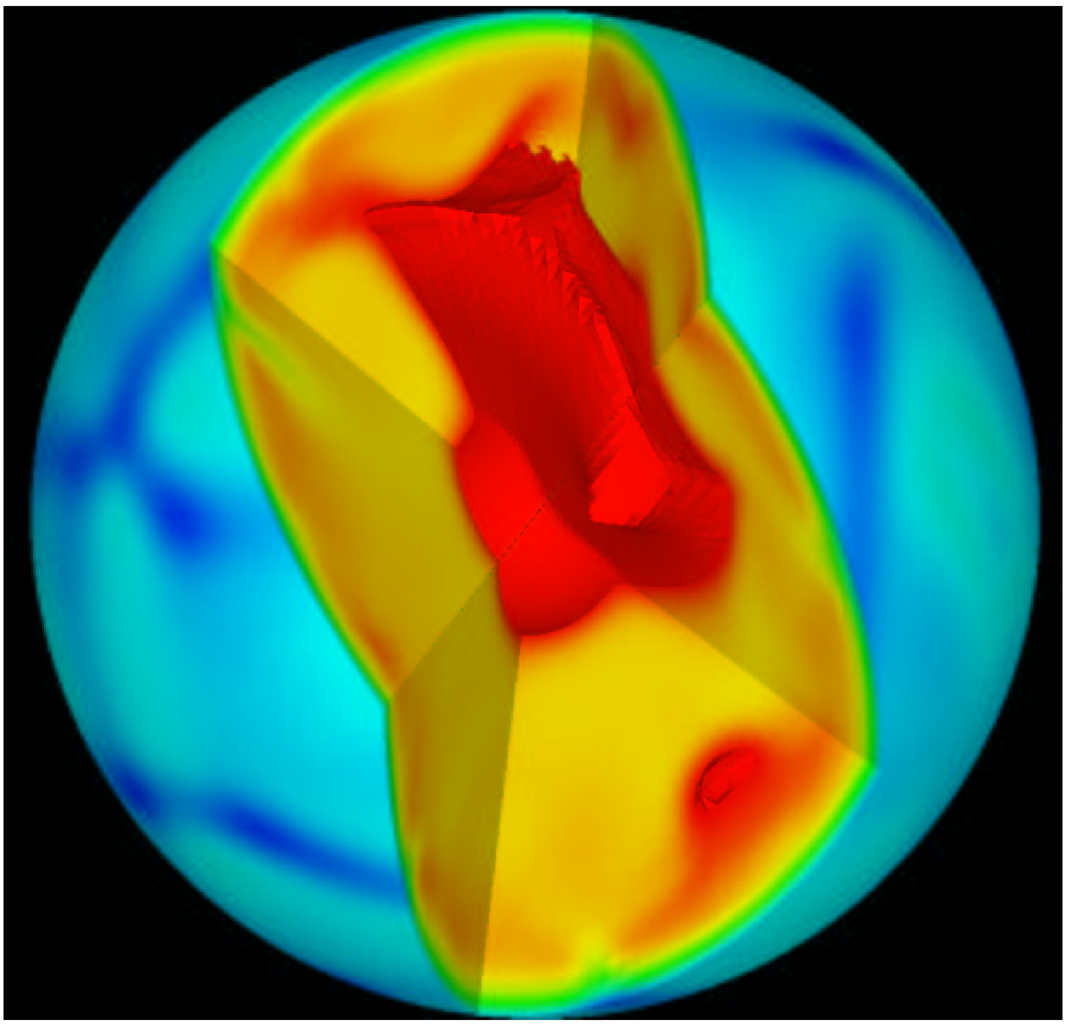
Berkeley Seismological Laboratory



Annual Report July 2002 - June 2003

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Introduction

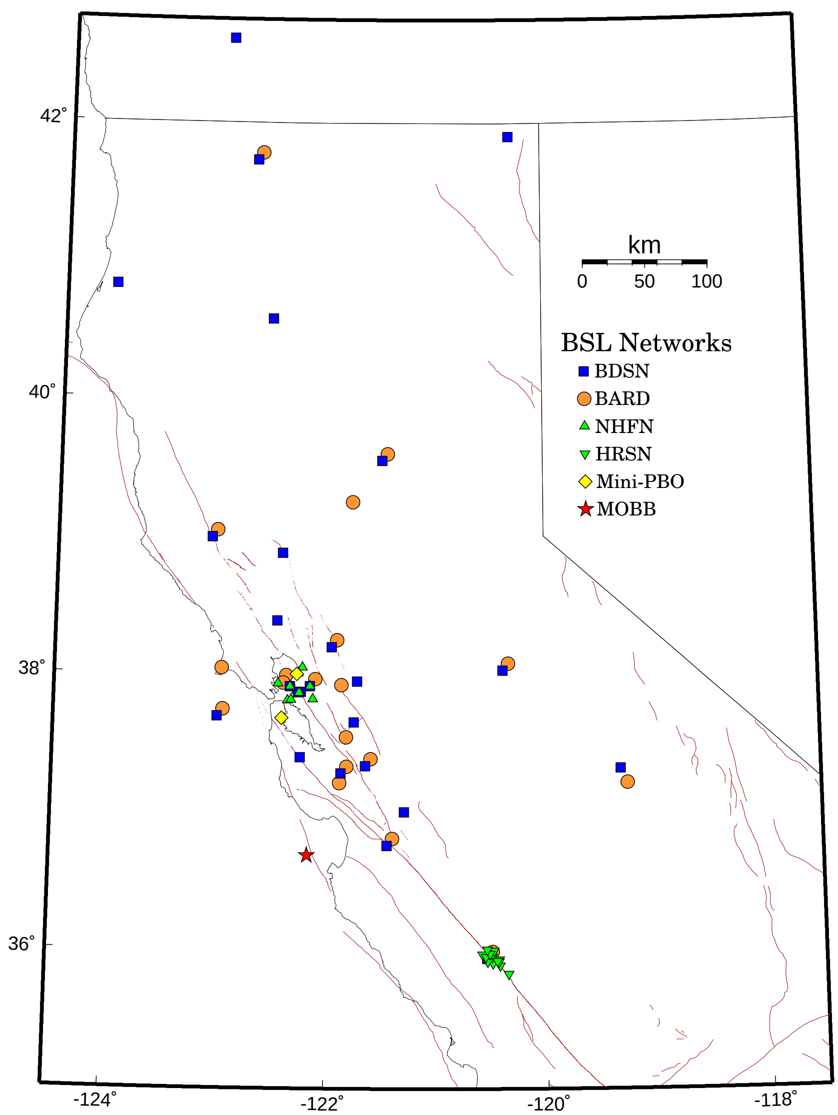

Figure 1: Map illustrating the distribution of stations in the BDSN, NHFN, HRSN, BARD, and Mini-PBO networks in northern and central California. A star indicates the location of the MOBB deployment.

Chapter 1

Director's Report

1. Background and Facilities

The Berkeley Seismological Laboratory (BSL), formerly the Berkeley Seismographic Station (BSS), is the oldest Organized Research Unit (ORU) on the U. C. Berkeley campus. Its mission is unique in that, in addition to research and education in seismology and earthquake-related science, it is responsible for providing timely information on earthquakes (particularly those that occur in northern and central California) to the UC Berkeley constituency, the general public, and various local and state government and private organizations. The BSL is therefore both a research center and a facility/data resource, which sets it apart from most other ORUs. A major component of our activities is focused on developing and maintaining several regional observational networks, and participating, along with other agencies, in various aspects of the collection, analysis, archival and distribution of data pertaining to earthquakes, while maintaining a vigorous research program on earthquake processes and Earth structure. In addition, the BSL staff spends considerable time with public relations activities, including tours, talks to public groups, responding to public enquiries about earthquakes and, more recently, World-Wide-Web presence (`http://www.seismo.berkeley.edu/seismo/`).

U.C. Berkeley installed the first seismograph in the Western Hemisphere at Mount Hamilton (MHC) in 1887. Since then, it has played a leading role in the operation of state-of-the-art seismic instruments and in the development of advanced methods for seismic data analysis and interpretation. Notably, the installation, starting in 1927, of Wood-Anderson seismographs at 4 locations in northern California (BKS, ARC, MIN and MHC) allowed the accurate determination of local earthquake magnitude (M_L) from which a unique historical catalog of regional earthquakes has been maintained to this day, providing crucial input to earthquake probabilities studies.

