, 2003 San Simeon earthquake and its aftershocks, however, sent the HRSN into a nearly continuous triggering state. As a result, BSL staff had to disabled the transmission of triggered data.

At present, all 38 continuous 20 sps data streams are telemetered to the BSL. All continuous 250 sps data are migrated periodically from HRSN computer in Parkfield to DLT tape. These tapes are then mailed periodically to the BSL and are then processed and archived at the NCEDC. Seven vertical 250 sps channels are also telemetered to the NCEDC for purposes of quality control and SAFOD related activities. These data are archive temporarily (for 10 days) and then removed. Copies of the data are later restored for permanent archiving during uploading of the 38 250 sps continuous data streams from the DLT tapes.

A feature of the new system that has been particularly useful both for routine maintenance and for pathology identification has been the Internet connectivity of the central site processing computer and the station dataloggers with the computer network at BSL. Through this connection, select data channels and on-site warning messages from the central site processor are sent directly to BSL for evaluation by project personnel. If, upon these evaluations, more detailed information on the HRSN's performance is required, additional information can also be remotely accessed from the central site processing computer at Parkfield. Analysis of this remotely acquired information has been extremely useful for trouble shooting by allowing field personnel to schedule and plan the details of maintenance visits to Parkfield. The connectivity also allows certain data acquisition parameters to be modified remotely when needed, and commands can be sent to the central site computer and dataloggers to modify or restart processes when necessary.

The network connectivity also allows remote monitoring of the background noise levels being recorded by the HRSN stations. For example, shown in Figure 7.3 are power spectral density plots of background noise for vertical components of the 7 HRSN stations that are most critical for monitoring seismicity in the region containing SAFOD. The PSD analysis gives a rapid assessment of the HRSN seismometer responses across their wide bandwidth. By routinely generating these plots with data telemetered from Parkfield, changes in the seismometer responses, often indicating problems with the acquisition system, can be easily identified, and corrective measures can then be planned and executed on a relatively short time-frame.

2.5 Data Flow

Initial Processing Scheme. Continuous data streams on all 38 HRSN components are recorded at 20 and 250 sps on disk on the local HRSN computer at the CDF facility. The 20 sps data are transmitted continuously to the Berkeley Seismological Laboratory (BSL) over a frame-relay link and then archived at the NCEDC. In addition, the vertical component channels for the 7 stations critical to resolving seismicity in the SAFOD area are also being transmitted continuously at 250sps over a frame-relay circuit to the USGS and have been integrated into their NCSN (Norther California Seismic Network) trigger detection scheme to increase the sensitivity of the NCSN in the SAFOD area. The 7-channel 250 sps data is also being transmitted to the BSL for purposes of quality control and fine tuning the triggering algorithm for the detection of the smallest possible events around SAFOD. These telemetered 250 sps data are archived on disk for only about 1 week at the BSL and are then deleted. When the local HRSN computer disk space is full, the continuous 250 sps data on the HRSN local computer are migrated onto DLT tape, and the tapes sent to Berkeley for long-term storage and for upload to disc into the NCEDC archive. Efforts are currently underway to transmit all 38 HRSN channels to the USGS and BSL over a T1 line to enhance NCSN detection further and to make the data web-available in near-real-time.

Shortly after being recorded to disk on the central site HRSN computer, event triggers for the individual station data are determined, and a multi-station trigger association routine then processes the station triggers and identifies potential earthquakes. For each potential earthquake that is detected, a unique event identification number (compatible with the NCEDC classification scheme) is assigned. Prior to San Simeon earthquake of December 22, 2003, 30 second waveform segments were then collected for all stations and components and saved to local disk as an event gather, and event gathers were then periodically telemetered to BSL and included directly into the NCEDC earthquake database (dbms) for analysis and processing.

Because of its mandate to detect and record very low magnitude events in the Parkfield area, the HRSN is extremely sensitive to changes in very low amplitude seismic signals. As a consequence, in addition to detecting very small local earthquakes at Parkfield, the HRSN also detects numerous regional events. For example spot checks of aftershocks following the M6.5 San Simeon earthquake of December 22, 2003 using continuous data and HRSN event detection listings have revealed that the overwhelming majority of HRSN detections following San Simeon resulted from seismic signals generated by San Simeon's aftershocks despite the HRSN's ~ 50 km distance from the events. Data from the California Integrated Seismic Network (CISN) show that there were $\sim$ 1,150 San Simeon aftershocks with magnitudes > 1.8 in the week following San Simeon, and during this same period, the number of HRSN event detections was $\sim 10{,}500$ (compared to an average weekly rate before San Simeon of 115 detections) This suggests that despite the ~ 50 km distance the HRSN is detecting San Simeon aftershocks well below magnitude 1.

Since the beginning of the network's data collection in 1987 and up until recently, the local and regional events were discriminated based on analyst assessment of S-P times, and only local events with S-P times less than ~ 2.5 sec at the first arriving station were picked and located as part of the HRSN routine catalog. However, because of the large swarms of aftershocks from the San Simeon and M6 Parkfield earthquake of September 2004 and because of declining funding levels, this approach has had to be abandoned.

Current Processing. Subsequent to the M6.5 San Simeon earthquake on December 22, of 2003, our long-standing data handling procedure was no longer viable due to the enormous rate of San Simeon aftershock detections (Figures 7.2) In the first 5 months following the San Simeon mainshock, over 70,000 event detections were made by the HRSN system (compared to an average 5 month detection rate of 2500 prior to San Simeon). In the first month following the 28 September 2004 Parkfield M6 quake, over 40,000 detections were also made. Numerous additional (false) detections have also been occurring as a result of drilling activities associated with SAFOD drilling.

The dramatic increase in event detections vastly exceed the HRSN's capacity to process both the continuous and triggered event waveform data. To prevent the loss of seismic waveform coverage, processing of the triggered waveform data has been suspended to allow archiving of the 250 sps continuous data to tape to continue uninterrupted. Cataloging of the event detection times from the modified REDI real-time system algorithm is also continuing, and the continuous 250 sps waveform data is currently being periodically uploaded from the DLT tape archive onto the NCEDC for access to the research research community.

Funding to generate catalogs of local events from the 10's of thousands of aftershock detections has not been forthcoming, and as a consequence major changes in our approach to cataloging events have had to be implemented, which involves integration of HRSN data into

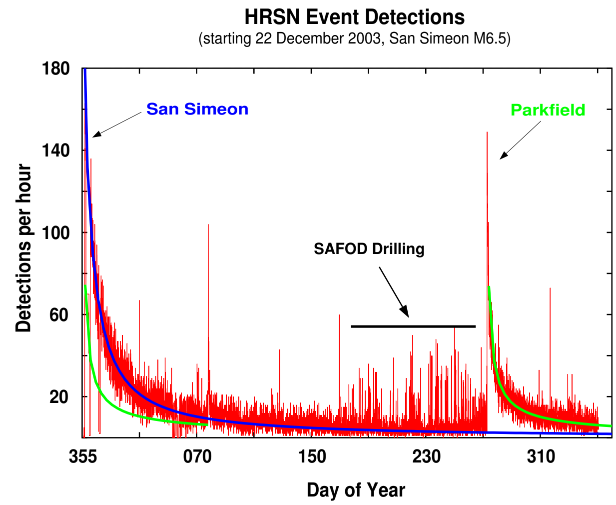


Figure 7.2: Shown are the number of HRSN triggers per hour for a period beginning with the San Simeon earthquake and continuing through several months after the Parkfield earthquake. For comparison, before these two large events, the average number of hourly HRSN triggers was less than 0.5 (i.e., about 10 per day). "Eyeball" fits of the decay curves for both events are also shown. The cumulative number of HRSN triggers in the first 5 months following San Simeon exceeded 70,000, and trigger levels continued to be over 150 triggers per day through the Parkfield quake. In the first month following the Parkfield quake nearly 20,000 triggers were recorded. Extrapolation of the decay curve indicates that daily trigger levels will not return to near pre-San Simeon levels until well into 2007. At the same time, funding to support analyst's time for routine processing and cataloging of the events has virtually dried-up, requiring the development and implementation of a new scheme for cataloging events.

NCSN automated event detection and cataloging (with no analyst review) combined with a high resolution procedure now being developed to automatically detect, pick, locate and determine magnitudes for similar and repeating events down to very low magnitudes (i.e., below magnitude -1.0Ml). These new schemes are discussed in more detail in the activities section below.

3. 2005-2006 Activities

In addition to the routine operations and maintenance of the HRSN (California's first and longest operating borehole seismic network), research into: 1) How to process the enormously increased rate of network detections 2) similar and repeating aftershocks from the 28 September 2004 Parkfield M6 earthquake, 3) ongoing non-volcanic tremors in the Parkfield-Cholame area and 4) SAFOD related activities have been the primary driving forces behind most of the HRSN project's activities this year.

3.1 Operations and Maintenance

Routine maintenance tasks required this year to keep the HRSN in operation, include cleaning and replacement of corroded electrical connections, grounding adjustments, cleaning of solar panels, re-seating, resodering and replacement of faulty pre-amp circuit cards, the testing and replacement of failing batteries, and insulation and painting of battery and datalogger housings to address problems with low power during cold weather.

Remote monitoring of the networks health using the Berkeley Seismological Laboratory's SeisNetWatch software are also performed to identify both problems that can be resolved over the Internet (e.g. rebooting of data acquisition systems due to clock lockups) and more serious problems requiring field visits.

Over the years, such efforts have paid off handsomely by providing exceptionally low noise recordings (Figure 7.3) of very low amplitude seismic signals produced by microearthquakes (below magnitude 0.0Ml) and nonvolcanic tremors (*Nadeau and Dolenc, 2005*).

3.2 Enhancing HRSN Performance

Detection, monitoring, and high-resolution recording of low-amplitude seismic signals (e.g., nonvolcanic tremors and earthquakes down to the smallest possible magnitude) with the highest possible signal-to-noise (especially in the region of SAFOD drilling) are major objectives of the HRSN data collection effort. The minimization of data loss due to station outages and data-dropouts is also critical to these objectives.

Over the previous several years, we have had a serious decline in the robustness of the power system components (primarily the aging solar panels and batteries that have

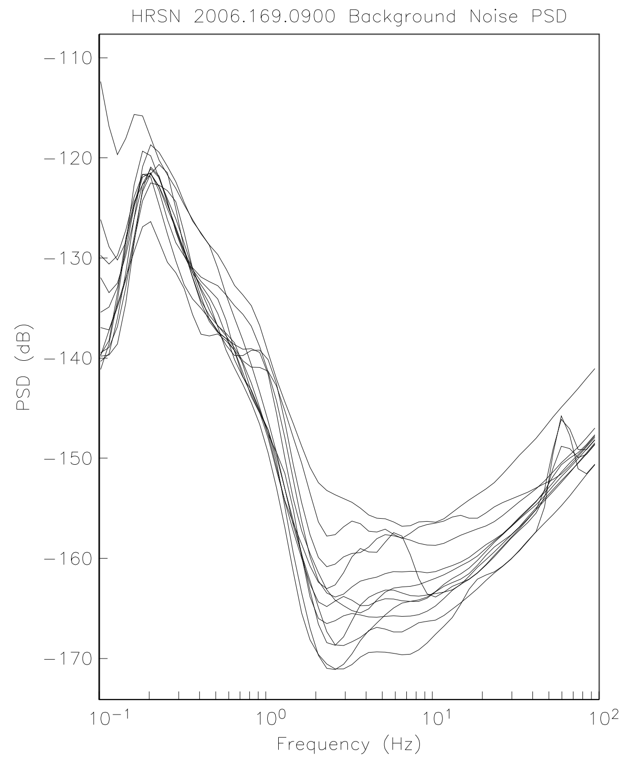


Figure 7.3: Typical background noise PSD for the 250 sps vertical component channels of the HRSN borehole stations as a function of frequency. The data are from 2 AM Local time on 6/18/2006 (Sunday morning). Note the relatively low PSD levels and the overall consistency for all the HRSN stations. The 2 Hz minimum for the sensors occurs because of the 2 Hz sensors used at these sites. Below 2 Hz, noise levels rise rapidly and the peak at 3 sec (.3 Hz) is characteristic of teleseismic noise observed throughout California. EADB, GHIB and SCYB have a 60 Hz noise peak in the PSD, which is indicative of a ground loop problem. The PSD (dB) ranking of the stations of the stations at 2.9 Hz (near minimum PSD for most of the stations) is:
SCYB.BP.DP1 -171.05231
LCCB.BP.DP1 -170.58481
MMNB.BP.DP1 -168.70798
JCNB.BP.DP1 -167.85416
EADB.BP.DP1 -165.73283
SMNB.BP.DP1 -164.71182
FROB.BP.DP1 -163.79599
CCRB.BP.DP1 -163.56433
GHIB.BP.DP1 -161.44427
VCAB.BP.DP1 -159.84996
RMNB.BP.DP1 -156.86127
VARB.BP.DP1 -154.02579

been in use since initiation of the network in 1987) of the network. Simultaneous outages at multiple stations are now becoming an all too frequent occurrence and are seriously affecting efforts to monitor tremor and micro- and repeating earthquake activity in the Parkfield area.

For example, during the winter of late 2004/early 2005, monitoring for nonvolcanic tremor activity using a standard detection set of 8 HRSN channels revealed significant (and sometimes catastrophic) gaps in the data. Figure 7.4 illustrates the seriousness of the problem with an example from tremor monitoring during periods of overcast weather. During the 7 day period shown, all 8 stations used for monitoring tremor activity were out simultaneously for over 50% of the time. The remaining 50% of the time, outages occurred for at least some of these 8 stations, resulting in significantly degraded capability for unambiguous detection of the low-amplitude tremor activity.

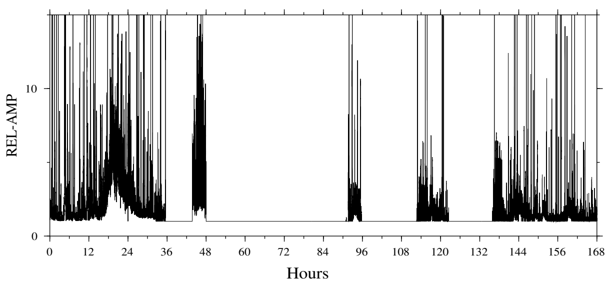


Figure 7.4: Stacked root-mean-square seismograms for the 8 stations of the HRSN used in monitoring tremor activity. Shown are 7 days of data starting at Hour 00 (UTC) of day 7 of 2005. Times when relative RMS amplitudes (REL-AMP) are 1.0 indicate periods when all 8 stations were out simultaneously.

As suspected, further investigation, both remotely and on site, showed that these gaps occurred due to insufficient battery re-charge at many of the network's stations, which are remote solar powered installations. In previous years, similar but less severe data gaps have occurred during the winter months and have been attributed to overcast skies during the rainy season. In the winter of 2005 exceptionally heavy rainy season exacerbated the outage problem to an intolerable level, and to avoid a potential repeat of the situation, efforts were undertaken to refurbish and upgrade the solar power systems.

Specifically, the following steps were and continue to be taken:

1) replacement of the oldest batteries and switching of the remaining old batteries to the less power consuming pre-amplifiers;

2) improvement of the wiring scheme along the lines suggested by the solar power representative;

3) upgrade/replacement of solar panels. (Solar panels degrade at $\sim$ 1% per year, and newer versions have improved output. Since the installation of the HRSN over 18 years ago, the same size/format panel has gone from 40 watts to 55). This is a relatively easy field task, and should gain us 20-30% capacity at each site.

Among the three newer sites (CCRB, SCYB, LCCB), both the batteries and solar panels are relatively new. Nonetheless, stations CCRB and LCCB both had some outages last winter, which is most likely explained by the limited sunlight in these areas due to hilly terrain. We have, therefore, added one more solar panel at each of these sites to enhance their power system robustness.

The table shown in figure 7.4 summarizes the tasks of the power system upgrade effort, and shows the state of completion of the tasks as of the end of 2005. To date all tasks have now been completed.

3.3 Tremor Monitoring

The HRSN data played an essential role in the discovery of nonvolcanic tremors along the San Andreas Fault (SAF) below Cholame, CA (*Nadeau and Dolenc, 2005*). This location occupies a critical location between the smaller Parkfield ($\sim$ M6) and much larger Ft. Tejon ($\sim$ M8) rupture zones of the SAF. Because the time-varying nature of tremor activity is believed to reflect time-varying deep deformation and presumably episodes of accelerated stressing of faults, and because an anomalous increase in the rate of Cholame tremor activity preceded the 2004 Parkfield M6 by $\sim$ 21 days, we are continuing to monitor the tremor activity observable by the HRSN to look for anomalous rate changes that may signal an increased likelihood for another large SAF event to the SE. Results of monitoring effort are described further in the "Research" section of this report.

3.4 High Resolution Similar Event Catalog

As described in the "Data Flow" section above, circumstances relating to the dramatic increase in HRSN event detections spawned by larger earthquakes and by SAFOD drilling activity have required new thinking on how to catalog microearthquakes detected by the HRSN. One action taken to help address this problem has been to integrate HRSN data streams into the NCSN event detection and automated cataloging process (described below).

This approach has been successful at discriminating small events in the local Parkfield area from other types of event detections and for providing automated locations of a significantly increased number of small events in the local area (approx. double that of the NCSN network alone). However, the rate of local events from the HRSN sensitized NCSN catalog is still only catching about 1/2 the number of local events previously cataloged

HRSN POWER UPGRADES

Fall, 2005

Site	Data Logger Batteries (3/site)			Preamp Battery (1/site)		Data Logger Controller		Data Logger Solar Panels		Preamp Solar Panel		Q730 Serial Port		Site
	Age	Action	Rewiring	Age	Action	Type	Action	Status	Action	Status	Action	TD Output	Action	
JCSB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	All model M63**	REPLACE w/ old	M63**	REPLACE	4.6V	repaired	JCSB
RMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	5 M75 panels	good	M75	none	?	Repair	RMNB
VCAB	Recent	keep	done	Recent	keep	Flexcharge	replaced	Needs more panel	replaced w/ bigger	M40	replaced	4.2V	Repair	VCAB
SMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Flexcharge	replaced	Needs more panel	replaced w/ bigger	SM50-H	none	6.1V	Marginal	SMNB
CCRB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	Needs more panel	replaced w/ bigger	two 10-watt	none	7.9V	good	CCRB
JCNB	Recent	keep	done	OLD	replaced w/ used	Prostar	good	Needs more panel	replaced w/ bigger	good	none	4.2V	repaired	JCNB
GHIB	OLD	replaced w/ new	done	"New Jan '99"	replaced w/ used	Prostar	good	1 M40, 3 M75	M40 replaced w/ M75	M40	replaced	failed	repaired	GHIB
MMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Flexcharge	replaced	5 M75 panels	good	M75	none	1.1V	repaired	MMNB
VARB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	4 M65**	replaced w/ 4 M75s	M65**	replaced	3.4V	repaired	VARB
EADB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	1 M55, 3 M75	M55 replaced w/ M75	M40	replaced	4.4V	repaired	EADB
FROB	Recent	keep	done	OLD	replaced w/ used	Prostar	good	1 model M40	done	M75 (2)	none	failed	repaired	FROB
LCCB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	5 SM50-H	good	SM50-H	none	3.2V***	good (?)	LCCB
SCYB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	5 SM50-H	good	SM50-H	none	7.6V	good	SCYB
GAS PK	4-YR OLD	replaced w/ new	done	NA	none	2 Prostar-30s	good	12 SP75	none	NA	none	NA	NA	GAS PK

NOTES:

*Replace (very) old preamp batteries with 4-yr-old batteries removed from Gastro Peak.

**Lower-voltage panels, intended to be used without a controller, 30 cells instead of the 33 cells on the 50-watt panels. Also very old.