Over the years, the BSS continued to keep apace of technological improvements. The first centrally telemetered network using phone lines in an active seismic region was installed by BSS in 1960. The BSS was the first institution in California to operate a 3-component "broadband" system (1963). Notably, the BSS played a major role in the early characterization of earthquake sources using "moment tensors" and source-time functions, and made important contributions to the early definitions of detection/discrimination of underground nuclear tests and to earthquake hazards work, jointly with UCB Engineering. Starting in 1986, the BSS acquired 4 state-of-the-art broadband instruments (STS-1), while simultaneously developing PC-based digital telemetry, albeit with limited resources. As the telecommunication and computer technology made rapid progress, in parallel with broadband instrument development, paper record reading could be completely abandoned in favor of largely automated digital data analysis.

The current modern facilities of BSL have been progressively built over the last 13 years, initiated by significant "upgrade" funding from U.C. Berkeley in 1991-1995. The BSL currently operates and acquires data, continuously and in real-time, from over 60 regional observatories, housing a combination of broadband and strong motion seismic instrumentation installed in vaults, borehole seismic instrumentation, permanent GPS stations of the BARD network, and electromagnetic instrumentation. The seismic data are fed into the BSL real-time processing and analysis system and are used in conjunction with data from the USGS NCSN network in the joint earthquake notification program for northern California, started in 1996. This program capitalizes on the complementary capabilities of the networks operated by each institution to provide rapid and reliable information on the location, size and other relevant source parameters of regional earthquakes. In recent years, a major emphasis in BSL instrumentation has been in densifying the state-of-the-art seismic and geodetic networks, while a major on-going emphasis in research has been the development of robust methods for quasi-real time automatic determination of earthquake source parameters and predicted strong ground motion, using a sparse network combining broadband and strong motion seismic sensors, as well as permanent geodetic GPS receivers.

The backbone of the BSL operations is a regional network of 25+ digital broadband and strong motion seismic stations, the Berkeley Digital Seismic Network (BDSN), with continuous telemetry to UC Berkeley. This network provides the basic regional data for the real-time estimation of location, size and rupture parameters for earthquakes of M 3 and larger in central and northern California, within our Rapid Earthquake Data Integration (REDI) program and is the Berkeley contribution to the California Integrated Seismic Network (CISN). It also provides a fundamental database for the investigation of three-dimensional crustal structure and its effects on regional seismic wave propagation, ultimately crucial for estimating ground shaking for future earthquakes. Most stations also record auxiliary temperature/pressure channels, valuable in particular for background noise quality control. Complementing this network is a 25 station "high-resolution" network of borehole seismic sensors located along the Hayward Fault (HFN) and under the Bay Area bridges, operated jointly with the USGS/Menlo Park and linked to the Bridge Safety Project of the California Department of Transportation (Caltrans). The latter has facilitated the installation of sensor packages at 15 bedrock boreholes along 5 east-bay bridges in collaboration with LLNL. A major science goal of this network is to collect high signal-to-noise data for micro-earthquakes along the Hayward Fault to gain insight into the physics that govern fault rupture and its nucleation. The BSL is also involved in the operation and maintenance of the 13 element Parkfield borehole seismic array (HRSN), which is yielding enlightening results on quasi-periodic behavior of micro-earthquake clusters and important new constraints on earthquake scaling laws and is currently playing an important role in the characterization of the site for the future San Andreas Fault Observatory at Depth (SAFOD). Since April 2002, the BSL is also involved in the operation of a permanent broadband ocean bottom station, MOBB, in collaboration with MBARI (Monterey Bay Aquarium Research Institute).

In addition to the seismic networks, the BSL is involved in data archival and distribution for the permanent geodetic BARD (Bay Area Regional Deformation) Network as well as the operation and maintenance, and data processing of 22 out of its 70+ sites. Whenever possible, BARD sites are collocated with BDSN sites in order to minimize telemetry costs. In particular, the development of analysis methods combining the seismic and geodetic data for the rapid estimation of source parameters of significant earthquakes has been one focus of BSL research.

Finally, two of the BDSN stations (PKD, SAO) also share data acquisition and telemetry with 5-component electromagnetic sensors installed with the goal of investigating the possibility of detection of tectonic signals.

Archival and distribution of data from these and other regional networks is performed at the Northern California Earthquake Data Center (NCEDC), operated at the BSL in collaboration with USGS/Menlo Park. The data reside on a mass-storage device (2.5+ Terabyte capacity), and are accessible "on-line" over the Internet (`http://www.quake.geo.berkeley.edu`). Among others, data from the USGS Northern California Seismic Network (NCSN), are archived and distributed through the NCEDC. The NCEDC also maintains, archives and distributes the ANSS/CNSS earthquake catalog.

Core University funding to our ORU has suffered from permanent budget cuts to research programs from the State of California, and currently provides salary support for 2 field engineers, one computer expert, 2 data analysts, 1 staff scientist and 2 administrative staff. This supports a diminishing portion of the operations of the BDSN and provides seed funding for our other activities. All other programs are supported through extramural grants primarily from the USGS and NSF, and in the past two years, the Governor's Office of Emergency Services (OES). We acknowledge valuable recent contributions from other sources such as Caltrans, the CLC program, PEER, as well as our Earthquake Research Affiliates.

2. Highlights of 2002-2003

2.1 Infrastructure and Earthquake Notification

In 2002-2003, the BSL has continued its involvement in several major projects, including the CISN, and the installation and operation of *Mini-PBO* instrumentation. We have also taken initial steps in preparation of our involvement in the deployment in California of the *BigFoot* component of USArray/Earthscope.

We are entering the 3rd year of our participation in the efforts of the CISN, for which we received support in 2002-2003 from the State of California through the Office of Emergency Services (OES) (Chapter 2).

The main goal of the CISN is to ensure a more uniform system for earthquake monitoring and reporting in California. The highest priority, from the point of view of emergency responders in California, is to improve the robustness of statewide real-time notification and to achieve a uniform interface across the State to the California OES and other emergency responders. This represents a major challenge, as the CISN started as a heterogeneous collection of networks with disparate instrumentation, software systems and culture. Therefore, in the past year, the emphasis has been on software development for seamless data exchange between institutions, the establishment of redundant links to data sources, as well as the construction of a single interface to access the different products, such as earthquake locations, magnitudes and, most importantly "ShakeMaps".

Another goal of the CISN program is to improve the seismic infrastructure in northern California. Because funding is limited, this goal is currently pursued at a slower pace. Nevertheless, two new broadband/strong motion stations have been installed in 2002-2003, and three additional sites have been selected and permitted. They are currently at different stages of completion. The CISN has held its first Northern California outreach workshop on "ShakeMaps" in January 2003, with BSL participation, and has been actively engaged in working with its Advisory Committee towards meeting the needs of the users, among which Caltrans as well as utilities companies.

BSL staff spend considerable efforts in organizational activities for CISN, notably by participating in the CISN Project Management Group (Gee), which includes weekly 2 hour phone conferences, and the Standards Committee (Neuhauser-chair, Gee, Lombard), which strives to define and coordinate software development tasks. Romanowicz and Gee serve on the CISN Steering Committee, which was chaired by Romanowicz in 2001. The CISN also represents California as a designated region of ANSS (Advanced National Seismic System) and the BSL is actively involved in planning activities for the ANSS.