***Capacitors are correct, yet voltage level is low. (??)

red =	To do	Jobs Remaining:	1 site replace solar panels	Panel inventory at Base: 1 M75, 4 SM50-H
orange =	Maybe do (2nd priority)		3 sites repair/test serial port	
green =	Done			

Figure 7.5: Table of power upgrade tasks undertaken since early 2005. Red indicates tasks yet to be completed as of the end of 2005. These tasks have now been completed, and as expected data drops out and gaps that had plagued the network during the winter months have been effectively eliminated.

by the HRSN, and waveforms for the small events are not typically made available. In addition, unlike the previous HRSN catalog, the additional events added by the NCSN-HRSN integration are not reviewed by an analyst nor do they generally have magnitude determinations associated with them. In some cases, the selection rules used for the integrated catalog also result in exclusion of events that are otherwise included by the NCSN.

These limitations severely hamper efforts relying on similar and characteristically repeating microearthquakes. They also reduce the effectiveness of research relying on numerous very small magnitude events in the SAFOD zone (e.g. for targeting the SAFOD targets).

To help overcome these limitations, we have embarked on an effort to develop an automated similar event cataloging scheme based on cross-correlation and pattern scanning of the continuous HRSN data now being archived. The method uses a small number of reference events whose waveforms, picks, locations, and magnitudes have been accurately determined, and it automatically detects, picks, locates and determines magnitudes for events similar to the reference event to the level of accuracy and precision that only relative event analysis can bring.

The similar event detection is also remarkably insensitive to the magnitude of the reference event used, allowing similar events ranging over several magnitude units to be fully cataloged using a single reference event. It also does a remarkably good job even when seismic energy from multiple events is superposed. Once a cluster of similar events has been cataloged, it is a relatively straight forward process to identify characteristically repeating microearthquake sequences within the cluster (frequently a single similar event "cluster" will contain several sequences of repeating events).

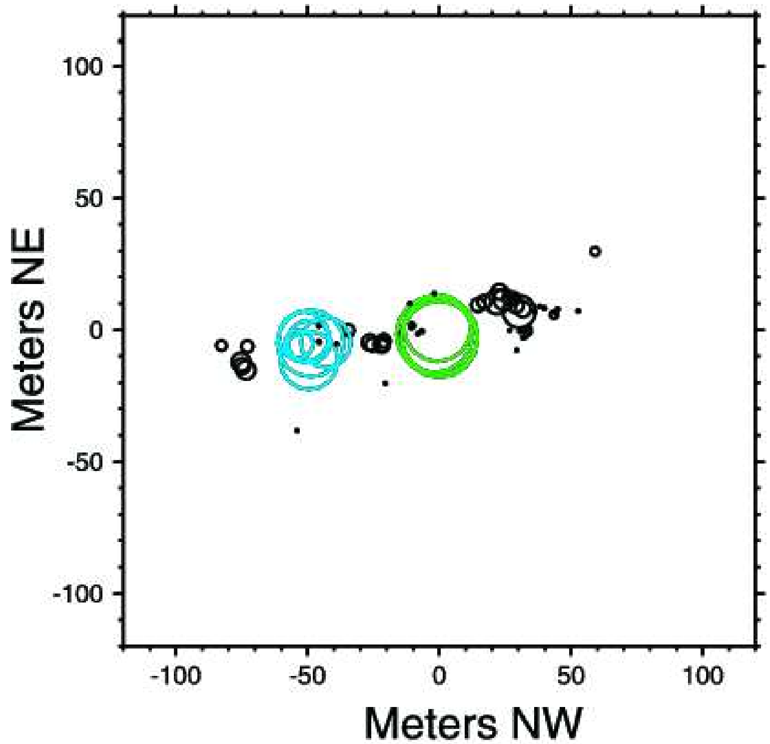
Application of the method using one of the SAFOD target events as a reference is illustrated in Figure 7.6. The magnitude of the reference event is ~ 2.2. This event was scanned through 5 years of continuous data, and 67 other events occurring within a zone of $\sim$ 150 m were detected (including 3 very small quakes that were not even by the HRSN REDI-type system). The magnitudes of these events ranged down to magnitude -1.2 Ml. In addition to the SAFOD target sequence from which the reference was derived, several other repeating sequences within the 150m zone were also identified (5 of which had not previously been known to exist).

The procedure is still being refined to capture even smaller events, events over a larger area and for increased processing speed. Eventually, a composite catalog of similar event groups from throughout the HRSN coverage zone is planned.

The approach also holds promise in other applications where automated and precise monitoring of bursts of seismic activity to very low magnitudes is desirable (e.g. in aftershock zones or in volcanic regions) or where automated updates of preexisting repeating sequences and their associated deep slip estimates are desired.

3.5 Efforts in Support of SAFOD

An intensive and ongoing effort by the EarthScope component called SAFOD is underway to drill through, sample and monitor the active San Andreas Fault at seismogenic depths and in very close proximity (within a



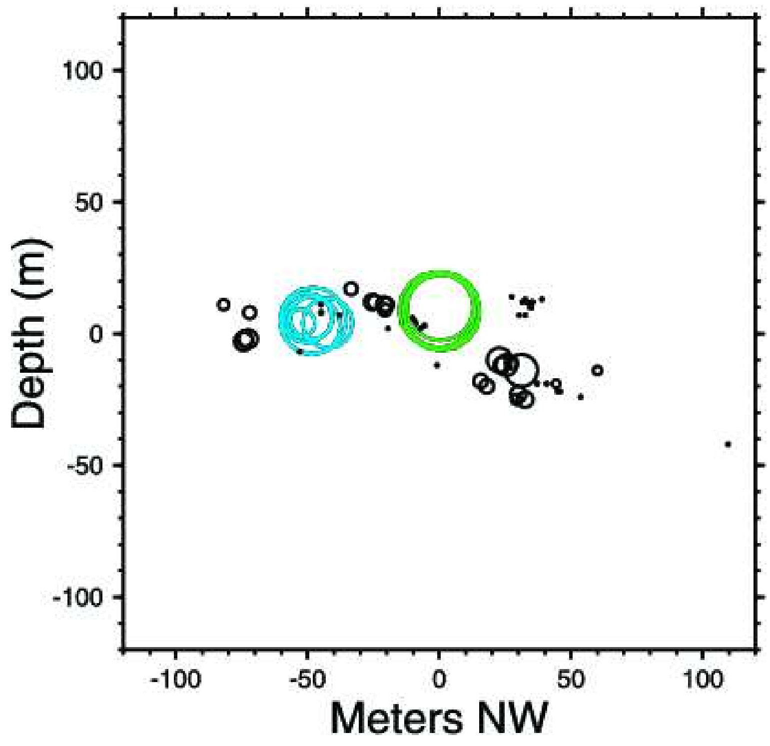


Figure 7.6: Map (top) and along fault depth section (bottom) views of double-difference locations resulting from application of the similar event pattern scanning and automated cataloging method using one of the SAFOD target events (green circles) as a reference. The magnitude of the reference event is ~ 2.2. This event was scanned through 5 years of continuous data, and 67 other events occurring within a zone of $\sim$ 150 m were detected (including 3 v. small quakes that were not even by the HRSN detection scheme). The magnitudes of the 67 events ranged from 2.2 down to -1.2 Ml. In addition to the SAFOD target sequence from which the reference was derived, several other repeating sequences within the 150m zone were also identified (5 of which had not previously been known to exist).

few 10's of km or less) of a repeating magnitude 2 earthquake site. The HRSN data plays a key role in these efforts by providing low noise and high sensitivity seismic waveforms from active and passive sources, and by providing a backbone of earthquake and tremor detection and continuous waveform data from the numerous microearthquakes and tremors that are occurring in the general vicinity of SAFOD.

At this stage SAFOD drilling has penetrated the fault with a sub-horizontal hole slightly beneath the SAFOD target sequences, and current efforts have been focused on obtaining final estimates of the targets relative location to the existing hole to accuracies of meters if possible. This high degree of accuracy is required in order to target accurately three multi-lateral side cores for sampling and monitoring within the final target zone.

HRSN Activities this year have contributed in three principal ways to these and longer-term SAFOD monitoring efforts:

1) In collaboration with the USGS, we have integrated the 7 vertical HRSN channels telemetered from Parkfield into the NCSN triggering scheme (described above) to increase the sensitivity of NCSN detection in the SAFOD area. This has effectively doubled the number of small events the target location working group has for constraining the relative location of the target sequences.

2) Again in collaboration with the USGS, we have nearly completed a telemetry upgrade that will allow all 38 channels of the HRSN data (both 20 sps and 250 sps data streams) to flow directly from Parkfield, through the USGS Menlo Park processing center, and also to the BSL for near-real-time processing and archiving on the web based NCEDC. This will provide near immediate access of the HRSN data to the community without the week's to month's delay associated with having to transport DLT tapes to Berkeley, upload, and quality check the data.

3) We have also applied our prototype similar event automated catalog approach to the primary and two secondary SAFOD target zones and were able to provide the SAFOD event location working group with rapid and precise double-difference and relative magnitude catalogs of 82 similar events in the zone immediately surrounding target region occurring between 2001 day 178 and 2006 day 218 (August 6 of this year).

Figure 7.6 shows the double difference locations and estimated rupture dimensions (based on Nadeau and Johnson, 1998) of 67 of these events that were derived using one event from the SAFOD primary target sequence as the reference. Other primary target events are shown in green, and events from a secondary target located $\sim$ 40 m to the southeast are shown in blue. Several other suspected repeating sequences can be seen as tight clusters of similarly sized events. We are in the process of confirming these events as characteristically repeating sequences members.

The SAFOD similar event catalogs are now being used by the working group to extract data from the corresponding PASO array, Pilot Hole, NCSN and mainhole data sets for integration with the HRSN data to provide as much and as detailed information as possible in the final push at locating the target sequence for the lateral side core drilling.

4. Acknowledgments

Thomas V. McEvilly, who passed away in February 2002, was the PI on the HRSN project for many years. Without his dedication, continued operation of the HRSN would not have been possible. Under Bob Nadeau's and Doug Dreger's general supervision, Rich Clymer, Bob Uhrhammer, Doug Neuhauser, Don Lippert, Bill Karavas, John Friday, Rick Lellinger and Pete Lombard all contribute to the operation of the HRSN. Bob Nadeau prepared this chapter. During this reporting period, operation, maintenance, and data processing for the HRSN project was supported by the USGS, through grant 05HQGR0080.

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Chapter 8

Bay Area Regional Deformation Network

1. Introduction

The last year has been a transition period for BSL, with the departure of Mark Murray in January 2006 and that of his assistant Cedric dela Beaujardiere in November 2005. We have been lucky to hire Nicolas Houlie on a post-doctoral position to assume the responsibility for the routine operations and development of the BARD network and related data acquisition and processing. Some of the field related tasks that Cedric performed have been transferred to the BSL's field engineering group. This reorganization of the tasks has caused some temporary disruption in the processing of the GPS data, but we are now back on track on all of the processing and archiving tasks. A significant effort in the last three years has been to upgrade thoses stations where it is possible to 1Hz continuous data acquisition, to respond to a growing interest in the community for this type of data, for the estimation of earthquake ground motions and real time earthquake quantification.

2. BARD overview

2.1 Description of the network

The BSL currently maintains and operates 30 (twenty-six bi-frequency sites and four L1 sites) BARD stations. The sampling rate vary from 1 to 30 seconds rate and the data recorded are transmitted continuously over serial connection. Most stations use frame relay technology, either alone or in combination with radio telemetry.

Of the 30 sites, ten (BRIB, CMBB, FARB, HOPB, MHCB, ORVB, PKDB, SAOB, SUTB, YBHB) are colocated with broadband seismic stations of the Berkeley Digital Seismic Network (BDSN) with which they share continuous frame-relay telemetry to UC Berkeley. These sites use the Quanterra data loggers to store and retrieve the GPS data converted to MiniSEED format (Perin et al., 1998). The MiniSEED approach provides more robust data recovery from onsite backup on the Quanterra disks following telemetry outages.

Another five stations (SVIN, MHDL, OHLN, OXMT and SBRN) have been installed in the last 3 years in the SFBA and along the Hayward fault as the Berkeley part of a multi-institutional effort funded by the NSF/MRI program to improve strain monitoring in the SFBA using an integrated approach, with significant participation of the USGS/MP (Murray et al., 2002a). These stations include borehole tensor strainmeters, three-component borehole seismic velocity sensors, downhole pore pressure and tilt sensors and GPS receivers. This project served as a prototype for the strainmeter installations planned for PBO, which faces many of the same station installation, configuration, and data retrieval issues we have addressed. Consequently, these 5 stations have received the nickname *mini-PBO*. From July 2001 to August 2002, five boreholes were drilled to about 200-m depth and equipped with tensor strainmeters recently developed by CIW and 3-component L22 (velocity) seismometers. For this project, we developed a self-centering GPS antenna mount for the top of the borehole casings, which are mechanically isolated from the upper few meters of the ground, to provide a stable, compact monument that allows access to the top of the borehole casing for downhole maintenance. The 5 GPS receivers were progressively installed and connected to Quanterra 4120 data loggers, which provide backup and telemetry capabilities. The completion of the last station (MHDL), located in the Marin Headlands, took longer because it required AC power, which PG&E installed in December 2005. The site is operational as of Sept 1, 2006. In addition, 10-minute interval data, which are retrieved from all the sites by the USGS via a backup GOES satellite system, show that all the sites are successfully measuring strains due to tidal effects and to local and teleseismic earthquakes (Murray et al., 2002b). The remaining BSL/BARD stations only record C-GPS data. Each BSL/BARD station uses a low-multipath choke-ring antenna, most of which (except the mini-PBO ones discussed above) are mounted to a reinforced concrete pillar approximately 0.5-1.0 meter above the 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

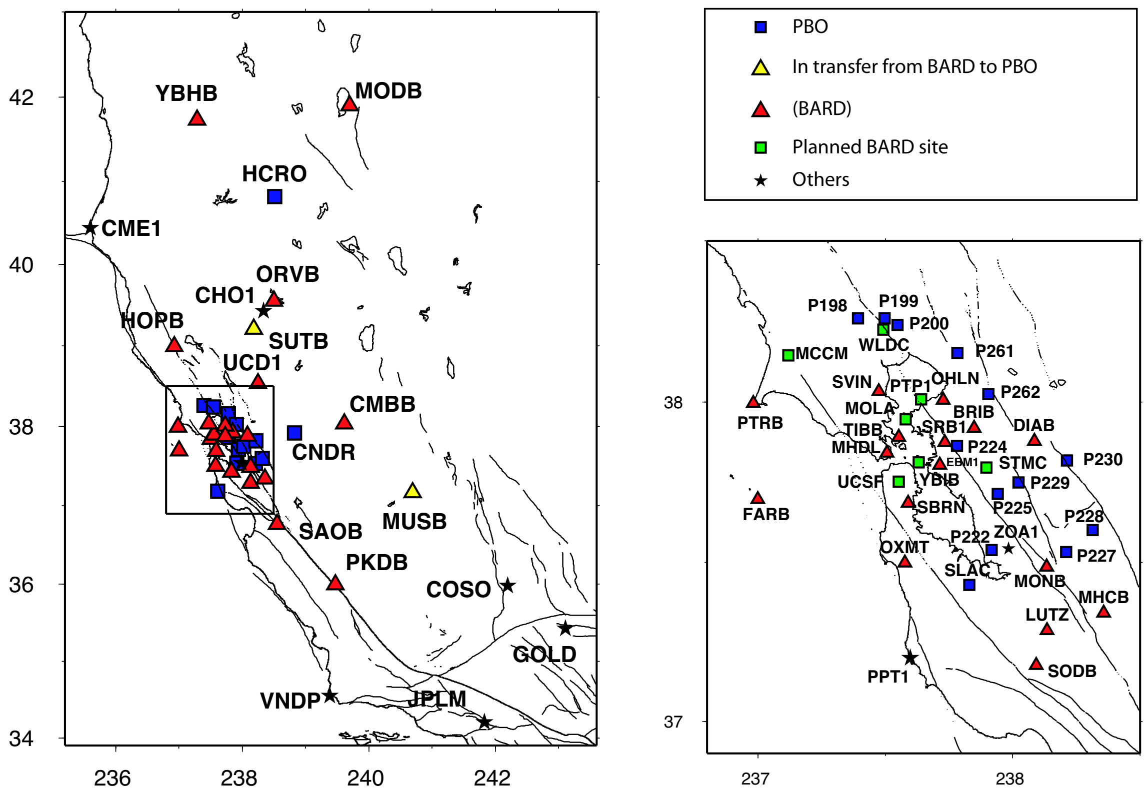

Figure 8.1: Operational BARD stations (dark triangles) in northern California (top) and in the San Francisco Bay area (bottom), including an 18-station network near the Long Valley Caldera (LVC) and a 14-station network near Parkfield (PKFD). In the oblique Mercator projection expected Pacific–North America relative plate motion is parallel to the horizontal. Circled stations use continuous real-time telemetry. The small black triangles near BRIB are the experimental L1 stations. Light triangles are PBO and Nucleus (previously existing continuous stations now part of PBO) stations operating in July 2005.

that normally would require signal amplification. Low-voltage cutoff devices are installed to improve receiver performance following power outages. Most stations are equipped with aging Z-12 receivers, which were originally programmed to record data once every 30 s and observe up to 12 satellites simultaneously at elevations down to the horizon. 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. The BSL acquired 7 Ashtech MicroZ-CGRS (uZ) receivers with NSF funding for the Mini-PBO project. These have been installed at the mini-PBO stations, and two have been used to replace failing Z12 at other stations (CMBB and MODB). At these sites, the data are collected using only direct serial connections and are susceptible to data loss during telemetry outages.

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). We started collecting 1 Hz observations at 2 stations (DIAB and MONB) in 2003. In the last year, we have progressively upgraded the telemetry to continuous 1 Hz telemetry at 9 additional stations (CMBB, MHCB, OHLN, OXMT, SBRN, SVIN, TIBB and two new stations , SRB1, see below, and MHDL), where the bandwidth of the existing telemetry system allowed it. At stations collocated with broadband seismic sensors, the seismic data has priority for telemetry, because it is used in the Northern California real-time earthquake notification system (see http://www.cisn.org/ncmc/) making this upgrade more difficult and in general not feasible with the current Z12 receivers because of insufficient data compression. All data collected from BARD/BSL, including the 1Hz data are publicly available at the Northern California Earthquake Data Center (NCEDC; http://www.ncedc.org/bard/).

Between 1993 and 2001, the BSL acquired 29 Ashtech Z-12 and Micro-Z receivers from a variety of funding sources, including from federal (NSF and USGS), state (CLC), and private (EPRI) agencies. The network enhances continuous strain measurements in the Bay Area and 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 8.1).

The number of continuous GPS stations in northern California is significantly increasing with over 250 new site installations planned by 2008 as part of the Plate Boundary Observatory (PBO) component of the NSF-funded Earthscope project. UNAVCO and researchers from BARD and the other regional networks, such as SCIGN, BARGEN, and PANGA, are funded by NSF to fold operation and maintenance of about 200 existing stations, which constitute the PBO Nucleus network, into the PBO array by 2008. Two BSL-maintained stations (SUTB and MUSB) are included in the PBO Nucleus network. The other 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. Another 23 northern California stations, including most of the Parkfield network, will be included in the PBO Nucleus, and we are working with UNAVCO to facilitate their transition to UNAVCO control.

2.2 BARD Stations

The majority 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 simultaneously at elevations down to the horizon. 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 15 or 30-second intervals and transmitted continuously over serial connections (Table 2.1). 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 (Table 4.2). 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, MHCB, MONB, OHLN, OXMT, SBRN, SRB1, SVIN, and TIBB in the Bay Area, and 13 stations in the Parkfield region (all but PKDB), are now

	Sites	Lat. (deg.)	Lon. (deg)	Receiver	Telem. .	Sampling rate	Collocated Network	Location
1	BRIB	37.91	237.84	A-Z12	FR	30 s	BDSN	Briones Reservation, Orinda
2	CMBB	38.03	239.61	A-UZ12	FR	1Hz	BDSN	Columbia College, Columbia
3	DIAB	37.87	238.08	A-Z12	FR	1Hz		Mt. Diablo
4	FARB	37.69	236.99	A-Z12	R-FR/R	15 s	BDSN	Farallon Island
5	EBMD	37.81	237.71	T-SSI	WEB	1Hz		East Bay Mud Headquarter
6	HOPB	38.99	236.92	A-Z12	FR	15 s	BDSN	Hopland Field Stat., Hopland
7	LUTZ	37.28	238.13	A-Z12	FR	30 s		SCC Comm., Santa Clara
8	MHCB	37.34	238.35	A-Z12	FR	1Hz	BDSN	Lick Obs., Mt. Hamilton
9	MHDL	37.84	237.50	T-NETRS	FR	1Hz	mini-PBO	Marin Headland
10	MODB	41.90	239.69	A-UZ12	NSN	15 s		Modoc Plateau
11	MONB	37.48	238.13	A-Z12	FR	1Hz		Monument Peak, Milpitas
12	MUSB	37.16	240.69	A-Z12	R-Mi-FR	30 s		Musick Mt.
13	OHLN	38.00	237.72	A-UZ12	FR	1Hz	mini-PBO	Ohlone Park, Hercules
14	ORVB	39.55	238.49	A-Z12	FR	15 s	BDSN	Oroville
15	OXMT	37.49	237.57	A-UZ12	FR	1Hz	mini-PBO	Ox Mountain
16	PKDB	35.94	239.45	A-Z12	FR	30 s	BDSN	Bear Valley Ranch, Parkfield
17	PTRB	37.99	236.98	A-Z12	R-FR	15 s		Point Reyes Lighthouse
18	SAOB	36.76	238.55	A-Z12	FR	30 s	BDSN	San Andreas Obs., Hollister
19	SBRN	37.68	237.58	A-Z12	FR	1Hz	mini-PBO	San Bruno
20	SODB	37.16	238.07	A-Z12	R-FR	30 s		Soda Springs, Los Gatos
21	SRB1	37.87	237.73	T-SSE	FR	1Hz		SRB building, Berkeley
22	SUTB	39.20	238.17	A-Z12	R-FR	30 s	BDSN	Sutter Buttes
23	SVIN	38.03	237.47	A-UZ12	R-FR	1Hz	mini-PBO	St Vincents
24	TIBB	37.89	237.55	A-UZ12	R	1Hz		Tiburon
25	UCD1	38.53	238.248	T-SSE	WEB	1Hz		UC - Davis
26	YBHB	41.73	237.289	A-Z12	FR	15 s	BDSN	Yreka Blue Horn Mine, Yreka

Table 8.1: List of the BARD maintained by the BSL. Five models of receiver are operating now: Trimble 4000 SSE (T-SSE), Trimble 4000 SSI (T-SSI), Trimble NETRS, (T-NETRS), Ashtech Z12 and Ashtech Micro Z (A-UZ12). The replacement of the Ashtech Z12 by Trimble NETRS will make the receiver park more homogeneous. The telemetry types are listed in column 6. FR = Frame Relay, R = Radio, Mi= Microwave, WEB = DSL line. Some sites are transmiting data over several legs with different telemetry.

being collected at 1-second intervals. All high-rate observations collected by these stations are currently available from the NCEDC. Collecting at such high-frequency (for GPS) allows dynamic displacements due to large earthquakes to be better measured; however, this 30-fold increase in data can pose telemetry bandwidth limitations. We are planning to convert additional stations to 1-second sampling where possible during the next year. The acquisition of the 5 NETRS bundles will help to complete this project (see subsection 3.1). In the Bay Area, we have converted stations that have sufficient bandwidth and are currently assessing bandwidth issues at other stations. Prior to the September 28, 2004 M6 Parkfield earthquake, data from the Parkfield stations were 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 response to the earthquake, we modified the procedures to download 1-second data converted to compact RINEX format at hourly intervals, which does not significantly impact the telemetry bandwidth.

2.3 Data archival

The Northern California Earthquake Data Center (NCEDC), operated jointly by the BSL and USGS, archives all permanent-site GPS data currently being collected in northern California. In the past months, and due to the transition to PBO, some sites are not present in the NCEDC archive (PPT1 for instance). All the sites available will be as soon as possible archived as in the past. We archive the Federal Aviation Administration (FAA) sites all over the west pacific coast (the closest one is ZOA1). Data importation and quality assurance are automated, although some manual correction of unusual data problems is still required.

As part of the activities funded by the USGS through the BARD network, the NCEDC has established an archive of the 7000+ survey-mode occupations collected by the USGS since 1992. The NCEDC continues to archive non-continuous survey GPS data. The initial dataset archived is the survey GPS data collected by the USGS Menlo Park for northern California and other locations. The NCEDC is the principal archive for this dataset. Significant quality control efforts were implemented by the NCEDC (Romanowicz et al., 1994) to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS MP GPS data has been transferred to the NCEDC and virtually all of the data from 1992 to the present has been archived and is available for distribution. We are also archiving additional high-precision GPS data sets from northern California (mainly Parkfield measurements). Together with students in the department who are now using the GAMIT software to process survey-mode data in the San Francisco Bay area, we are working to combine the survey-mode and C-GPS solutions into a self-consistent velocity field for northern California. The campaign velocity field computed from campaign measurements by university and USGS groups has been published by *dAlessio et al.*, (2005).

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. We helped to define database schema and file formats for the GSAC project, and produce monumentation and data holdings records for the data archived at the NCEDC to provide GSAC with 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. The records for these data have been incorporated into the retailer system that became publicly available in early 2003.

Data from five of our sites (HOPB, MHCB, CMBB, OHLN, YBHB) are sent to the National Geodetic Survey (NGS) in the framework of the CORS (Continuous Operating Reference Stations) project (http://www.ngs.noaa.gov/ CORS/). The data from these five sites are also distributed to the public through the CORS ftp site.

3. 2005-2006 Activities

3.1 New stations and upgrades

During the last year we have installed one additional site on the SRB1 building on the Berkeley Campus, a building built to emergency grade standards that are designed to withstand the next M7 earthquake on the Hayward Fault. This site is equipped with a TRIMBLE 4000 SSE with a Zephyr Geodetic Antenna and is in a good location to reduce the baseline length between surrounding sites (OHLN, BRIB, TIBB, and EBM1, see Figure 2.1) and increase the accuracy of the real-time processing application. It is providing 1Hz data in real time and has been archived at the NCEDC since day 210 in 2006.

We have also assisted collaborators in installations and upgrades of several continuous stations, including at Thales Navigation (THAL), Hat Creek Radio Observatory (HCRO), and EBMD in downtown Oakland, which is being upgraded to real-time 1 Hz telemetry with a direct radio link to the BSL. This site, which belongs to East Bay Municipal Utilities District (EBMUD) has been renamed EBM1 was operated for part of 2004-2005 at 30s sampling rate. It was upgraded to 1Hz using a new DSL line provided by EBMUD. It is not currently operating because the PC failed and EBMUD is looking for ways to restore the data flow. EBM1 will be the reference station for the East Bay Park surveyor teams for real time kinematic positioning (RTK) applications.

A similar collaboration has been engaged with East Bay Parks in collaboration with Mr. Jim Swanson in order to get, archive and process data from the PBO-East Bay Mud GPS sites in real time (Figure 2.1). The site P222 located south of the bay will be equipped to become a RTK reference base during the next year. This site will help define the standard used by East Bay Parks to upgrade (to real time and 1Hz) the PBO sites in the SFBA.

In the last year, we also performed routine maintenance at several sites replacement of a failing receiver at CMBB (lightning), MODB, TIBB (lightning), YBHB and repair of the failing receivers at mini-PBO stations (SBRN, SVIN). Cylink radios used for FARB were replaced by a Wi-Lan radio as part of a reconfiguration of the telemetry paths through UC San Francisco rather than Mount Tamalpais (2005). As part of this reconfiguration and coincident with the replacement of a badly rusted antenna mast, the Freewave radio path at PTRB was adjusted to be routed through UCSF. In February 2003, the BSL assumed responsibility for data telemetry from a 14-station GPS network in the Parkfield region, in addition to the BSL station PKDB. Most of these stations were constructed using Mini-PBO funding with contributions from the USGS and SCIGN. We replaced a computer at Carr Hill with the appropriate scripts to sequentially download the stations over radio connections, and then retrieve the data over our existing frame relay circuit. All the Parkfield GPS sites are being transferred to the PBO network except the PKDB site, which remains at BSL/BARD site, as it is collocated with a long-term BDSN station.

Five Ashtech receivers (Ashtech μZ) purchased by the *mini PBO* project have been repaired during the Fall 2005. The whole series was delivered with factory defects by Ashtech corp. However, the replacement of the capacitor and shipment fees have been covered by Ashtech corp. These receivers have been installed mainly at the mini-PBO sites. The first site affected was SVIN in September 2005. The receiver was able to see fewer and fewer satellites every day at the same time. After a few hours the number of visible satellites increased again until the next day. This problem increased dramatically with time and the state of the capacitor.

BSL acquired five NETRS Bundle pack that will be dispatched in the next year over sites where a internet DSL connection access will be available and where telemetry bandwidth does not allow to increase the sampling rate without changing the receiver (BRIB is one the priority site).

Sites	Lon. (deg.)	Lat. (deg.)	dV_e (mm/y)	dV_n (mm/y)
BAY1	197 .293	55 .19	-0 .03	0 .01
GOLD	243 .111	35 .425	1 .20	-0 .11
JPLM	241 .827	34 .205	0 .50	0 .59
PPT1	237 .61	37 .187	0 .82	0.27
VNDP	239 .384	34 .556	-0 .05	-0 .81

Table 8.2: Comparison between previous published values and recomputed values. The adjustment with the ITRF2000 is good. The errors provided here are formal and cannot be qualified as realistic (From *Houlié and Romanowicz,* in prep).

4. Data Analysis and Results

4.1 CALREF, a stable reference frame for northern California

The BARD dataset have been processed in the ITRF2000 (*Altamimi et al.*, 2002). The solutions (*Houlié and Romanowicz*, in prep) are in good agreement with previous campaign solutions (BAVU and USGS) previously released (*d'Alessio et al.,* 2005). The new coordinates release of the BARD network includes the presently operating site and the velocity of the sites already transferred from BSL to PBO during the last two years.

All the BARD sites have been processed jointly with IGS sites in California. No *a priori* constraints have been assumed during the processing. A specific troposphere study is under progress to estimate the troposphere gradient over the bay area. The velocities computed for a small selection of sites (Table 8.2) are accurate and well compatible with ITRF2000 solutions (*Altamimi et al.,* 2002). All the velocities included in the first release of California Reference Frame (CALREF) are given in Table 8.3. The CALREF will provide velocities and coordinates of sites located in the bay area at specific epochs. Each solution will be associated to discussed error estimations (formal and real). Every surveyor will be able to control the reference site coordinates for a given survey.

5. Acknowledgements

Since the departure of Mark Murray at the end of 2005, Barbara Romanowicz oversees the BARD program. Rich Clymer, Cedric de La Beaujardiere, Bill Karavas, Rick Lellinger, John Friday, Nicolas Houlié and Doug Neuhauser contributed to the operation of the BARD network. The operation of the BARD network is partially supported by funding from the USGS/NEHRP program and funding from the NSF/UNAVCO *PBO nucleus* grant

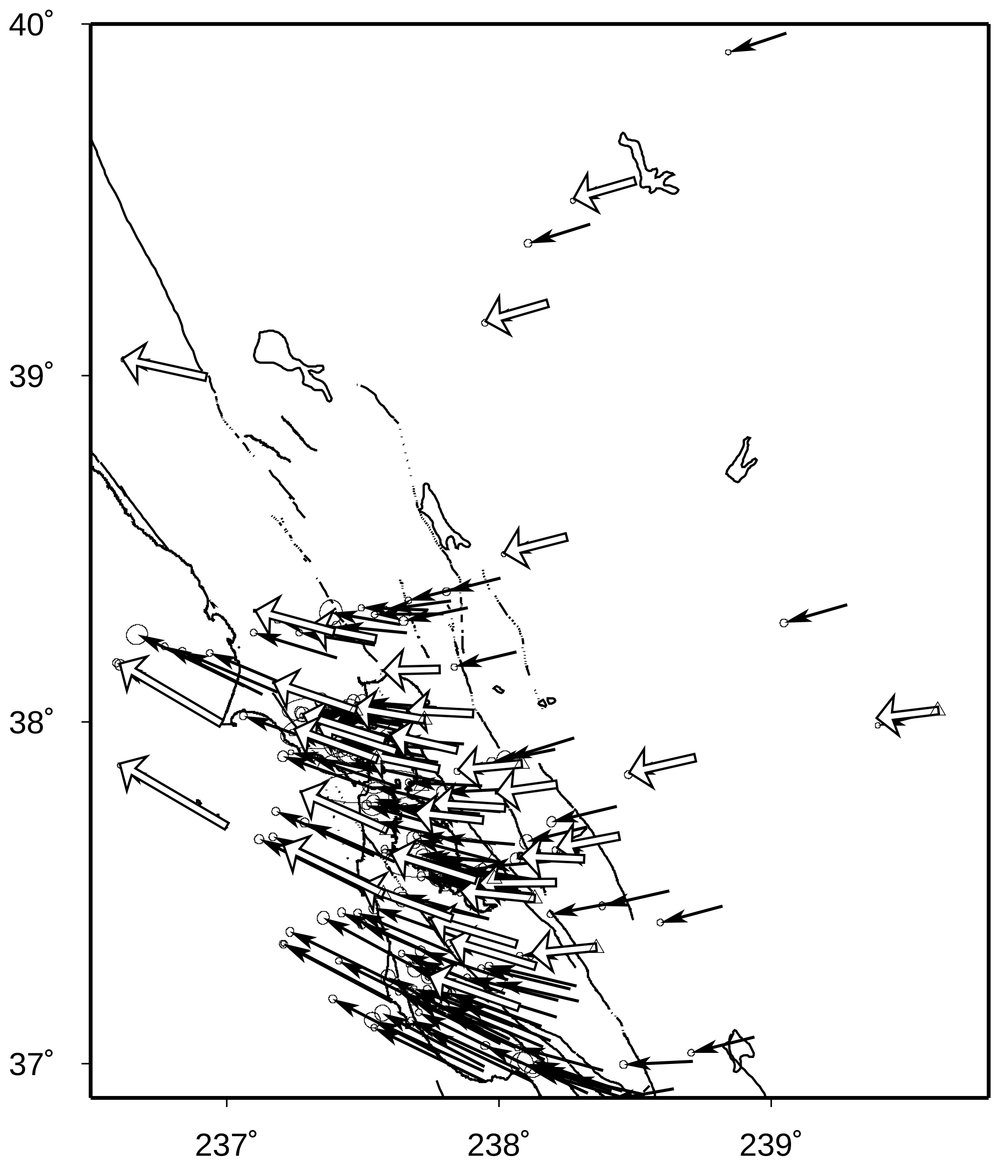

Figure 8.2: Comparison of the BARD solutions (white arrows) with the Bay Area Velocity Unification (BAVU) solutions (black arrows). All the data available at the BSL between 1994 and 2006 have been reprocessed (From *Houlié and Romanowicz,* in prep).BAVU website: http://seismo.berkeley.edu/ burgmann/RESEARCH/BAVU/

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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 8.3: CALREF 2006 official velocities. All velocities and estimated errors (σ)are indicated in mm per year. For each site, the relevant time-span and the network are specified. The sites with a star are the sites for which the velocities have been used during the combination of the daily solutions.

Chapter 9

Northern California Earthquake Data Center

1. Introduction

The Northern California Earthquake Data Center (NCEDC), a joint project of the Berkeley Seismological Laboratory (BSL) and the U.S. Geological Survey at Menlo Park, serves as an online archive for various types of digital data relating to earthquakes in central and northern California. The NCEDC is located at the Berkeley Seismological Laboratory, and has been accessible to users via the internet since mid-1992.

The primary goal of the NCEDC is to provide a stable and permanent archival and distribution center of digital geophysical data for networks in northern and central California. These data include seismic waveforms, electromagnetic data, GPS data, strain, creep, and earthquake parameters. The seismic data comes principally from the Berkeley Digital Seismic Network (BDSN) operated by the Seismological Laboratory, the Northern California Seismic Network (NCSN) operated by the USGS, the Berkeley High Resolution Seismic Network (HRSN) at Parkfield, the EarthScope USArray Transportable Array stations in northern California, the various Geysers networks, and selected stations from adjacent networks such as the University of Reno, Nevada network and the Southern California Seismic Network (SCSN). GPS data are primarily from the Bay Area Regional Deformation (BARD) GPS network and the USGS/Menlo Park GPS surveys. The collection of NCSN digital waveforms dates from 1984 to the present, the BDSN digital waveforms date from 1987 to the present, and the BARD GPS data date from 1993 to the present. The BDSN includes stations that form the specialized Northern Hayward Fault Network (NHFN) and the MiniPBO (MPBO) borehole seismic and strain stations in the SF Bay Region.

The NCEDC also provides support for earthquake processing and archiving activities of the Northern California Earthquake Management Center (NCEMC), a component of the California Integrated Seismic Network (CISN). The CISN is the California regional organization of the Advanced National Seismic Network (ANSS).

2. 2005-2006 Activities

By its nature, data archiving is an ongoing activity. In 2005-2006, the NCEDC continued to expand its data holdings and enhance access to the data. Projects and activities of particular note include:

- Began continuous archiving of the entire NCSN network, This includes data from all USGS NC stations, continuous telemetry stations in northern California from the USGS National Strong Motion Program (NSMP), and continuous data from contributing networks.
- Developed and implemented the NCEDC DART (Data Available in Real Time), a system that provides access to real-time timeseries data.
- Developed software and procedures to read and archive continuous NCSN seismograms from tapes for 2001-2005.
- Expanded archiving of data from EarthScope USArray (network TA) stations for northern California.
- Support NCEMC database efforts to supply the NCEDC with real-time earthquake parameters.

These activities and projects are described in detail below.

3. Data Collections

The bulk of the data at the NCEDC consists of waveform and GPS data from northern California. Figure 9.1 shows the geographic distribution of data archived by the NCEDC. Figure 9.2 shows the relative proportion of each data set at the NCEDC. The total size of the datasets archived at the NCEDC is shown in Table 9.1. Figure 9.3 shows the amount of data for each year that is archived at the NCEDC.