This past year has seen progress in the installation efforts of the *Mini-PBO* project (Chapter 8), a project supported partly by a grant from the NSF/MRI program, in collaboration with CIW, UCSD and USGS/Menlo Park, with matching from participating institutions (including UCB) as well as Caltrans (`http://www.seismo.berkeley.edu/seismo/bdsn/mpbo_overview.html`). This project's focus is the installation of a network of multi-parameter stations in the San Francisco Bay Area to monitor the evolution of tectonic strain in time and space - a pilot project for the Plate Boundary Observatory (PBO) component of Earthscope (a national infrastructure program funded by NSF within its Major Research Equipment program). *Mini-PBO* instrumentation comprises 3 component borehole strainmeters and seismometers, GPS receivers and auxiliary sensors (such as pore pressure, temperature, and tilt). The data are telemetered to UC Berkeley and distributed through the NCEDC. Five holes have now been drilled and instrumented with considerable involvement of BSL staff (Murray, Basset, W. Johnson, Karavas, Friday, Rapkin, Thomas). The initial goal of 10 stations has been reduced to 6 due to budgetary constraints and delays related to considerable difficulties and cost-overruns in drilling. We are still hoping that the 6th and last hole will be drilled with Caltrans's help, as a "hole of opportunity", in 03-04. Meanwhile, all existing 5 stations now have borehole strainmeters and seismometers, as well as tiltmeters. Two sites are completed, while the remaining three are in the final stages of the installation of GPS receivers, Quanterra data loggers and/or power and communications systems.

The MOBB (Monterey Ocean bottom Broad Band observatory) is a collaborative project between the BSL and MBARI and builds upon the experience gained in 1997 through the MOISE project, which involved the temporary deployment of a broadband ocean bottom system in Monterey Bay. MOBB is now a permanent installation and comprises a broadband seismic package (Guralp CMG-1), a battery and recording package, as well as auxiliary sensors: a current-meter and a DPG (differential Pressure Gauge). The system was assembled and tested at BSL in early 2002, and successfully deployed in April 2002 (Chapter 3). In particular, extensive testing and seismometer insulation procedures, which were developed at Byerly Vault on the UCB campus prior to MOBB deployment (Chapter 9) have now been applied to three similar systems destined for the KECK project (Juan de Fuca plate), in collaboration with University of Washington at Seattle. There have been 4 dives in 2002-2003 to recover and exchange battery packages and recording systems from the seafloor. Software problems have unfortunately led to the loss of much data during the first part of 2003. We will know after the next dive, scheduled for 09/15/03, whether these problems have definitely been fixed.

In the past year, the BSL has continued to be involved in the coordination of site characterization for the SAFOD drilling project (another component of Earthscope) in the Parkfield area (Chapter 5). A new central data acquisition system with near real time transmission to Berkeley of event data and waveform samples allows routine checks of quality of operation, and more timely response to failures and sources of noise. The resulting dataset is of primary importance for monitoring the evolution of microseismicity, particularly in the SAFOD drilling zone, where the new triggering scheme allows detection of events down to magnitude -1.0, a three-fold higher detection rate compared to the local surface seismic network, in a 30 km stretch around the M6 earthquake of 1966.

Other accomplishments in the past year include the completion of a new BDSN station (HUMO - Chapter 3) in southern Oregon, in collaboration with USGS/NSN and IRIS programs, and, as mentioned previously in the framework of CISN, the installation of two new broadband stations.

The NHFN network project has seen the upgrade of infrastructure at 7 stations on the Bay Bridge (Chapter 4), in anticipation of the deployment of the Quanterra recording systems and associated telemetry to UC Berkeley. Stations BBEB and W02B are now online, and the remaining five sites will be brought up this fall. In parallel, we have been working on improvement of data processing techniques. The datastreams from the borehole seismometers of the *Mini-PBO* project are progressively being integrated with those of the NHFN (Chapter 8).

On the NCEDC front (Chapter 11), we continue archiving and distribution on-line of data from expanding BDSN, NHFN, HRSN, BARD, Mini-PBO, and other networks and data collections in northern California and Nevada. There has been progress in the construction of the "metadata" for the NCSN and a major "revamping" of the NCEDC Webpage. The NCEDC is participating in the UNAVCO-sponsored GPS Seamless Archive Centers (GSAC) initiative, which is developing common protocols and interfaces for the exchange and distribution of continuous and survey-mode GPS data, and is now both a primary provider for BARD/BSL data, a wholesale collection point for other northern California GPS data, and a retail center for all GSAC data.