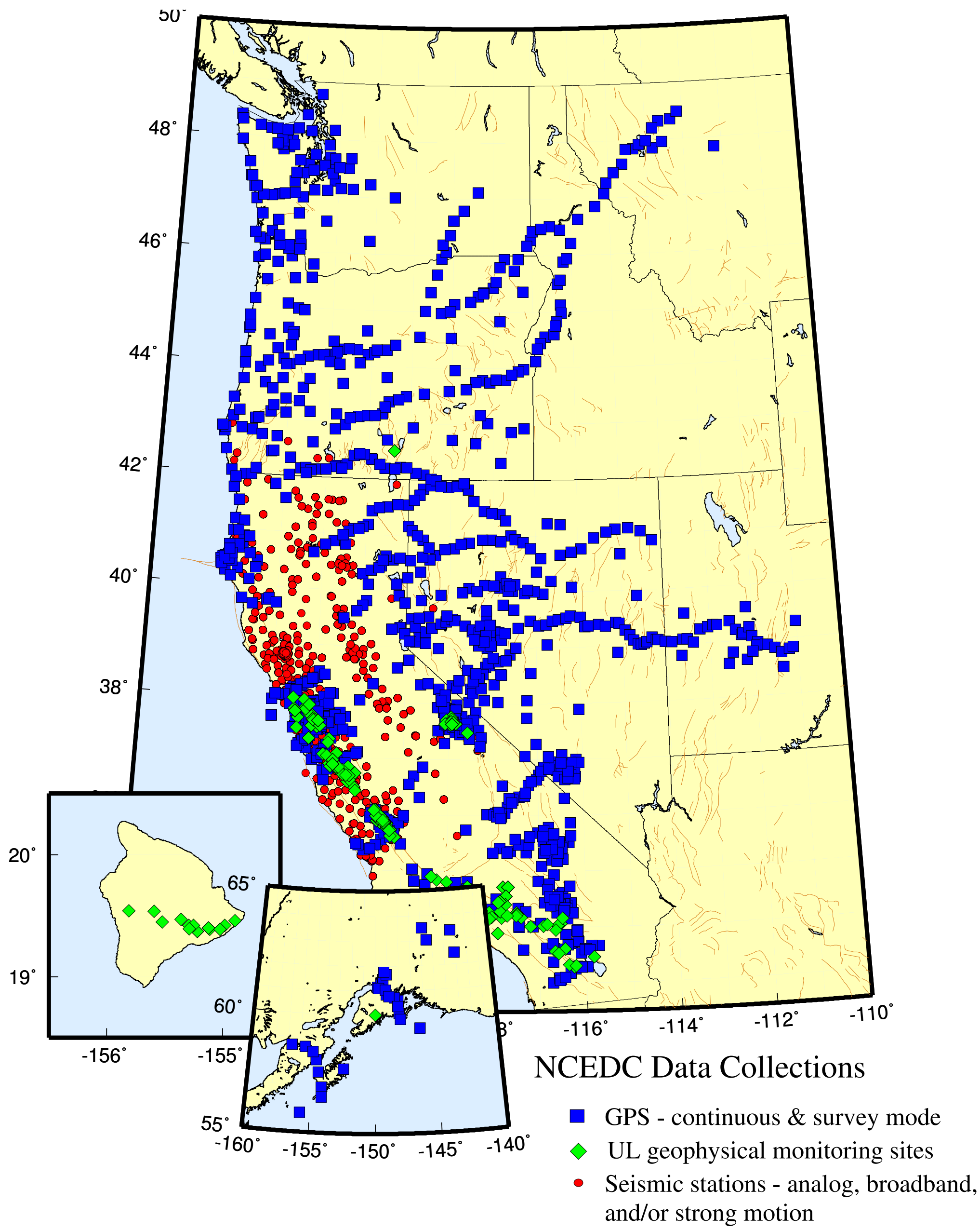

Figure 9.1: Map showing the location of stations whose data are archived at the NCEDC. Circles are seismic sites; squares are GPS sites, and diamonds are the locations of USGS Low-frequency experiments.

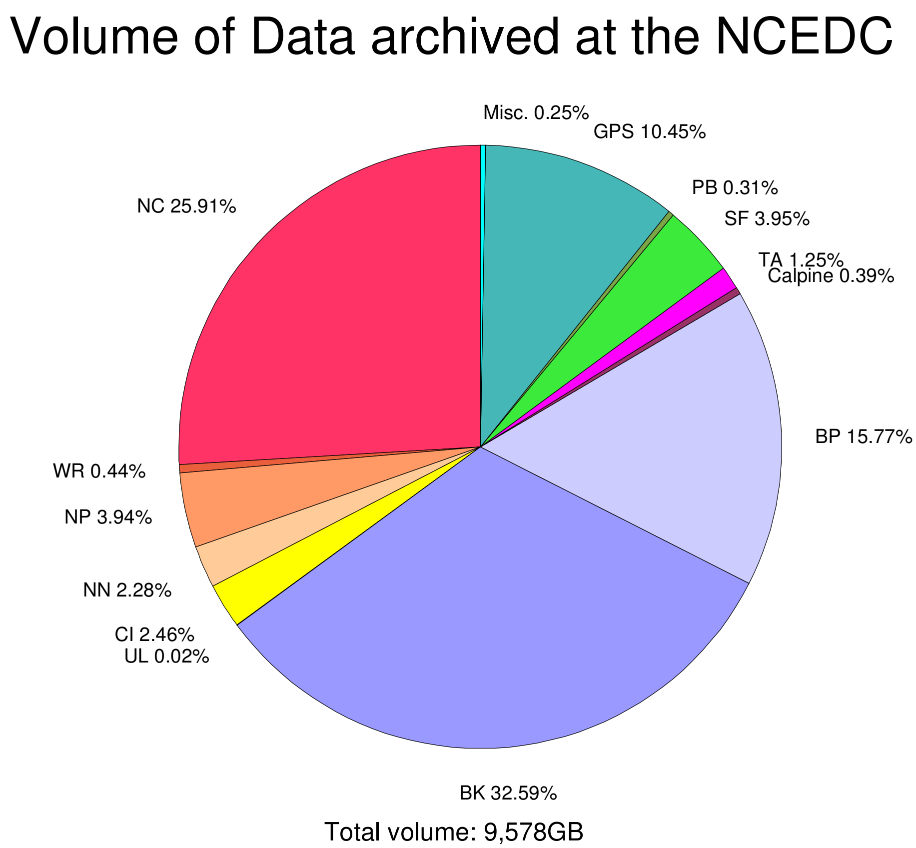

Figure 9.2: Chart showing the relative proportion of each data set at the NCEDC.

Data Type	GBytes
BDSN/NHFN/MPBO (broadband, electric and magnetic field, strain) waveforms	3,111
NCSN seismograms	2,463
Parkfield HRSN seismograms	1,536
BARD GPS (RINEX and raw data)	998
UNR Nevada seismograms	216
SCSN seismograms	234
Calpine/Unocal Geysers region seismograms	37
EarthScope SAFOD seismograms	378
EarthScope USArray seismograms	119
EarthScope PBO strain waveforms	3
USGS Low frequency geophysical waveforms	2
Misc data	24
Total size of archived data	9,534

Table 9.1: Volume of Data Archived at the NCEDC by network

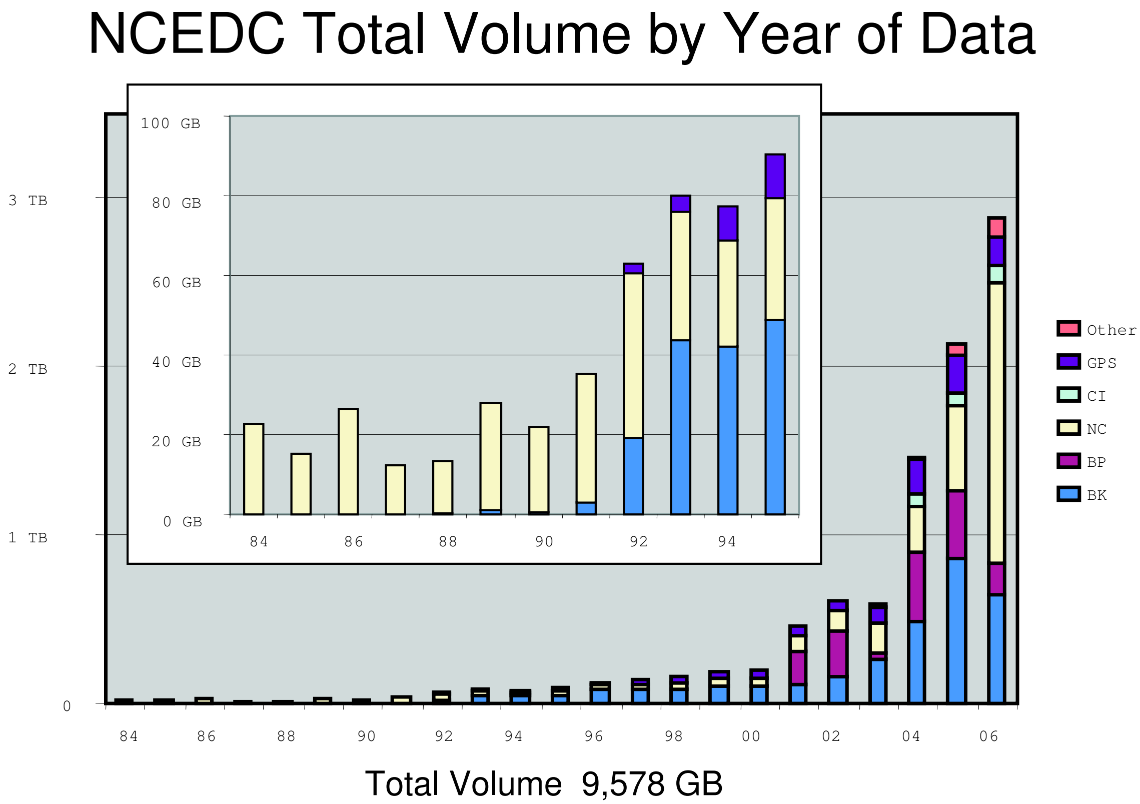

Figure 9.3: Figure showing the total volume of data archived at the NCEDC, broken down by data year.

3.1 BDSN/NHFN/MPBO Seismic Data

Archiving current BDSN (Chapter 4), NHFN (Chapter 6), and Mini-PBO (Chapter ??) (all stations using the network code BK) seismic data is an ongoing task. These data are telemetered from 47 seismic dataloggers in real-time to the BSL, where they are written to disk files, used for CISN real-time earthquake processing, and delivered in real-time to the DART (Data Available in Real Time) system on the NCEDC, where they immediately available to anyone on the internet. In September 2004, the NCEDC began to archive continuous high frequency data (80 Hz and 100 Hz) from all of the BDSN broadband, strong motion, and strainmeter sensors. Previously, 20 Hz and lower rate data channels were archived continuously, and high frequency data was archived only for events. In early 2006, the NCEDC started to receive all of the BK stations in real-time and making them available to users through the DART. All timeseries data from the Berkeley networks continue to be process and archived by an NCEDC analyst using *calqc* in order to provide the highest quality and complete data stream to the NCEDC.

3.2 NCSN Seismic Data

NCSN continous and event waveform data are sent to the NCEDC via the internet and/or private IP network. The NCSN event waveform files are currently assembled and analyzed at Menlo Park, and are then delivered to the NCEDC, where they are automatically converted to MiniSEED and archived.

The NCEDC maintains a list of teleseismic events recorded by the NCSN, which is updated automatically whenever a new NCSN event file is received at the NCEDC, since these events do not appear in the NCSN catalog.

Since 2002 the NCEDC has archived continuous data from the 15 continuously telemetered digital NCSN broadband stations: 11 stations in northwest California and southwest Oregon in support of the USGS/NOAA Consolidated Reporting of EarthquakeS and Tsunamis (CREST) system, two digital broadband stations in the Mammoth region, and two digital broadband stations in the Parkfield region. At the USGS's request, we also continuously archived the 3 component 500 Hz data from the Mammoth Deep Hole.

In January 2005, in response to interest in non-volcanic tremors detected in northern and central California, the NCEDC began archiving continuous high frequency data from 21 additional NCSN stations in selected regions of northern California and Parkfield. In response to requests for additional continuous NCSN data, we received approval to rebudget funds to purchase disk and tape systems to support the reading and archiving of continuous waveforms from the entire NCSN from 2001 to the present and to establish procedures continuous archiving of current NCSN data. We purchased the require hardware, and developed procedures to read, convert, and archive the continuous data from the NCSN tapes.

In December 2005, the NCEDC began archiving all available continuous data from the NCSN continuously telemetered stations. We initially started with the stations owned and operated by the USGS Menlo Park (USGS/MP) NCSN (network code NC), and in early 2006, and after discussions with the other cooperating networks that supply data to the NCSN, we expanded the continuous archive to include data from all stations that are contributed to the NCSN.

The NCEDC installed a freeorb server at the USGS in Menlo Park to acquire and buffer the NCSN data for delivery to the NCEDC over the internet. The orbserver currently provides 2 hours of storage in the memory-mapped ring buffer file at Menlo Park. The NCEDC developed an Earthworm-to-Orb-MiniSEED acquisition program to acquire all NCSN waveform data from an Earthworm ring on a USGS/MP, convert the data to MiniSEED format, and insert the data into the observer's ring buffer. We created an orbserver client that runs on the NCEDC computer that connects to the orbserver in Menlo Park, retrieves the the NCSN waveform data records, and writes them to daily channel files in the NCEDC DART.

Most of the NCSN data are automatically archived at the NCEDC, but data from the NCSN broadband stations and Mammoth Deep Hole, most of which can deliver out-of-order data through the USGS Nanometrics satellite system, are processed by an NCEDC analyst using *calqc*.

3.3 Parkfield High Resolution Seismic Network Data

Event seismograms from the Parkfield High Resolution Seismic Network (HRSN) from 1987 through June 1998 are available in their raw SEGY format via NCEDC research accounts. A number of events have faulty timing due to the lack or failure of a precision timesource for the network. Due to funding limitations, there is currently no ongoing work to correct the timing problems in the older events or to create MiniSEED volumes for these events. However, a preliminary catalog for a significant number of these events has been constructed, and the catalog is available via the web at the NCEDC.

As described in Chapter 7, the original HRSN acquisition system died in late 1998, and an interim system of portable RefTek recorders were installed at some of the sites. Data from this interim system are not currently available online.

Starting in 2000, the HRSN was upgraded with Quanterra Q730 dataloggers and digital telemetry, and 3 new borehole stations were added to the network. In 2000-2003 the PASO array, a temporary IRIS PASSCAL broadband network with real-time telemetry, was installed in the Parkfield area and its recording system was housed at the HRSN recording site in Parkfield. During this time, the HRSN collected event data from both the HRSN and PASO array and provided this integrated data set to researchers in near-real-time. The HRSN detected triggers using the HRSN stations and delivered triggered high-rate data from the HRSN and the PASO stations in real-time to the NCEDC, where they were made available to the research community via anonymous ftp until they are reviewed and permanently archived. In addition, the HRSN 20 Hz (BP) and state-of-health channels were archived continuously at the NCEDC. As an interim measure, the NCEDC also archived the continuous 250 Hz (DP) data channels through late 2002 in order to help researchers retrieve events that were not detected during the network upgrade.

The increased seismic activity related to the magnitude 6.5 earthquake in nearby San Simeon on December 22, 2003 drastically increased the number of triggers by the HRSN network. From December 2003 through August 2004, the HRSN had over 70,000 triggers. The 56Kb frame relay connection from Parkfield to UC Berkeley, which was installed to transmit continuous 20 Hz data, selected 250 Hz channels, and event triggered 250 Hz waveforms from the network, was saturated from the increased activity. The HRSN stopped telemetering the event-triggered waveforms, and the NCEDC started to archive continuous 20 and 250 Hz data from the entire network from tapes created at the HRSN operations center in Parkfield in order to preserve this unique dataset. The seismicity again increased after the magnitude 6.0 Parkfield earthquake on September 28, 2004.

In early 2006 the NCEDC started to receive the HRSN 20 Hz data and a subset of the 250 Hz data in real-time for distribution through the DART. The NCEDC continues to archive continuous 250 Hz and 20 Hz data streams from the HRSN tapes written in Parkfield and processed at the NCEDC.

3.4 EarthScope USArray Transportable Array

EarthScope began installing broadband stations for the Transportable Array component of USArray in California in 2005. The NCEDC started acquiring telemetered continuous data from the northern California and surrounding stations as they were installed, and is archiving these data to support users working with northern

California seismic data. These data are made available to users using the same data request methods as all other continuous data waveform data at the NCEDC. The Transportable Array stations have a limited operational timespan of 18 to 24 months, after which they will be relocated to new sites across the country. Data from these stations are delivered to the NCEDC as they are received by the BSL for distribution through the DART.

3.5 EarthScope Plate Boundary Observatory (PBO) strain data

The NCEDC has been designated by EarthScope as one of two archives for PBO borehole and laser strain data. Strain data are collected from all of the PBO strain sites and are processed by UNAVCO. MiniSEED data are delivered to the NCEDC using SeedLink, and raw and XML processed data are delivered to the NCEDC using Unidata's Local Data Manager (LDM). The MiniSEED data are inserted into the NCEDC DART, and are subsequently archived from the DART. UNAVCO provides EarthScope funding to the NCEDC to help cover the processing, archiving, and distribution costs for these data.

3.6 EarthScope SAFOD

The NCEDC is designated as the primary archive center for the SAFOD event data, and will also process the continuous SAFOD data. Starting in July 2002, scientists from Duke University successfully installed a three component 32 level downhole-seismic array in the pilot hole at the EarthScope SAFOD site in collaboration with Steve Hickman (USGS), Mark Zoback (Stanford University) and the Oyo Geospace Engineering Resources International (GERI) Corporation. High frequency event recordings from this array have been provided by Duke University for archiving at the NCEDC. We converted data from the original SEG-2 format data files to MiniSEED, and have developed the SEED instrument responses for this data set. We continue to receive data from the various SAFOD seismic deployments in the Pilot Hole and Main Hole, and will convert, archive, and distributed these data. SAFOD will provide EarthScope funding to the NCEDC to cover the processing, archiving, and distribution costs for these data. A small subset of the continuous SAFOD data channels are also incorporated into the NCSN, and are available in real-time from the NCEDC DART.

3.7 UNR Broadband data

The University of Reno in Nevada (UNR) operates several broadband stations in western Nevada and eastern California that are important for northern California earthquake processing and analysis. Starting in August 2000, the NCEDC has been receiving and archiving continuous broadband data from four UNR stations. The data are transmitted in real-time from UNR to UC Berkeley, where they are made available for CISN real-time earthquake processing and for archiving. Initially, some of the stations were sampled at 20 Hz, but all stations are now sampled and archived continuously at 100 Hz.

The NCEDC installed Simple Wave Server (SWS) software at UNR, which provides an interface to UNR's recent collection of waveforms. The SWS is used by the NCEDC to retrieve waveforms from UNR that were missing at the NCEDC due to real-time telemetry outages between UNR and UC Berkeley.

In early 2006 the NCEDC started to archive continuous data from the UNR short-period stations that are contributed to the NCSN. Both the broadband and short-period UNR stations contributed to the CISN are available in real-time through the NCEDC DART.

3.8 Electro-Magnetic Data

The NCEDC continues to archive and process electric and magnetic field data acquired at several UC Berkeley sites. dataloggers at PKD, SAO, and JRSC acquire data from 3 components of magnetic field and 2 or 4 components of electric field at 40 Hz, 1 Hz, and 0.1 Hz, and are telemetered in real-time along with seismic data to the Berkeley Seismological Laboratory, where they are processed and archived at the NCEDC in a similar fashion to the seismic data (Section 3.17.).

Using programs developed by Dr. Martin Fullerkrug at the Stanford University STAR Laboratory (now at the University of Bath), the NCEDC has computed and archived magnetic activity and Schumann resonance analysis using the 40 Hz data from this dataset. The magnetic activity and Schumann resonance data can be accessed from the Web.

The NCEDC also archives data from a low-frequency, long-baseline electric field project operated by Dr. Steve Park of UC Riverside at site PKD2. These data are acquired and archived in an identical manner to the other electric field data at the NCEDC.

3.9 GPS Data

The NCEDC continues to archive GPS data through the BARD (Bay Area Regional Deformation) network of continuously monitored GPS receivers in northern California (Chapter 8). The NCEDC GPS archive now includes 67 continuous sites in northern California. There are approximately 50 core BARD sites owned and operated by UC Berkeley, USGS (Menlo Park and Cascade Volcano Observatory), LLNL, UC Davis, UC Santa Cruz, Trimble Navigation, and Stanford. Data are also archived from sites operated by other agencies including East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, and the Jet Propulsion Laboratory.

In addition to the standard 15 second or 30 second continuous GPS datastream, the NCEDC is now archiving and distributing high-rate 1 Hz continuous GPS data from the 14 stations in Parkfield and from 10 BARD stations. These high-rate data are available via anonymous FTP from the NCEDC but are currently not included in the GPS Seamless Archive (GSAC), since the GSAC does not currently handle both high-rate and low-rate data from the same site and day.

The NCEDC continues to archive non-continuous survey GPS data. The initial dataset archived is the survey GPS data collected by the USGS Menlo Park for northern California and other locations. The NCEDC is the principal archive for this dataset. Significant quality control efforts were implemented by the NCEDC to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS/MP GPS data has been transferred to the NCEDC and virtually all of the data from 1992 to the present has been archived and is available for distribution.

3.10 Geysers Seismic Data

The Calpine Corporation currently operates a microseismic monitoring network in the Geysers region of northern California. Prior to 1999 this network was operated by Unocal. Through various agreements, both Unocal and Calpine have released triggered event waveform data from 1989 through 2000 along with preliminary event catalogs for the same time period for archiving and distribution through the NCEDC. This dataset represents over 296,000 events that were recorded by Calpine/Unocal Geysers network, and are available via research accounts at the NCEDC.