The BSL continues to collaborate with the USGS/Menlo Park in the generation of ShakeMap for northern California and has been developing and implementing successive upgrades to this system, integrated within the REDI environment (Chapter 10). ShakeMap is calculated routinely for magnitude 3.5 and larger events in northern California. Any magnitude 5.0 or larger will now also trigger the finite-fault processing. In 2002-2003, a 2nd ShakeMap system has been installed at UC Berkeley, to provide redundancy for northern California earthquakes. Also in the past year, we have implemented a database within the real-time system and have been involved in redesigning the Northern California operations, to achieve a single system at USGS/Menlo Park and UCB.

Finally, we have been routinely monitoring electric and magnetic field at two of our observatories since 1995. In 2002-2003, efforts in this direction have been stepped up: an automated quality control software has been implemented and a time domain processing software is currently being developed and perfected (Chapter 6).

In 03-04, a major new component of our activities will be coordinating with IRIS on the deployment in northern California of 50 temporary broadband stations of the BigFoot array of Earthscope. The BSL will contribute many (15+) of its existing sites to this effort. Likewise, we anticipate helping out with some aspects of the Plate Boundary Observatory component of Earthscope. In particular, we have received funding from NSF for the support of routine operations of the BARD GPS network for the next 1.5 years, as part of a collaborative proposal coordinated by UNAVCO Inc. We will be actively engaged in the next year in planning the integration of existing permanent GPS networks into the PBO.

2.2 Research Accomplishments

Chapter III documents the main research contributions of the past year. Research at the BSL spans a broad range of topics, from the study of microseismicity at the local scale to global deep earth structure, and includes seismological, geodetic and remote sensing (InSAR) techniques.

In the general area of earthquake source studies, a major earthquake (M 7.9) occurred in Alaska on the Denali Fault on 11/03/2002. This has been an opportunity for Professor Dreger and collaborators to combine his broadband waveform source tomography approach with GPS and surface displacement observations to study the complex fault geometry of this unusual event, documenting in particular evidence for discontinuous rupture propagations (III.1). Professor Dreger and graduate students Wucheng Chi (III.2), Dennise Templeton (III.9) and Gilead Wurman (III.7), as well as undergraduate student Sarah Minson (III.10) have pursued the study of various earthquake source problems in California, Taiwan, and Japan, in particular with a continued interest in the characterization of earthquakes related to fluid migrations in volcanic areas. Graduate student David Dolenc is using microtremors to illuminate basin structure in the San Francisco Bay Area to anticipate ground motions in large earthquakes (III.8), while Dr. Robert Uhrhammer has continued his efforts to characterize historical seismicity in the San Francisco Bay Area (III.3) as well as Northern California (III.4). Dr. Robert Nadeau continues to discover and analyze new sequences of micro-earthquakes at Parkfield (III.5) in an effort to better understand how the fault works. In particular, he has documented evidence for periodic pulsing along the central San Andreas Fault between Parkfield and the southern end of the Loma Prieta earthquakes. In collaboration with Dr. Nadeau and Professor Bürgmann, post-doctoral associate Frédérique Rolandone has been studying the time variations of the maximum depth of seismicity around major earthquakes during the earthquake cycle (III.6). With graduate student David Dolenc, we have started to analyze the background noise at the ocean bottom MOBB site with the goal of a-posteriori noise reduction using correlations with current, pressure and other auxiliary data (III.11). Dr. Peggy Hellweg has completed the installation and testing of our automated moment tensor inversion codes at the Center for Monitoring Research, in the framework of efforts to monitor the CTBT (III.13). With graduate student Junkee Rhie, we are perfecting a very low frequency event detection method, with the ultimate goal of trying to characterize sources of the continuous background excitation of earth's free oscillations (III.12).

The BSL has also been actively involved in studying active deformation using various geodetic techniques. Working with Professor Roland Bürgmann, graduate students Matt d'Alessio and Ingrid Johanson have been analyzing campaign GPS data and InSAR to monitor fault slip and strain accumulation in the San Francisco Bay region, characterizing creep events and delineating rigidly behaving crustal blocks (III.14,III.16). Studies of strain accumulation and distribution have also been pursued by Dr. Mark Murray in northern California (III.15) and the New Madrid Seismic Zone (III.18), while post-doctoral associate Maurizio Battaglia documented the existence of a microplate in the Adriatic region (III.19). Finally, Dr. Andy Freed used GPS data to characterize the nature of viscous flow associated with the coupled 1992 Landers and 1999 Hector Mine earthquakes (III.17).