The Lawrence Berkeley National Laboratory (LBNL), with funding from the California Energy Commission, operates a 22 station network in the Geysers region with an emphasis on monitoring seismicity related to well water injection. The earthquake locations and waveforms from this network are sent to the NCEDC, and the locations are forwarded to the NCSN so that they can be merged into the NCSN earthquake catalog. The LBNL Geysers waveforms will be available at the NCEDC after the NCSN catalog has been migrated from flat files to the database.

3.11 USGS Low Frequency Data

Over the last 30 years, the USGS at Menlo Park, in collaboration with other principal investigators, has collected an extensive low-frequency geophysical data set that contains over 1300 channels of tilt, tensor strain, dilatational strain, creep, magnetic field, water level, and auxiliary channels such as temperature, pore pressure, rain and snow accumulation, and wind speed. In collaboration with the USGS, we assembled the requisite information for the hardware representation of the stations and the instrument responses for many channels of this diverse dataset, and developed the required programs to populate and update the hardware database and generate the instrument responses. We developed the programs and procedures to automate the process of importing the raw waveform data and convert it to MiniSEED format. Since these data are delivered to the NCEDC on a daily basis and immediately archived, these data are not inserted into the NCEDC DART.

We have currently archived timeseries data from 887 data channels from 167 sites, and have instrument response information for 542 channels at 139 sites. The waveform archive is updated on a daily basis with data from 350 currently operating data channels. We will augment the raw data archive as additional instrument response information is assembled by the USGS for the channels, and will work with the USGS to clearly define the attributes of the "processed" data channels.

3.12 SCSN/Statewide seismic data

In 2004 the NCEDC started to archive broadband and strong motion data from 15 SCSN (network CI) stations that are telemetered to the NCEMC. These data are used in the prototype real-time state-wide earthquake processing system and also provide increased coverage for northern California events. Since the data are telemetered directly from the stations in real-time to both the SCSN and to the NCEMC, the NCEDC archives the NCEMC's copy of the data to ensure that at least one copy of the data will be preserved.

In early 2006 the NCEDC started to continuously archive all of the selected SCSN short-period stations that are contributed to the NCSN. All of these data are available in real-time from the NCEDC DART.

3.13 Northern California Seismicity Project

The objective of Northern California Seismicity Project is to characterize the spatial and temporal evolution of the northern and Central California seismicity during the initial part of the earthquake cycle as the region emerges from the stress shadow of the great 1906 San Francisco earthquake. Although the current BSL catalog of earthquakes for the region appears to be a simple list of events, one must remember that it really is a very complex data set. The existing catalog is inhomogeneous in that it suffers from the three types of man-made seismicity changes: namely detection changes, reporting changes, and magnitude shifts. The inherent catalog inhomogeneity exists because the location and magnitude determination methodologies have changed as the instrumentation and computational capabilities improved over the past century. It is easy to misinterpret observed variations in seismicity if we do not understand these inherent limitations of the catalog. As a result, the northern and central California seismicity since 1906 is poorly understood.

Creation of a northern and central California catalog of seismicity that is homogeneous, that spans as many years as possible, and that includes formal estimates of the parameters and their uncertainty is a fundamental prerequisite for probabilistic studies of the seismicity. The existence of the invaluable BSL seismological archive, containing the original seismograms as well as the original reading/analysis sheets allows the application of modern analytical algorithms towards the problem of determining the source parameters of the historical earthquakes.

Our approach is to systematically re-analyze the data acquired from the reading/analysis sheet archive to develop a homogeneous catalog of earthquake location and local magnitude (M_L) including formal uncertainties on all parameters which extends as far back in time as the instrumental records allow and which is complete above appropriate threshold magnitudes. We anticipate being able to compile a new catalog of location and M_L which spans 1930 to the present and is which complete at the M_L 3 threshold.

During the year 2005-2006 we have completed the transcription of the original reading/analysis sheets to computer readable flat files for all M_L 3.0 and larger earthquakes which have occurred in northern and central California and vicinity back to January 1, 1951. We started with the events that occurred in 1983 and worked backwards in time. The events from January 1, 1984 onwards were already in computer readable form. Data were transcribed from the original reading/analysis sheets for 5204 earthquakes and preliminary locations and local magnitudes have been calculated. We plan to transcribe reading/analysis sheet data back to at least 1932 but the process is more complicated and time consuming since we will have to pull the original Wood-Anderson seismograms from the archive to read the maximum trace amplitudes in order to calculate the local magnitude of the events. The research reports (Sections 3.12. and 3.13.) by R. Uhrhammer discuss these projects in more detail.

3.14 Earthquake Catalogs

Northern California

The NCEDC provides searchable access to both the USGS and BSL earthquake catalogs for northern and central California. The "official" UC Berkeley earthquake catalog begins in 1910 and runs through 2003, and the "official" USGS catalog begins in 1966. Both of these catalogs are archived and available through the NCEDC, but the existence of 2 catalogs has caused confusion among both researchers and the public.

In late 2006, the NCEMC will begin providing a single unified northern California earthquake catalog in real-time to the NCEDC through database replication from the NCEMC's real-time systems. The NCEDC has developed and is testing the required programs that will be used to enter all previous NCSN catalog data into the NCEDC database. We will then merge the the BSL catalog with the NCEMC catalog to form a single unified northern California catalog from 1910 to the present. The BSL and the USGS have spent considerable effort over the past years to define procedures for merging the data from the two catalogs into a single northern and central California earthquake catalog in order to present a unified view of northern California seismicity. The differences in time period, variations in data availability, and mismatches in regions of coverage all complicate the task.

Worldwide

The NCEDC, in conjunction with the Council of the National Seismic System (CNSS), produced and distributed a world-wide composite catalog of earthquakes based on the catalogs of the national and various U.S. regional networks for several years. Each network updates their earthquake catalog on a daily basis at the NCEDC, and the NCEDC constructs a composite worldwide earthquake catalog by combining the data, removing duplicate entries that may occur from multiple networks recording an event, and giving priority to the data from each network's *authoritative region*. The catalog, which includes data from 14 regional and national networks, is searchable using a Web interface at the NCEDC. The catalog is also freely available to anyone via ftp over the internet.

With the demise of the CNSS and the development of the Advanced National Seismic System (ANSS), the NCEDC was asked to update its Web pages to present the composite catalog as a product of the ANSS. This conversion was completed in the fall of 2002. We continue to create, house, distribute, and provide a searchable web interface to the ANSS composite catalog, and to aid the regional networks in submitting data to the catalog.

4. NCEDC Operations

In 2005, the NCEDC relocated its archive and distribution system from McCone Hall to a new state-of-the-art computer facility in a new seismically braced building on the Berkeley campus. The facility provides seismically braced equipment racks, gigabit ethernet network, air condioning and power conditioning. The entire facility is powered by a UPS with generator backup.

The currently installed NCEDC facilities consist of a mass storage environment hosted by a Sun V240 host computer, a 100 slot LTO-2 tape library with two tape drives and a 20 TByte capacity, and 30 TBytes of RAID storage, all managed with the SAM-FS hierarchical storage management (HSM) software. A dual processor Sun Ultra 60 provides Web services and research account access to the NCEDC, a dual Sun 280R processor provide data import and export services, and a Sun Ultra 450 computer is used for quality control procedures. Two AIT tape libraries will be used to read NCSN continuous data tapes. An 64-bit Linux system hosts a database dedicated to providing data to external users. A new Sun Opteron processor has recently been purchased to upgrade the NCEDC web server.

The hardware and software system is configured to automatically create multiple copies of each timeseries file. The NCEDC creates an online copy of each file on online RAID, a second copy on LTO-2 tape which is stored online in the tape libraray, and a third copy on LTO-2 tape which is stored offline and offsite. All NCEDC data are online and rapidly accessible by users.

The NCEDC operates two instances of its Oracle database, one for internal operations, and one for external use for user data queries and data distribution programs. The databases are synchronized using multimaster replication.

5. Data Quality Control

The NCEDC developed a GUI-based state-driven system *calqc* to facilitate the quality control processing that is applied to the continuously archived data sets at the NCEDC.

The quality control procedures for these datasets include the following tasks:

- data extraction of a full day of data,
- quickcheck program to summarize the quality and stability of the stations' clocks,
- determine if there is missing data for any data channel,
- provided procedures to retrieve missing data from the stations and incorporate it into the day's data,
- optional creation of multi-day timeseries plots for state-of-health data channels,
- optional timing corrections for data,
- optional extraction of event-based waveforms from continuous data channels,
- optional repacking of MiniSEED data,
- creating waveform inventory entries in the NCEDC database,
- publishing the data for remote access on the NCEDC.

Calqc uses previously developed programs to perform each function, but it provides a graphical point-and-click interface to automate these procedures, and to provide the analyst with a record of when each process was started, whether it executed correctly, and whether the analyst has indicated that a step has been completed. *Calqc* is used to process all data from the BDSN network, and all continuous broadband data from the NCSN, UNR, SCSN, and HRSN networks that are archived by the NCEDC. The remainder of the continuously archived data are automatically archived without any analyst interaction.

6. Database Development

Due to restrictions imposed by the USGS/MP NCSN CUSP event analysis system, the NCEDC still stores the the official NCSN earthquake catalog, phase, amplitude, and coda readings in flat text files. However, the NCEDC has worked closely with the NCEMC to develop and test procedures that will allow the USGS/MP to replace the CUSP analysis system with *jiggle*, the analysis tool developed by the SCSN and to deliver earthquake parametric data in real-time to the NCEDC database. We have developed the database tools to insert the NCEMC earthquake parametric information into databases in the real-time earthquake analysis systems, and have extensively tested database replication between the NCEMC databases and the NCEDC database. We have developed the programs necessary to migrate the NCSN catalog into the CISN parametric schema and to search and retrieve earthquake data from the database. In fall 2006, we will coordinate the retirement of CUSP with the migration of the NCEMC system to the replicated database environment.

During 2002-2004, the NCEDC and NCSN jointly developed a system consisting of an extensive spreadsheet containing per-channel information that describes the hardware of each NCSN data channel and provides each channel with a SEED-compliant channel name. This spreadsheet, combined with a limited number of of files that describe the central-site analog digitizer, FIR decimation filters, and general characteristics of digital acquisition systems, allow the NCSN to assemble its station history in a format that the NCEDC can use to populate the hardware tracking and instrument response database tables for the NCSN.

The NCEDC instrument response schema represents full multi-stage instrument responses (including filter coefficients) for the broadband dataloggers. The hardware tracking schema represents the interconnection of instruments, amplifiers, filters, and dataloggers over time, and is used to describe all of the UC Berkeley and

USGS stations and channels archived at the NCEDC. All NCSN event waveform and continuous timeseries data has been converted from CUSP and Earthworm format to MiniSEED, and are available along with the UC Berkeley data and data from the other networks archived at the NCEDC in full SEED format.

The NCEDC has developed XML import and export procedures to provide better maintenance of the hardware tracking information and resulting instrument responses for stations in our database. When changes are made to either existing hardware or to station configurations, we export the current view in XML format, use a GUI-based XML editor to easily update the information, and import the changes back into the database. When adding new stations or hardware, we can easily use information from existing hardware or stations as templates for the new information. This allows us to treat the database as the authoritative source of information, and to use off-the-shelf tools such as the XML editor and XML differencing programs as part of our database maintenance procedures.

Additional details on the joint catalog effort and database schema development may be found at `http://www.ncedc.org/db`

7. Data Distribution

The NCEDC continues to use the World Wide Web as a principal interface for users to request, search, and receive data from the NCEDC. In fall 2005 the NCEDC acquired the domain name *ncedc.org*. The NCEDC's Web address is now `http://www.ncedc.org/`

Earthquake Catalogs

The NCEDC provides users with searchable access to northern California earthquake catalogs and to the ANSS world-wide catalog via the web. Users can search the catalogs by time, magnitude, and geographic region, and can retrieve either hypocenter and magnitude information or a full set of earthquake parameters including phase readings, amplitudes, and codas.

Station Metadata

In addition to the metadata returned through the various data request methods, the NCECD provides dataless SEED volumes and SEED RESP file for all data channels archived at the NCEDC. The NCEDC currently has full SEED instrument responses for 8462 data channels from 1379 stations in 14 networks. This includes stations from the California Geological Survey (CGS) strong motion stations that will contribute seismic waveform data for significant earthquake to the NCEDC and SCEDC.

SeismiQuery

We have ported and installed the IRIS *SeismiQuery* program at the NCEDC, which provides a common interface to query network, station, and channel attributes and query the availability of archived timeseries data. We have provided both IRIS and the SCEC Data Center with our modified version of *SeismiQuery*.

DART (Data Available in Real Time)

The DART (Data Available in Real Time) represents the first step in NCEDC's effort to make current and recent timeseries data from all networks, stations, and channels available to users in real-time. The NCEDC developed DART in December 2005 to provide a mechanism for users to obtain access to real-time data from the NCEDC. All real-time timeseries data stream delivered to the NCEDC are placed in MiniSEED files in a web-accessible directory structure. The DART waveforms can be accessed by web browsers or http command-line programs such as *wget*, a *FISSURES* waveform server, and a Berkelely-developed Simple Wave Server (SWS) which provides programmatic access to the DART data by specified SEED channel and time interval. We will be providing users with a client program to retrieve data from the SWS in the near future. The DART currently provide assess to the most recent 30 days of data.

We are using the Freeorb software, an enhanced version of the open-source orb software developed by the IRIS-funded Joint Seismic Project (JSP), as the primary method for delivering real-time data to the NCEDC and into the DART. The freeorb package implements an object ring buffer (ORB) and orbserver, which provides a reliable storage ringbuffer and an interface for orb client programs to read, write, and query the orbserver. Orbserver clients running at the NCEDC computer connect to remote orbservers at the BSL and USGS/Menlo Park, retrieve the MiniSEED timeseries data records, and write them to daily channel files in the NCEDC DART. Strain data from the EarthScope PBO network are delivered to the NCEDC using SeedLink, and are inserted into the DART using a similar SeedLink client program.

The NCEDC developed an automated data archiving system to archive data from the DART on a daily basis. It allows us to specify which stations should be automatically archived, and which stations should be handled by the NCEDC's Quality Control program *calqc*, which allow an analyst to review the waveforms, retrieve missing data from stations or waveservers that may have contain late arriving out-of-order data, and perform timing corrections on the waveform data. The majority of data channels are currently archived automatically from the DART.

NetDC

In a collaborative project with the IRIS DMC and other worldwide datacenters, the NCEDC helped develop and implement *NetDC*, a protocol which will provide a seamless user interface to multiple datacenters for geophysical network and station inventory, instrument responses, and data retrieval requests. The *NetDC* builds upon the foundation and concepts of the IRIS *BREQ_FAST* data request system. The *NetDC* system was put into production in January 2000, and is currently operational at serveral datacenters worldwide, including NCEDC, IRIS DMC, ORFEUS, Geoscope, and SCEDC. The *NetDC* system receives user requests via email, automatically routes the appropriate portion of the requests to the appropriate datacenter, optionally aggregates the responses from the various datacenters, and delivers the data (or ftp pointers to the data) to the users via email.

STP

In 2002, the NCEDC wrote a collaborative proposal with the SCEDC to the Southern California Earthquake Center, with the goal of unifying data access between the two data centers. As part of this project, the NCEDC and SCEDC are working to support a common set of 3 tools for accessing waveform and parametric data: *SeismiQuery*, *NetDC*, and *STP*.

The *Seismogram Transfer Program* or *STP* is a simple client-server program, developed at the SCEDC. Access to *STP* is either through a simple direct interface that is available for Sun or Linux platforms, or through a GUI Web interface. With the direct interface, the data are placed directly on a user's computer in several possible formats, with the byte-swap conversion performed automatically. With the Web interface, the selected and converted data are retrieved with a single ftp command. The *STP* interface also allows rapid access to parametric data such as hypocenters and phases.

The NCEDC has continued work on *STP*, working with the SCEDC on extensions and needed additions. We added support for the full SEED channel name (Station, Network, Channel, and Location), and are now able to return event-associated waveforms from the NCSN waveform archive.

EVT_FAST

In order to provide Web access to the NCSN waveform before the SEED conversion and instrument response for the NCSN has been completed, the NCEDC implemented *EVT_FAST*, an interim email-based waveform request system similar to the *BREQ_FAST* email request system. Users email *EVT_FAST* requests to the NCEDC and request NCSN waveform data based on the NCSN event id. Initially the NCSN waveform data was converted to either SAC ASCII, SAC binary, or AH format, and placed in the anonymous ftp directory for retrieval by the users. *EVT_FAST* event waveforms can now also be provided in MiniSEED format, and are now named with their SEED channel names.

FISSURES

The *FISSURES* project developed from an initiative by IRIS to improve earth scientists' efficiency by developing a unified environment that can provide interactive or programmatic access to waveform data and the corresponding metadata for instrument response, as well as station and channel inventory information. *FISSURES* was developed using CORBA (Common Object Request Broker Architecture) as the architecture to implement a system-independent method for the exchange of this binary data. The IRIS DMC developed a series of services, referred to as the *Data Handling Interface (DHI)*, using the *FISSURES* architecture to provide waveform and metadata from the IRIS DMC.

The NCEDC has implemented the *FISSURES Data Handling Interface (DHI)* services at the NCEDC, which involves interfacing the DHI servers with the NCEDC database schema. These services interact with the NCEDC database and data storage system, and can deliver NCEDC channel metadata as well as waveforms using the *FISSURES* interfaces. We have separate *FISSURES DHI* waveform servers to serve archived and DART data stream. Our *FISSURES* servers are registed with the IRIS *FISSURES naming services*, which ensures that all *FISSURES* users have transparent access to data from the NCEDC.

GSAC

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, and as a wholesale collection point for other data collected in northern California. We helped to define database schema and file formats for the *GSAC* project, and 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 138,000 data files from over 1400 continuous and survey-mode monuments. The data holdings records for these data have been incorporated into the *GSAC* retailer system, which became publicly available in late 2002.

In addition, the NCEDC is archiving and distributing high-rate 1 Hz GPS data from 10 BARD stations in addition to the normally sampled 15 second or 30 second data. These high-rate data are available by FTP from the NCEDC, but are not available through GSAC due to GSAC's inability to distinguish multiple data streams with different sample rates for the same day and station.

8. Acknowledgements

The NCEDC is a joint project of the BSL and the USGS Menlo Park and is funded primarily by the BSL and the USGS. Additional funding for the handling and archiving of the EarthScope PBO and SAFOD data is provided through subawards from the respective NSF EarthScope projects.

Doug Neuhauser is the manager of the NCEDC. Stephane Zuzlewski, Rick McKenzie, Nicolas Houlie, Bob Uhrhammer, and Peggy Hellweg of the BSL and David Oppenheimer, Hal Macbeth, and Fred Klein of the USGS Menlo Park contribute to the operation of the NCEDC. Doug Neuhauser, Peggy Hellweg, Stephane Zuzlewski, and Bob Uhrhammer contributed to the preparation of this chapter.

Chapter 10

Data Acquisition and Quality Control

1. Introduction

Stations from most networks operated by the BSL transmit data continuously to the BSL facilities on the UC Berkeley campus for analysis and archive. In this chapter, we describe activities and facilities which crosscut the individual networks described in Chapters 4, 6 and 7, including procedures for data acquisition and quality control, and sensor testing capabilities and procedures. This year the computer and networking facilities used for data acquisition moved from McCone Hall to the University's seismically safe building at 2195 Hearst Ave.

While some of these activities are continuous from year to year, we have identified changes or activities which are specific to 2005-2006.

2. Data Acquisition Facilities

Until 2005-2006, both the BSL staff monitoring routine data acquisition, and the computers and facilities to acquire, process, and archive the data were situated in McCone Hall. There the BSL has facilities designed to provide air conditioning, 100-bit switched network, and reliable power with UPS and generator. During this year, the computers and telemetry equipment associated with data collection and archival were moved to the new campus computer facility in 2195 Hearst Avenue.

2.1 The Move to 2195 Hearst Avenue

After several years of actively working with the campus, the BSL has finally relocated the infrastructure supporting the critical operations of data acquisition, processing, archiving, and data distribution to a more robust facility than McCone Hall. With assistance from the Office of the Vice Chancellor for Research, the BSL has been granted space in 2195 Hearst, a recently completed building on the Oxford Tract. 2195 Hearst was constructed to current seismic codes, and the hardened campus computer facility within was designed with special attention for post-earthquake operations. The computer center contains state-of-the art seismic bracing, UPS power and air conditioning with generator backup, and extensive security and equipment monitoring.

During 2005-2006, the BSL completed the relocation of equipment to the new facilities in 2195 Hearst. This includes all of its data acquisition and real-time earthquake processing computers, as well as the data archive and distribution computers. Following the computer move, all telemetry equipment (5 T1s lines, dedicated leased phone circuit to our paging service, dialin/dialout modems, as well as various radio and VSAT communication equipment) were also transferred to the new location over the course of several months. The final elements were moved in February, 2006. During the transition, the private network used for seismic data acquisition and earthquake processing was temporarily bridged between McCone Hall and 2195 Hearst using an encrypted tunnel across the campus backbone network.

2.2 Power and Air Conditioning in McCone Hall

In the past, mission-critical earthquake monitoring and review processes ran on several computers in McCone Hall. Thus, these computer systems run on circuits with both UPS and generator power. Air conditioning is provided through both "building air" and two additional AC units. Over the years, the BSL has experienced problems with both the McCone generator system and the air conditioning.

With the move of many BSL and NCEDC operations servers to the campus computer center at 2195 Hearst (SRB1), our generator power and air conditioning resources in the BSL server room in 237 McCone have better matched our needs over the past year. The BSL generator and UPS battery system supported servers during one brief power outage this year. The air conditioning systems for room 237 required maintenance and some parts replacement, but no serious problems resulted during these events. The BSL generator is maintained by Physical Plant Capital Services and was run without load twice monthly.

BSL is developing a long range plan with UCB Communications Network Services (CNS), a division of Infor-

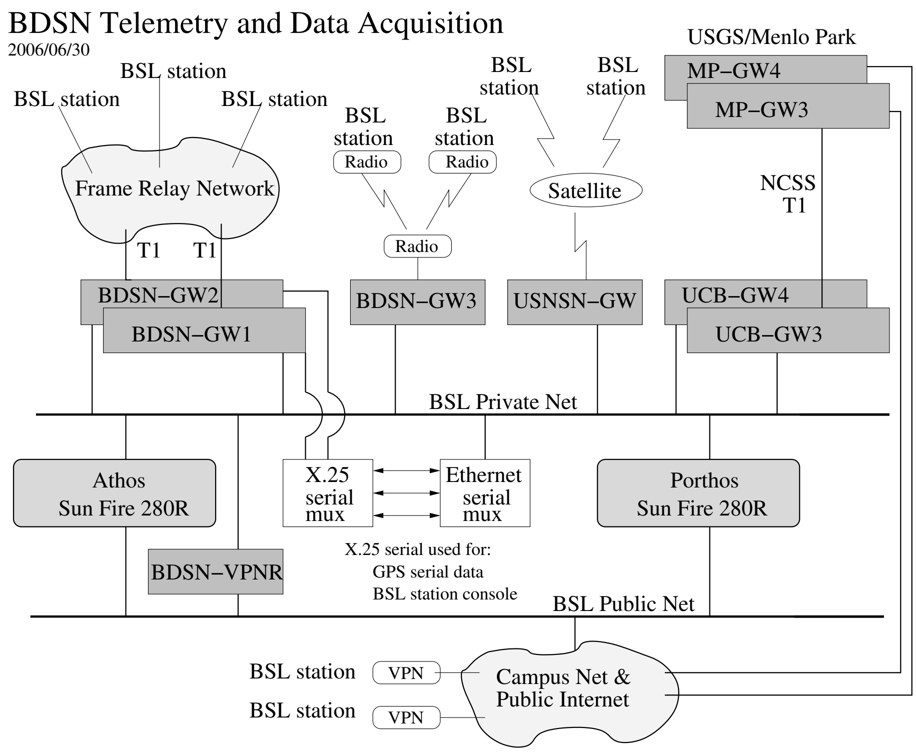

Figure 10.1: Data flow from the BDSN, NHFN, MPBO, HRSN, and BARD network into the BSL central processing facility.

mation Services and Technology, to replace the generator with a larger, 100 kW unit, and to upgrade the UPS battery backup systems. This joint project is designed to provide generator/UPS power for the two CNS-operated network equipment closets serving all of McCone Hall, in addition to providing emergency power to the BSL suite and the BSL engineering lab in room 298 McCone. BSL and CNS will present this plan to the Vice Chancelor Academic Council for approval and assistance with funding for this proposal.

3. Data Acquisition

Central-site data acquisition for the BDSN/NHFN/MPBO is performed by two computer systems located at the BSL (Figure 10.1). These acquisition systems are also used for the Parkfield-Hollister electromagnetic array and for the BARD network. A third system is used primarily as data exchange system with the USNSN and transmits data to the USNSN from HOPS, CMB, SAO, WDC, HUMO, MOD, MCCM, and YBH. Data acquisition for the HRSN follows a more complicated path, as described in Chapter 7.

3.1 Comserv

The BSL uses the `comserv` program for central data acquisition, which was developed by Quanterra. The `comserv` program receives data from a remote Quanterra data logger, and redistributes the data to one or more comserv client programs. The comserv clients used by REDI include `datalog`, which writes the data to disk files for archival purposes, `cdafill`, which writes the data to the shared memory region for REDI analysis, and other programs such as the seismic alarm process, the DAC480 system, and the feed for the Memento Mori Web page (Figure 10.2).

The two computers that perform data acquisition also serve as REDI processing systems. In order to facilitate REDI processing, each system maintains a shared memory region that contains the most recent 30 minutes of data for each channel used by the REDI analysis system. All REDI analysis routines first attempt to use data in the shared memory region, and will only revert to retrieving data from disk files if the requested data is unavailable in the shared memory region.

Each BDSN datalogger that uses frame relay telemetry is configured to enable data transmittion simultaneously to two different computers over two different frame relay T1 circuits to UCB. However, the BSL normally actively enables and uses only one of these data stream from each

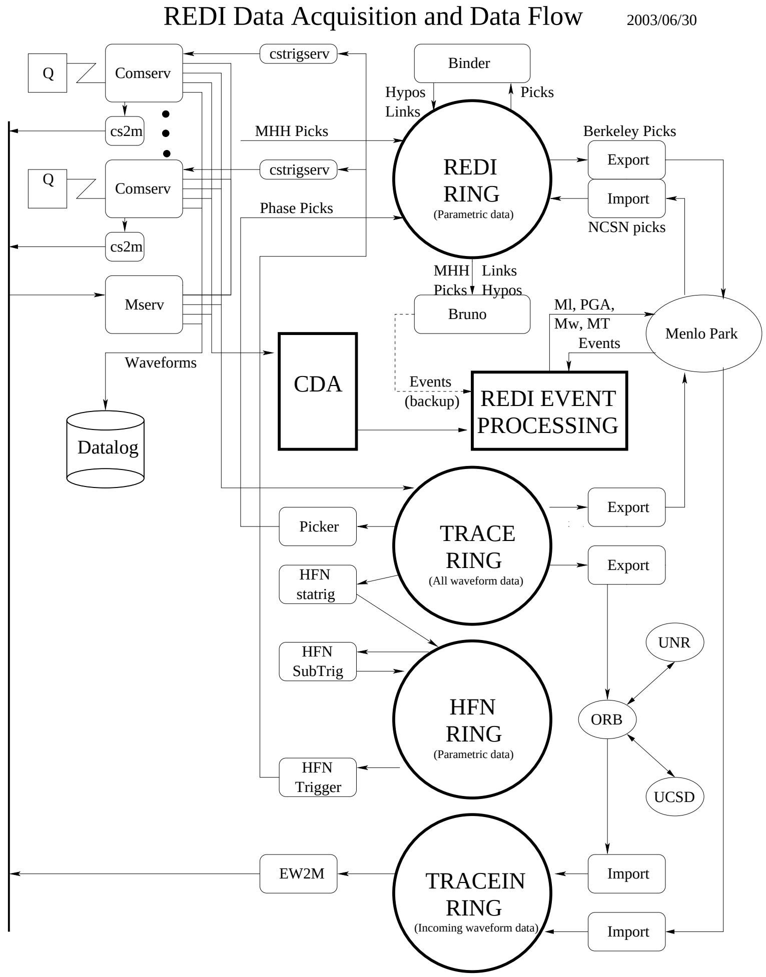

Figure 10.2: Dataflow in the REDI processing environment, showing waveform data coming in from the Quanterra data loggers (Q) into `comserv`. From comserv, data are logged to disk (via `datalog`), distributed to other computers (`mserv`), fed into the CDA for REDI processing, and spooled into a trace ring for export.

station at any given time. The comserv client program `cs2m` receives data from a comserv and multicasts the data over a private ethernet. The program `mcast`, a modified version of Quanterra's `comserv` program, receives the multicast data from `cs2m`, and provides a comserv-like interface to local comserv clients. This allows each REDI system to have a comserv server for every station, and each of the two systems have a complete copy of all waveform data.

We have extended the multicasting approach to handle data received from other networks such as the NCSN and UNR. These data are received by Earthworm data exchange programs, and are then converted to MiniSEED and multicast in the same manner as the BSL data. We use `mserv` on both REDI computers to receive the multicast data, and handle it in an identical fashion to the BSL MiniSEED data.

In 2006, the BSL established a real-time data feed of all BSL waveform between the BSL acquisition systems and the NCEDC computers using the open source Freeorb software. This allows the NCEDC to provide near-real-time access to all BSL waveform data through the NCEDC DART (Data Availabile in Real Time) system.

4. Seismic Noise Analysis

BSL seismic data are routinely monitored for state-of-health. An automated analysis is computed weekly to characterize the seismic noise level recorded by each broadband seismometer. The estimation of the Power Spectral Density (PSD) of the ground motion recorded at a seismic station provides an objective measure of background seismic noise characteristics over a wide range of frequencies. When used routinely, the PSD algorithm also provides an objective measure of seasonal and secular variation in the noise characteristics and aids in the early diagnoses of instrumental problems. A PSD estimation algorithm was developed in the early 1990's at the BSL for characterizing the background seismic noise and as a tool for quality control. As presently implemented, the algorithm sends the results via email to the engineering and some research staff members and generates a bargraph output which compares all the BDSN broadband stations by components. A summary of the results for 2005-2006 is displayed in Figure 4.2. Other PSD plots for the NHFN, HRSN, and MPBO are shown in Figures 6.2, 7.3, respectively.

Four years ago, we expanded our use of the weekly PSD results to monitor trends in the noise level at each station. In addition to the weekly bar graph, additional figures showing the analysis for the current year are produced. These cumulative PSD plots are generated for each station and show the noise level in 5 frequency bands for the broadband channels. These cumulative plots make it easier to spot certain problems, such as failure of a sensor. In addition to the station-based plots, a summary plot for each channel is produced, comparing all stations. These figures are presented as part of a noise analysis of the BDSN on the WWW at `http://www.seismo.berkeley.edu/seismo/bdsn/psd/`.

The PSD algorithm has been documented in previous annual reports.

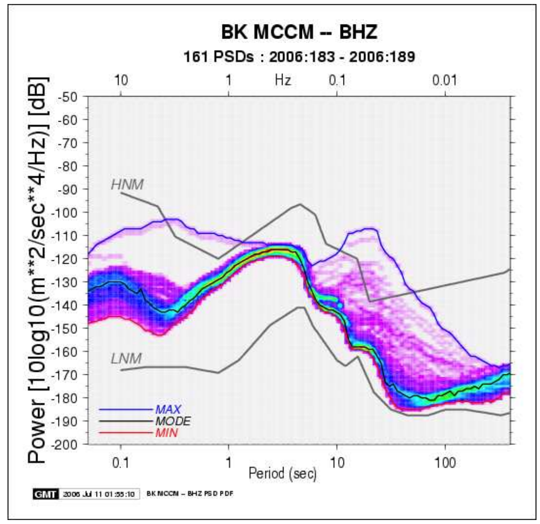

Figure 10.3: Noise analysis results for the week of 07/02/06 at the newest BDSN station MCCM, on the BHZ component. The prominent feature at short periods are produced by waves from the nearby earthquake offshore of Fort Ross, California, (2006/07/06, 20:43 UTC; M_L 3.7). At long periods, the surface waves of a M_w 6.6 earthquake in the Aleutian Islands (2006/07/08, 20:40 UTC) dominate the spectrum.

4.1 PDF Noise Analysis

In addition to the PSD analysis developed by Bob Uhrhammer, the BSL has implemented the Ambient Noise Probability Density Function (PDF) analysis system developed by *McNamara and Buland* (2004). This system does its noise analysis over all the data of a given time period (week or year), including earthquakes, calibration pulses, and cultural noise. This is in contrast to Bob Uhrhammer's PSD analysis, which looks at only the quietest portion of data within a day or week. Pete Lombard of the BSL extended the McNamara code to cover a larger frequency range and support the many different types of sensors employed by the BSL. Besides the originally supported broadband sensors, our PDF analysis now includes surface and bore-hole accelerometers, strain meters, and electric and magnetic field sensors. These enhancements to the PDF code, plus a number of bug fixes, were provided back to the McNamara team for incorporation in their work. The results of the PDF analysis are presented on the web at `http://moho/seismo/PDF/`. Figure 10.3 shows noise analysis results for a typical week. We review these plots as part of our assessment of station health.

5. Sensor Testing Facility

The BSL has set up an instrumentation test facility in the Byerly Seismographic Vault in order to systematically determine and to compare the characteristics of up to eight sensors at a time. The test equipment consists of an eight-channel Quanterra Q4120 high-resolution data logger and a custom interconnect panel that provides isolated power and preamplification, when required, to facilitate the connection and routing of signals from the sensors to the data logger with shielded signal lines. This year a GPS rebroadcaster was installed, so that all data loggers in the Byerly vault will operate on the same time base. Upon acquisition of the 100 samples-per-second (sps) data from the instruments under test, PSD analysis and spectral phase coherency analysis are used to characterize and compare the performance of each sensor. Tilt tests and seismic signals with a sufficient signal level above the background seismic noise are also used to verify the absolute calibration of the sensors. A simple vertical shake table is used to assess the linearity of a seismic sensor.

The sensor testing facility of the BSL is described in detail in the 2001-2002 Annual Report.

6. STS-1 Electronics Development

In February 2006, we embarked on a project to develop new electronics for the STS-1 very broadband seismometer. This is a collaborative project with Tom VanZandt of Metrozet, LLC (Redondo Beach, CA) and is funded by a grant from NSF through the IRIS/GSN program.

The STS-1 VBB (*Wielandt and Streckeisen*, 1982; *Wielandt and Steim*, 1986), widely viewed as the finest VBB sensor in the world, is currently the principal broadband seismometer used by the Incorporated research Institutions for Seismology (IRIS) Global Seismographic Network (GSN), GEOSCOPE, and several other global or regional seismic networks operated by members of the Federation of Digital Broad-Band Seismograph Networks (FDSN). The installed base (approximately 750 sensor axes) represents a very significant international investment for low frequency seismology. The BDSN includes 10 STS-1's in its network. Unfortunately, many of the STS-1 seismometers, which were manufactured and installed 10-20 years ago, are encountering both operational failures and age-related errors (*Ekstrm and Nettles*, 2005). This problem is exacerbated by the fact that sensors are no longer being produced or supported by the original manufacturer, G. Streckeisen AG (Pfungen, Switzerland). The nature and severity of this problem has been discussed widely. For example, a report from a recent broadband seismic sensor workshop (*Ingate et al*, 2004) highlights the unique value of the installed base of STS-1 sensors, as well as the current lack of replacements with equivalent long period performance. In the absence of focused action by the seismological community, the state-of-health of the existing STS-1 instruments will continue to decline. Numerous efforts, both commercial and government-funded, are underway to develop future replacements (*IRIS Workshop*, 2004). Regardless of how one views the potential of these new approaches to delivering a manufacturable, STS-1-equivalent product, given the present funding environment, it is clear that they all would mandate outright replacements of the existing STS-1 sensors.

In collaboration with its commercial partner, Metrozet, LLC (Redondo Beach, CA), the BSL is developing and testing new electronic hardware, and methods for mechanical repair, for the STS-1. The intent of this effort is to develop simple and economical long-term solutions to current and anticipated problems with the existing STS-1 sensors. A primary aim is to develop a fully-tested, modern electronics module that will be a drop-in replacement for the original electronics. This will provide users with a legitimate option for replacing old modules that are no longer functioning. This new electronics design will address environmental packaging problems that have led to operational errors and failures in the existing instruments. This effort will also provide the opportunity to implement a set of electronic improvements that will make the installation and operation of the sensors more efficient.

In the first half of 2006, Metrozet developed the first prototype and reverse engineered electronics for the STS-1, while the BSL engineering staff constructed a test-bed at the Byerly Vault (BKS) and developed the capability to simultaneously test 6-8 STS-1 components. Much time was spent locating spare STS-1's and the associated environmental shields and bringing them back to Berkeley.

7. Acknowledgements

Doug Neuhauser, Bob Uhrhammer, Peggy Hellweg, Pete Lombard, and Rick McKenzie are involved in the data acquisition and quality control of BDSN/NHFN/MBPO data. Development of the sensor test facility and analysis system was a collaborative effort of Bob Uhrhammer, Tom McEvilly, John Friday, and Bill Karavas. IRIS and DTRA provided, in part, funding for and/or incentive to set up and operate the facility and we thank them for their support. Bob Uhrhammer, Peggy Hellweg, Pete Lombard Doug Neuhauser and Barbara Romanowicz contributed to the preparation of this chapter. The STS-1 project is funded by NSF through the IRIS/GSN program.

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Chapter 11

Northern California Earthquake Monitoring

1. Introduction

Routine analysis of the data produced by BSL networks begins as the waveforms are acquired by computers at UC Berkeley, and ranges from automatic processing for earthquake response to analyst review for earthquake catalogs and quality control.

Over the last 12 years, the BSL has invested in the development of the hardware and software necessary for an automated earthquake notification system (*Gee et al.,* 1996; 2003a). The Rapid Earthquake Data Integration (REDI) project is a research program at the BSL for the rapid determination of earthquake parameters with three major objectives: to provide near real-time locations and magnitudes of northern and central California earthquakes, to provide estimates of the rupture characteristics and the distribution of ground shaking following significant earthquakes, and to develop better tools for the rapid assessment of damage and estimation of loss.

In 1996, the BSL and USGS began collaboration on a joint notification system for northern and central California earthquakes. The current system merges the programs in Menlo Park and Berkeley into a single earthquake notification system, combining data from the NCSN and the BDSN. Today, the joint BSL and USGS system forms the Northern California Earthquake Management Center (NCEMC) of the California Integrated Seismic Network (Chapter 5).

With partial support from the USGS, the BSL is currently embarking on the development and assessment of a system to warn of imminent ground shaking in the seconds after an earthquake has initiated but before strong motions begin at sites that may be damaged (Chapter 9.).

2. Northern California Earthquake Management Center

The details of the Northern California processing system and the REDI project have been described in previous annual reports. In this section, we describe how the Northern California Earthquake Management Center fits within the CISN system, detail recent developments, and discuss plans for the future development.

Figure 5.3 in Chapter 5 illustrates the NCEMC as part of the the CISN communications ring. The NCEMC is a distributed center, with elements in Berkeley and in Menlo Park. The 35 mile separation between these two centers is in sharp contrast to the Southern California Management Center, where the USGS Pasadena is located across the street from the Caltech Seismological Laboratory. As described in Chapter 5, the CISN partners are connected by a dedicated T1 communications link, with the capability of falling back to the Internet. In addition to the CISN ring, the BSL and the USGS Menlo Park have a second dedicated communications link to provide bandwidth for shipping waveform data and other information between their processing systems.