With graduate students Yuancheng Gung, Mark Panning, Akiko To, Sébastien Rousset and post-doctoral Miller fellow Yann Capdeville, Professor Romanowicz has been pursuing various aspects of wave propagation in the 3D spherical earth, adapting the coupled Spectral Element/normal mode method to study complex structure at the base of the mantle (III.20, III.23), experimenting with a neighborhood algorithm to explore the range of possible large scale variations in density in the mantle using normal mode observations (III.25) and implementing anisotropic parameterization in global mantle tomography (III.21, III.22). With graduate student Aimin Cao, Romanowicz has pursued the study of core structure, revisiting this past Spring the issue of the density jump at the Inner Core Boundary (III.24). Also included in this report is a contribution from graduate student David Stegman, working with Professor Mark Richards on a model of convection of the moon (III.26) featured this year on the cover of our Annual Report.

We are proud to note that Yuancheng Gung, Wuchen Chi and David Stegman successfully completed their Ph.D.'s in the summer of 2003, and will pursue post-doctoral appointments at BSL, Caltech and Canberra, Australia, respectively. Last but not least, post-doctoral fellow Andy Freed left last Fall to take a faculty position at Purdue University, while Miller Fellow Yann Capdeville went back to Paris, France at the end of August to join the research staff at the CNRS.

3. Acknowledgements

I wish to thank our technical and administrative staff, scientists and students for their efforts throughout the year and their contributions to this annual report. Individual contributions to activities and report preparation are mentioned in the corresponding sections, except for the Appendix section, prepared by Christina Jordan and Eleanor Blair.

Starting July 1st, 2002, Professor Douglas Dreger has been appointed Associate Director of the BSL. In particular, Doug has assumed overall responsibility, with help from Bob Nadeau, for the HRSN and NHFN programs, following Professor McEvilly's death.

I also wish to specially thank the individuals who have regularly contributed to the smooth operation of the BSL facilities: André Basset, Sierra Boyd, Rich Clymer, Doug Dreger, John Friday, Lind Gee, Wade Johnson, Bill Karavas, Pete Lombard, Rick McKenzie, Mark Murray, Bob Nadeau, Doug Neuhauser, Charley Paffenbarger, David Rapkin, Cathy Thomas, Bob Uhrhammer, and Stephane Zuzlewski. To our regret, Cathy Thomas went back home to the East Coast in March 2003.

In 2002-2003, there have been some changes in the BSL administrative office. Eleanor Blair, and Christina Jordan continue to provide critical support to the administration of our lab, but Heather Reed left in 11/2002. We welcome Myriam Cotton, who joined the administrative office in 11/2002, helping with accounting. They are assisted by part-time student employees Morgan Weibel, Patty Villa and Loan Pham.

I also wish to thank our undergraduate assistants Tom Fournier, Alex Goines, Lisa Krain, Edwin Kwan, Sarah Minson, and Gabriel Treves, for their contributions to our research and operational activities. Lisa left in December 2002 to follow her newly acquired husband and pursue graduate studies in southern California, and Sarah left in August 2003, to become a graduate student in Geophysics at Caltech.

As every year, I am particularly thankful to Lind Gee and Christina Jordan for their help in putting together this Annual Report.

The Annual Report of the Berkeley Seismological Laboratory is available on the WWW at `http://www.seismo.berkeley.edu/seismo/annual_report/`.

Barbara Romanowicz
Sept 15, 2003

4. Glossary of Common Acronyms

Table 1.1: 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
EM	Electromagnetic
EPRI	Electric Power Research Institute
FBA	Force Balance Accelerometer
FIR	Finite Impulse Response
FRAD	Frame Relay Access Device
GPS	Global Positioning System
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
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
NCSN	Northern California Seismic Network
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NHFN	Northern Hayward Fault Network
NGS	National Geodetic Survey
NSF	National Science Foundation
NSN	National Seismic Network
OES	Office of Emergency Services
ORU	Organized Research Unit
PBO	Plate Boundary Observatory
PEER	Pacific Earthquake Engineering Center
PH	Pilot Hole
PPE	Parkfield Prediction Experiment