Figure 11.1 provides more detail on the current system at the NCEMC. At present, two Earthworm-Earlybird systems in Menlo Park feed two "standard" REDI processing systems at UC Berkeley. One of these systems is the production or paging system; the other is set up as a hot backup. The second system is frequently used to test new software developments before migrating them to the production environment. The Earthworm-Earlybird-REDI systems perform standard detection and location, and estimate M_d, M_L, and M_w, as well as processing ground motion data. The computation of ShakeMaps is also performed on two systems, one in Menlo Park and one in Berkeley, as described below. An additional system performs finite-fault processing and the computation of higher level ShakeMaps.

The dense network and Earthworm-Earlybird processing environment of the NCSN provides rapid and accurate earthquake locations, low magnitude detection thresholds, and first-motion mechanisms for small quakes. The high dynamic range data loggers, digital telemetry, and broadband and strong-motion sensors of the BDSN along with the REDI analysis software provide

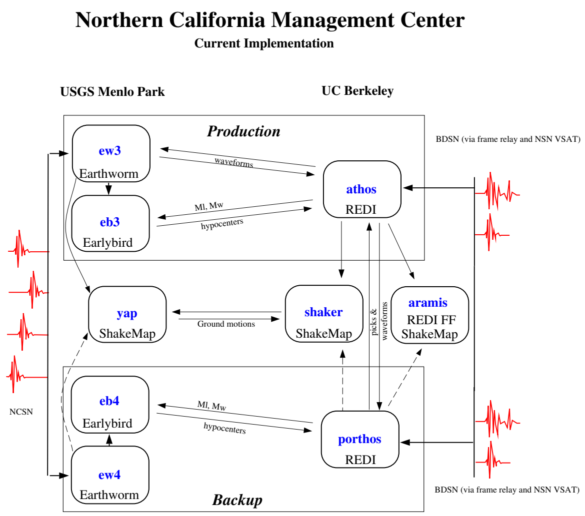

Figure 11.1: Detailed view of the current Northern California processing system, showing the two Earthworm-Earlybird-REDI systems, the two ShakeMap systems, and the finite-fault system.

reliable magnitude determination, moment tensor estimation, peak ground motions, and source rupture characteristics. Robust preliminary hypocenters are available about 25 seconds after the origin time, while preliminary coda magnitudes follow within 2-4 minutes. Estimates of local magnitude are generally available 30-120 seconds later, and other parameters, such as the peak ground acceleration and moment magnitude, follow within 1-4 minutes (Figure 11.2).

Earthquake information from the joint notification system is distributed by pager/cellphone, e-mail, and the WWW. The first two mechanisms "push" the information to recipients, while the current Web interface requires interested parties to actively seek the information. Consequently, paging and, to a lesser extent, e-mail are the preferred methods for emergency response notification. The *recenteqs* site has enjoyed enormous popularity since its introduction and provides a valuable resource for information whose bandwidth exceeds the limits of wireless systems and for access to information which is useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

3. 2005-2006 Activities

3.1 System Development

As part of ongoing efforts to improve the monitoring systems in northern California, the BSL and the USGS Menlo Park made progress in the development of the next generation of the northern California joint notification system or the Northern California Seismic System (NCSS).

Figure 11.1 illustrates the current organization of the two systems. As described above, each Earthworm/Earlybird component is tied to a REDI component and the pair form a single "joint notification system." Although this approach has functioned reasonably well over the last eight years, there are a number of potential problems associated with the separation of critical system elements by ~35 miles of San Francisco Bay.

Recognizing this, we are redesigning the Northern California operations so that identical, complete systems operate independently at the USGS and UC Berkeley. In FY01/02, specifications were established and the details required for design were determined. In the interim, however, much of the development effort focused on statewide CISN activities, and specific plans for the "next generation" Northern California system were put on hold. The enforced wait provided the opportunity for some ideas to mature and the current plans for the NCEMC are somewhat different from those envisioned in 2001.

The current design draws strongly on the experience in Southern California for the development of TriNet (Figure 11.3), with modifications to allow for local differences (such as very different forms of data acquisition and variability in network distribution). In addition, the BSL and the USGS want to minimize use of proprietary software in the system. The TriNet software used three forms of proprietary software: Talerian Smart Sockets (TSS) for inter-module communication via a "publish and subscribe" method, RogueWave software for database communication, and Oracle as the database management system. As part of the development of the Northern California Earthquake Data Center, the USGS and BSL have worked extensively with Oracle databases and extending this to the real-time system is not viewed as a major issue. However, we did take the opportunity to review options for replacing Smart Sockets and RogueWave with Southern California, resulting in joint agreement on replacement packages and shared development effort.

In the last four years, BSL staff, particularly Pete Lombard, have become extremely familiar with portions of the TriNet software. We have continued to adapt the software for Northern California, making adjustments and modifications along the way. For example, Pete Lombard has adapted the TriNet magnitude module to northern California, where it is running on a test system. Pete made a number of suggestions on how to improve the performance of the magnitude module and has worked closely with Caltech and the USGS/Pasadena on modifications.

The BSL and the USGS Menlo Park have developed and tested a design to exchange "reduced amplitude timeseries." One of the important innovations of the TriNet software development is the concept of contin-

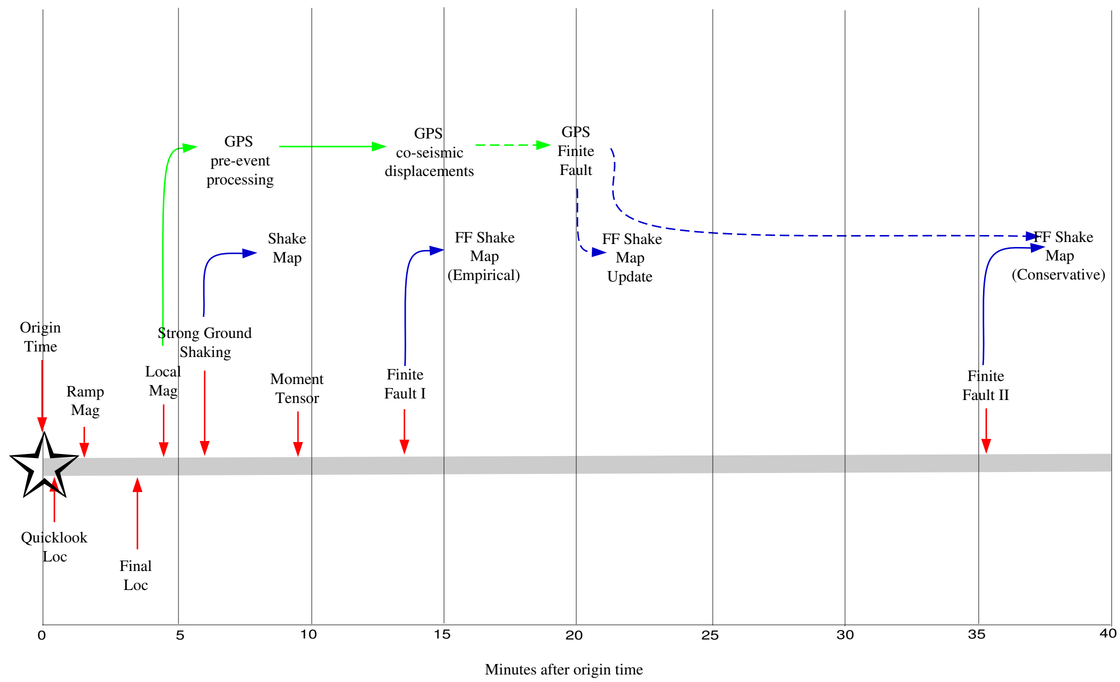

Figure 11.2: Illustration of the current (solid lines) and planned/proposed (dotted lines) development of real-time processing in northern California. The Finite Fault I and II are fully implemented within the REDI system at UC Berkeley and are integrated with ShakeMap. The resulting maps are still being evaluated and are not currently available to the public.

uous processing (*Kanamori et al.*, 1999). Waveform data are constantly processed to produce Wood Anderson synthetic amplitudes and peak ground motions. A program called `rad` produces a reduced timeseries, sampled every 5 secs, and stores it in a memory area called an "Amplitude Data Area" or ADA. Other modules can access the ADA to retrieve amplitudes to calculate magnitude and ShakeMaps as needed. The BSL and the USGS Menlo Park have collaborated to establish the tools for the ADA-based exchange. As part of the software development in northern California, a number of modules have been developed.

During 2005-2006, progress has continued toward the retirement of `CUSP` - the system used by the USGS Menlo Park to time earthquakes. `CUSP` was initially developed in Southern California during the late 1970s - early 1980s and has been used for a number of years in Northern California. However, the `CUSP` system is becoming increasingly outdated.

The NCEMC has implemented a plan to retire `CUSP`, using some components of the Southern California system. The primary responsibility for the necessary programming and development rest on the shoulders of BSL staff. They have implemented the `RequestCardGenerator` (a module that decides which channels to archive, given a particular earthquake), a waveform archiving module, and `iiggle` (the earthquake timing interface). The NCEMC and SCMC collaborated on modifications to `jiggle` for use in Northern California such as the computation of M_d. The test system is operating, and USGS timers have begun to assess `jiggle`.

Also during the past year, Northern and Southern California developers spent a day in Pasadena discussing issues of joint interest.

3.2 M_L and M_w

The REDI system has routinely produced automatic estimates of moment magnitude (M_w) for many years. However, wary of complications caused by the publication of multiple magnitudes, these estimates were not routinely used as the "official" magnitude until after the 05/14/2002 Gilroy earthquake (M_w 4.9, M_L 5.1).

In a past annual report, we discussed the question of when to report M_w. As currently implemented, solutions that meet a minimum quality criterion are automatically reported (a variance reduction of 40% or higher). This criterion appears to work very well and screens out events contaminated by teleseisms. Over the last few years,

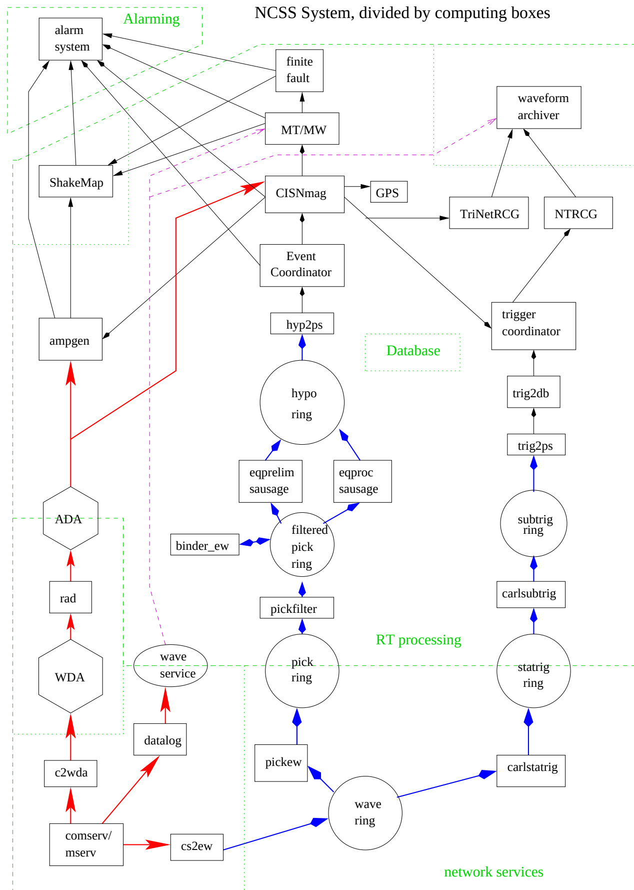

Figure 11.3: Schematic diagram of the planned NCSS system. The design combines elements of the Earthworm, TriNet, and REDI systems

nearly all events over 4.5 have met this criterion, as have a number of events in the M3.5-4.5 range. As part of the effort to establish a statewide magnitude reporting hierarchy, we have looked more closely at the estimates of M_w (*Gee et al.*, 2003b; 2004) and the comparison between M_w and M_L.

Two methods of determining regional moment tensor (RMT) solutions are part of the REDI system - the complete waveform modeling technique (CW) of *Dreger and Romanowicz* (1994) and the surface wave inversion (SW) of *Romanowicz et al.* (1993). In the past year processing for the SW algorithm was discontinued, however CW moment tensors continue to be calculated, reviewed and reported. Comparison between the results of the CW method and other regional moment tensor studies in northern California and the western United States show excellent agreement in the estimate of seismic moment and M_w. Over 128 events, the average difference in M_w is 0.002 magnitude units.

As we transition toward statewide reporting of earthquake information, a comparison of magnitudes calculated for southern and northern becomes important. We have collected a set of events recorded well by digital broadband and and strong motion stations of the Northern California (NC), Berkeley (BK) and Southern California (CI) networks and are assessing the computation of local magnitude for each station.

4. Routine Earthquake Analysis

In fiscal year 2005-2006, more than 30,000 earthquakes were detected and located by the automatic systems in northern California. This compares with over 38,800 in 2004-2005, and 12,000 in 2003-2004. Many of the large number of events in 2004-2005 are aftershocks of the 2004 Parkfield earthquakes. The number of events continues to remain high, because we are now receiving data from a network of seismometers in the Geysers, a region with a high level of small magnitude seismicity. Of the more than 30,000 events, over 170 had preliminary magnitudes greater than 3. Fourteen events had M_L greater than 4. The largest event recorded by the system occurred on 12 May 2006 with M_w4.6. This earthquake near the Geysers, California was actually two events within 70 seconds of each other.

As described in the 2003-2004 Annual Report, the BSL staff are no longer reading BDSN records for local and regional earthquakes (as of March 2004). This decision was in part intended to reduce duplication of effort between Berkeley and Menlo Park.

The BSL continues to focus on the unique contributions that can be made from the broadband network. From July 2005 through June 2006, BSL analysts reviewed nearly 30 earthquakes in northern California and adjoining areas of magnitude 3.5 and higher. Reviewed moment tensor solutions were obtained for 11 events (through 6/30/2006). Figure 11.4 and Table 11.1 display the earthquakes located in the BSL catalog and the moment tensor solutions.

4.1 Seismic Background Noise PSD in Northern and Central California

The density and distribution of broadband seismic stations located in Northern and Central California increased during the past year, with two new BK stations and additional broadband seismic stations installed as the USArray transportable array completes its station coverage in the region. One design goal of the transportable network is to complement the existing BDSN broadband stations and cover the region with an average interstation spacing of ∼70 km. Our motivation for characterizing the seismic background noise PSD level observed at the transportable stations is, in part, that we would like to occupy the best sites after the transportable array moves out of the region, in order to improve the coverage of the BDSN network.

PSD algorithm

We have been characterizing the vertical and horizontal seismic background noise levels observed in Northern and Central California via Power Spectral Density (PSD) analysis of the seismic background signals recorded by the BDSN broadband seismic stations (BK network), NCSN broadband stations (NC network) and by the USArray broadband seismic stations (TA network). Two frequency bands, the 1-5 Hz short-period (SP) band and the 30-60 second long-period (LP) band, are analyzed to characterize the background noise in the seismic bands of interest, particularly for the study of the seismic signals from local and regional seismic events.

The PSD algorithm uses a statistical approach to robustly estimate the background noise PSD. The PSD estimates are reported in dB relative to 1 (m/s2)2/Hz. The input time series is parsed into eight (possibly overlapping) time series and each of the resulting time series are appropriately windowed prior to calculating their PSD estimates. For short time series, less than 1.5 hours in length, the time series are detrended and sine tapered while for longer time series the dominant semi-diurnal gravitational tide signal is also removed to avoid biasing the long-period PSD estimates. The PSD estimates are smoothed and reported at twenty logarithmically spaced intervals per decade in period.

Owing to the statistical nature of the PSD algorithm, the time series processed must contain at least 65,635 (216) contiguous samples. Shorter time series are not processed and a warning is issued. The PSD algorithm can process data with a wide variety of sampling rates (from $<$ 0.01 sps to $>$ 500 sps). A typical usage with broadband data is for the time series to contain one day of continuous LH (1 sps) data (86,400 samples), say. Since the sensor transfer function representation in the SEED data volume for a typical inertial seismometer does not include the static component of the response, the background noise PSD estimates for periods longer than approximately an hour will be biased high; and hence, they will be unreliable.

The PSD code distribution along with examples of its usage are available via the Web at http://seismo.berkeley.edu/algorithms/.

Seismic Background Noise Analysis

We acquired SEED data volumes containing a network day (2006.022) of 1 Hz three- component broadband data from the broadband stations of the NC network, the TA transportable network and from the BK permanent network. This data was used to characterize the seismic background noise in the long period (LP) band between 30-60 seconds. We also acquired SEED data volumes containing two network hours (2006.022.0000-0200) of 40 Hz three- component broadband data from the same stations of all three networks. (day 2006.022.0000-0200). This data was used to characterize the seismic background noise in the short period (SP) band, between 1-5 Hz. This study was done to assess the broadband NC stations and to help identify TA sites that would be good candidates for upgrading to permanent BDSN sites once TA moves away from Northern California.

The vertical-component LP (30-60 second period) seismic background noise PSD is shown in Figure 11.5A and the corresponding horizontal- component noise is shown in Figure 11.5B. The spread between the quietest and noisiest stations on the vertical-component is ∼20 dB. Stations of both the BK and TA are relatively quiet. The spread between the quietest and noisiest stations on the horizontal-components in the LP band is ∼30 dB with a larger percentage of noisy stations. The stations with the lowest noise levels are situated on bedrock or in hard rock

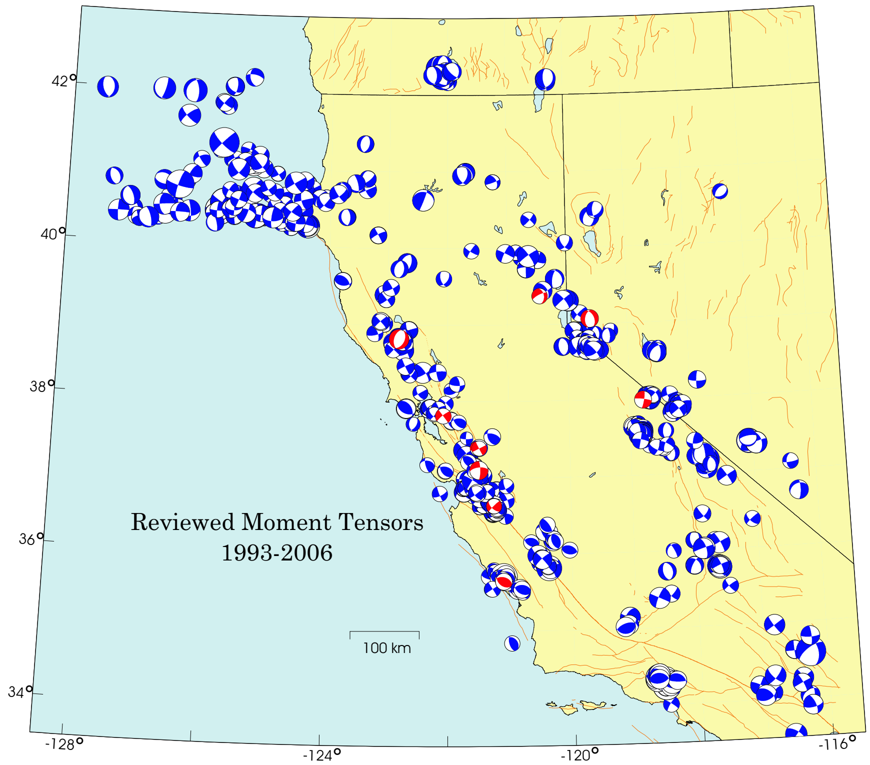

Figure 11.4: Map comparing reviewed moment tensor solutions determined by the BSL in the last 12 years (blue) with those from the fiscal year 2005-2006 (red).

mines and are far from cultural noise sources. Stations with high PSD noise levels on the horizontal components may either be on thick alluvium or have high ambient cultural noise levels.

The vertical-component SP (1-5 Hz) seismic background noise PSD is shown in Figure 11.5C and the corresponding horizontal-component noise is shown in Figure 11.5D. Here the spread between the quietest and noisiest stations on the vertical-component is larger than in the LP band, ~50 dB. The spread between the quietest and noisiest stations on the horizontal-component is likewise ~50 dB. Again, the stations with high horizontal-component PSD noise levels in the SP band are generally either sites with thick alluvial deposits or high ambient cultural noise levels.

Based on this analysis as well as criteria such as ownership, and access to power and telemetry, seven stations have been selected for upgrade to permanent sites within the next 18 months. These are: V04C (RAMR), HAST, O01C and P01C, as well as HATC, HELL and SUTB.

5. Acknowledgements

Peggy Hellweg oversees the REDI system and directs the routine analysis. Peter Lombard and Doug Neuhauser contribute to the development of software. Rick McKenzie, Doug Dreger, David Dolenc, Ayhi Kim, Ved Lekic, Mark Panning, Junkee Rhie, Dennise Templeton, and Akiko Toh contribute to the routine analysis. Peggy Hellweg, Doug Neuhauser and Bob Uhrhammer contributed to the writing of this chapter.

Partial support for the development and maintenance of the REDI system is provided by the USGS.

The facilities of the IRIS Data Management System, and specifically the IRIS Data Management Center, were used by Bob Uhrhammer for access to the TA network (USArray) waveform and metadata required in the noise comparison study.

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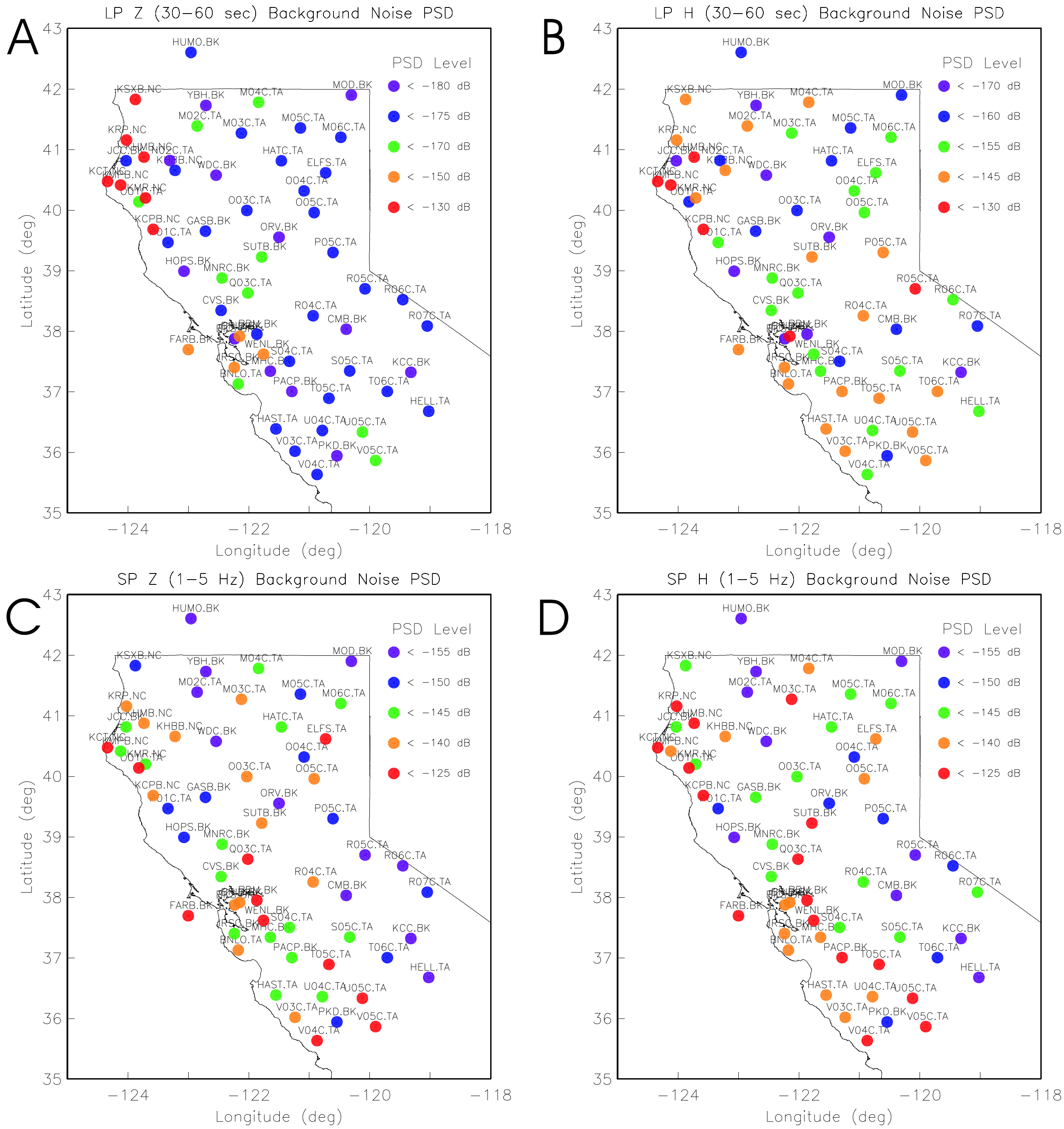

Figure 11.5: Results of seismic background noise PSD analysis for BK, broadband NC and TA network stations in Northern and Central California. A and B show results for the vertical and horizontal-components in the long period (LP) band (30-60 second), respectively. C and D show corresponding results for the short period (SP) band (1-5 Hz).

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Location	Date	UTC Time	Lat.	Lon.	MT Depth	M_l	M_w	Str.	Dip	Rake	Mo
Pinnacles	08/13/05	19:13:20.20	36.634	-121.25	8	3.7	3.7	226	85	29	3.17E+21
SE Carson City, NV	09/16/05	15:09:44.44	39.066	-119.624	11	4.2	4.2	336	48	-114	2.26E+22
San Simeon	10/02/05	13:48:09.9	35.648	-121.104	5	4.4	4	287	47	76	1.27E+22
Geysers	11/17/05	08:55:05.5	38.814	-122.782	5	3.9	3.9	42	83	-7	7.04E+21
Alum Rock	01/15/06	10:42:07.7	37.388	-121.514	8	3.6	3.6	75	87	-26	2.18E+21
Morgan Hill	01/25/06	15:29:57.57	37.389	-121.485	14	3.7	3.6	153	88	180	2.99E+21
Bodie	02/16/06	17:47:59.59	37.985	-118.775	11	4.3	4.1	279	82	-9	1.52E+22
Morgan Hill	03/21/06	21:41:42.42	37.812	-122.074	14	3.8	3.8	323	90	-170	5.15E+21
Geysers	05/12/06	10:37:29.29	38.814	-122.814	5	4.4	4.6	195	48	-97	1.13E+23
Truckee	05/29/06	10:38:44.44	39.371	-120.455	14	4	3.7	244	74	-49	3.97E+21
San Martin	06/15/06	12:24:51.51	37.102	-121.492	5	4.7	4.4	360	78	-152	4.18E+22

Table 11.1: Moment tensor solutions for significant events from July 1, 2005 through June 30, 2006 using a complete waveform fitting inversion. Epicentral information from the UC Berkeley/USGS Northern California Earthquake Management Center. Moment is in dyne-cm and depth is in km.

Chapter 12

Outreach and Educational Activities

1. Introduction

The BSL is involved in a variety of outreach activities ranging from lectures to lab tours and educational displays. Commemorating the centennial of the 1906 San Francisco earthquake on April 18 provided the focus for many of them during this year. The BSL's earthquake information tape (510-642-2160) and an extensive set of web pages continue to provide basic information on earthquakes and seismic hazards for northern and central California.

2. Highlights of 2005-2006

Many of the BSL's outreach activities in this year were related to the centennial of the 1906 earthquake. In addition to organizing a special lecture series with Stanford University, the BSL contributed to museum exhibits and brochures. It also co-hosted the 2006 Annual Meeting of the Seismological Society of America, which took place within the framework of the *100th Anniversary Earthquake Conference Commemorating the 1906 San Francisco Earthquake*. Many of the BSL tours, lectures, school visits and media interactions which occurred during the course of the year were related to or inspired by the earthquake's anniversary.

2.1 2006 SSA

In November of 1906, after the San Francisco earthquake, the Seismological Society of America (SSA) was founded here to study earthquakes and promote public safety. Thus, it was fitting that the meeting in the year of the centennials of the earthquake and the society's founding take place in San Francisco. Together with the USGS, the BSL co-hosted the society's annual meeting, from 4/18/2006 - 4/22/2006 in San Francisco's Moscone Center. The meeting was co-convened with the Earthquake Engineering Research Institute, and California Governor's Office of Emergency Services as the *100th Anniversary Earthquake Conference*, and more than 3500 particpants from all over the world attended. While offering a venue for interactions between the three professional groups who work with earthquakes, the seismologists, engineers and emergency managers, one goal of the meeting was to engender more communications between the professionals and policy makers on "Managing Risk in Earthquake Country". Thus, it was important that politicians were represented by such notables as Diane Feinstein, Arnold Schwarzenegger and Gavin Newsome. The 1906 earthquake, naturally a primary topic, was highlighted in plenary sessions each day, on "The Day of the Quake", "Learning from the Past", "Assessing the Present" and "Preparing for the Future". These sessions focused on what has been accomplished during the past century in terms of best practices and research results in science, engineering, and emergency management, as well as providing a view toward the future. The meeting also featured a *Gala Reception and Banquet* in honor of the society's centennial.

In the months leading up to the anniversary conference, first Lind Gee and later Peggy Hellweg represented the BSL on the Steering Committee participating in monthly conference calls and planning meetings, as well as in many of the other committees necessary to ensure the meeting ran well. Both contributed to the development of the overall meeting program, coordinating presentations of seismologists, engineers and emergency managers. They were also members of the SSA's program committee, along with Doug Dreger and USGS representatives.

2.2 1906 Lectures, Exhibits and Presentations

Members of the 1906 UC Berkeley community both felt the 1906 earthquake and were engaged in the response. University cadets were sent to support the police and troops in San Francisco, refugees were housed and fed on campus, and Professor Andrew Lawson chaired the State Earthquake Investigation Commission, which produced the first definitive earthquake report.

Together with Stanford University, the BSL organized the *Quake '06 Centennial Lecture Series*, a series of 8 public lectures, most held on both campuses. In the Fall of 2005, three lecturers introduced their audiences a historical view of what happened in 1906. The presentations in January - March 2006 covered a modern view of earth science, earthquake engineering, preparedness and disaster response.

Following an exhibit of 1906-related documents and pictures from the Bancroft Library's collection in the Brown Gallery of the Doe Library, the BSL and other campus units presented material on *1906: The Great Quake - Legacy of a Disaster*. This exhibit explored UC Berkeley's participation in advancing society's understanding of the seismological, engineering, social, and political implications of seismic events, and highlighted ongoing efforts to prepare the campus to withstand another big quake. The BSL's cases displayed the seismic hazard in the Bay Area as represented by the faults and seismicity, as well as both historical and modern instruments used to record earthquakes and some of the scientific contributions made by Berkeley professors to understanding them.

The BSL also contributed to the Oakland Museum's exhibit *Aftershock! Voices from the 1906 Earthquake and Fire*. In addition to the loan of a Wood-Anderson seismometer, we developed a sequence of webpages including maps of current earthquake activity in the Bay Area, California and the world. It also featured a very popular "Make Your Own Seismogram" demonstration.

The earthquake centennial also engendered more artistic efforts, to which the BSL contributed. Following several years the Momento Mori `http://memento.ieor.berkeley.edu/memento.html` has been an alternative way of viewing seismic data from BSL's station BKS in the Berkeley Hills. In honor of the 1906 centennial, Ken Goldberg and the San Francisco Ballet produced Ballet Mori. Ballerina Muriel Maffre danced to music created in realtime from the seismic data. The Pacific Film Archive prepared a film festival entitled *65 Seconds that Shook the Earth: Commemorating the 1906 San Francisco Earthquake*. Peggy Hellweg commented on the science in the final film of the series, *The Night the World Exploded*.

2.3 Putting Down Roots

One of the major activities associated with the 1906 Centennial is the publication of a booklet on earthquake preparedness. The last publication of this type in the Bay Area followed the 1989 Loma Prieta earthquake. *Putting Down Roots in Earthquake Country* is a collaborative effort among the American Red Cross, Association of Bay Area Governments, California Earthquake Authority, California Geological Survey, California Office of Emergency Services, Earthquake Engineering Research Center, San Francisco Office of Emergency Services and Homeland Security, Southern California Earthquake Center, Structural Engineers Association of Northern California, UC Berkeley, US Department of Homeland Security (FEMA), and the USGS. Publication of the booklet is expected in later this year, with additional releases scheduled for 2006. (*Putting Down Roots* was released in September and is available on the Web at `http://pubs.usgs.gov/gip/2005/15/`.)

3. On-Going Activities

3.1 Tours and Presentations

As every year, tours and presentations formed an important part of BSL's public relations activities. Each month several groups, ranging from middle-school students to scientists and engineers tour our laboratory under the guidance of a graduate student or a member of the staff.

The BSL hosted several special groups during 2005-2006. The geology class from Bishop Stopford School in England for made its annual stop for a tour of the laboratory and the Hayward Fault. Several classes at different grade levels received tours. In addition, BSL graduate students visited local elementary, middle and high schools to talk about earthquakes and how we measure them. In addition to the tours, Drs. Romanowicz, Allen, Dreger, Hellweg, and Uhrhammer presented talks on earthquakes and related phenomena to public groups and the media.

3.2 Open House

The BSL participated in *CalDay* this year on the weekend after the 1906 centennial anniversary. The attendance for the open house was good - visitors showed up before we opened the doors! The visitors learned about UC Berkeley's role in earthquake monitoring, watched a streaming feed of earthquake data, jumped up and down to "make a quake" played with the earthquake machine, made P and S-waves with springs, learned about earthquake preparedness, and were given sample seismograms. In addition, visitors had the opportunity to view several of the lectures from the *Quake '06* series.

3.3 Educational Displays

The BSL continues to make REDI earthquake data available to certain schools, universities, colleges, and museums for educational displays. Participating organizations receive a REDI pager and the Qpager software to display the earthquake information. The Qpager program maps the previous seven days of seismicity, with earthquakes shown as a dot. The size of the dot indicates the magnitude of the event, while the color of the dot indicates its age. These educational displays have been installed at UC Berkeley (McCone Hall, Earthquake Engineering Research Center, LHS), California Academy of Sciences, CSU Fresno, CSU Northridge, CSU Sacramento, Caltech, College of the Redwoods, Fresno City College, Humboldt State University, San Diego State

University, Sonoma State University, Stanford University (Blume Engineering Center, Department of Geophysics), UC Davis, UC Santa Cruz, UC San Diego, and USC. For the past three years, middle schools of the San Francisco Unified School District have participated in the program.

In addition to the seismicity displays, the BSL provides local waveform feeds for helicorders at visitor centers associated with BDSN stations (CMB and MHC). Organizations such as LHS, KRON, and KPIX receive feeds from BKS via dedicated phone lines for display, while the USGS Menlo Park uses data from CMB for display in the lobby of the seismology building. The BSL has also loaned a seismometer and helicorder display to the San Leandro Unified School District for their use in science classes.

3.4 WWW

We continue to maintain and update our presence on the WWW. The webpages are intended to provide a source of earthquake information for the public. They also present information about the networks we operate, including station profiles. This benefits the research community as well. The BSL web pages publicize seminar schedules, advertize courses, and describe our research, as well as our operations. They offer updates on recent earthquake activity, details on Bay Area seismicity and hazards, and links to other earthquake and earth science servers. We also use the WWW server to distribute information internally among BSL personnel, with such details as the computing and operational resources, rosters, and schedules for various purposes.

3.5 Earthquake Research Affiliates Program

The UC Berkeley Earthquake Research Affiliates (ERA) Program is an outreach project of the BSL, the Department of Earth and Planetary Science, and the Earthquake Engineering Research Center. The purpose is to promote the support of earthquake research while involving corporations and governmental agencies in academic investigation and education activities such as conferences and field trips. The ERA program provides an interface between the academic investigation and practical application of earthquake studies.

4. Acknowledgements

Peggy Hellweg oversees the outreach activities at the BSL. Barbara Romanowicz, Bob Uhrhammer, Rick McKenzie, and many other faculty, staff, and students at the BSL contribute to the outreach activities. Peggy Hellweg contributed to the preparation of this chapter.

Chapter 13

Glossary of Common Acronyms

Table 13.1: Standard abbreviations used in this report.

Acronym	Definition
AGU	American Geophysical Union
ANSS	Advanced National Seismic System
BARD	Bay Area Regional Deformation
BDSN	Berkeley Digital Seismic Network
BSL	Berkeley Seismological Laboratory
BSS	Berkeley Seismographic Station
CISN	California Integrated Seismic Network
CGS	California Geological Survey
CLC	Campus Laboratory Collaboration
CNSS	Council of the National Seismic System
CSRC	California Spatial Reference Center
DART	Data Available in Real Time
DRC	Disaster Resistent California
EM	Electromagnetic
EPRI	Electric Power Research Institute
EERI	Earthquake Engineering Research Institute
FBA	Force Balance Accelerometer
FEMA	Federal Emergency Management Agency
FIR	Finite Impulse Response
FRAD	Frame Relay Access Device
GPS	Global Positioning System
GSAC	GPS Seamless Archive Center
HFN	Hayward Fault Network
HRSN	High Resolution Seismic Network
IGS	International Geodetic Service
IMS	International Monitoring System
InSAR	Interferometric Synthetic Aperture Radar
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Center
ISTAT	Integrating Science, Teaching, and Technology
JPL	Jet Propulsion Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MBARI	Monterey Bay Aquarium Research Institute
MHH	Murdock, Hutt, and Halbert
MOA	Memorandum of Agreement

continued on next page

Table 13.1: *continued*

Acronym	Definition
MOBB	Monterey Ocean Bottom Broadband observatory
MOISE	Monterey Bay Ocean Bottom International Seismic Experiment
MPBO	Mini-Plate Boundary Observatory
MRI	Major Research Initiative
MRE	Major Research Equipment
MT	Magnetotelluric
NCEDC	Northern California Earthquake Data Center
NCEMC	Northern California Earthquake Management Center
NCSN	Northern California Seismic Network
NCSS	Northern California Seismic System
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NHFN	Northern Hayward Fault Network
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NSMP	National Strong Motion Program
NSF	National Science Foundation
NSN	National Seismic Network
OES	California Governer's Office of Emergency Services
ORU	Organized Research Unit
PBO	Plate Boundary Observatory
PEER	Pacific Earthquake Engineering Center
PH	Pilot Hole
PMG	CISN Program Management Group
PPE	Parkfield Prediction Experiment
PREM	Preliminary Reference Earth Model
PSD	Power Spectral Density
QDDS	Quake Data Distribution System
REDI	Rapid Earthquake Data Integration
SAF	San Andreas Fault
SAFOD	San Andreas Fault Observatory at Depth
SAR	Synthetic Aperture Radar
SCEC	Southern California Earthquake Center
SCEDC	Southern California Earthquake Data Center
SCIGN	Southern California Integrated GPS Network
SCMC	Southern California Management Center
SCSN	Southern California Seismic Network
SEED	Standard for the Exchange of Earthquake Data
SEM	Spectral Element Method
SHFN	Southern Hayward Fault Network
SIO	Scripps Institutions of Oceanography
SNCL	Station Network Channel Location
SSA	Seismological Society of America
STP	Seismogram Transfer Program
UCB	University of California at Berkeley
UNAVCO	University NAVSTAR Consortium
UNR	University of Nevada, Reno
UrEDAS	Urgent Earthquake Detection and Alarm System
USGS	United States Geological Survey