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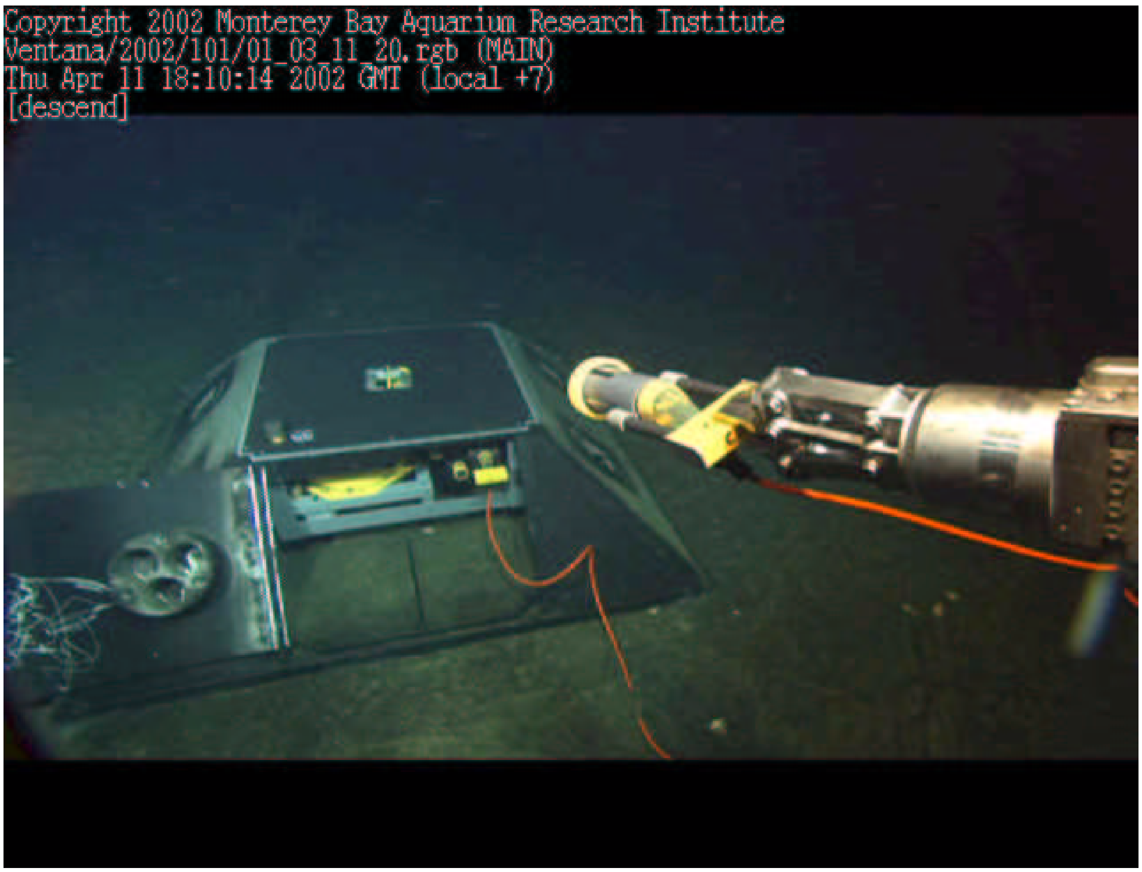
Table 1.1: *continued*

Acronym	Definition
PREM	Preliminary Reference Earth Model
PSD	Power Spectral Density
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
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
UrEDAS	Urgent Earthquake Detection and Alarm System
USGS	United States Geological Survey

Part II

Operations



Chapter 2

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 was initiated under the TriNet Project in southern California, where Caltech, the then California Division of Mines and Geology, and the USGS combined their efforts to create a unified seismic system for southern California. With major funding provided by FEMA, OES, and the USGS, the TriNet project provided the opportunity to upgrade and expand the monitoring infrastructure, combining resources in federal, state, university partnership. More recently, the California Geological Survey, Caltech Seismological Laboratory, Berkeley Seismological Laboratory, USGS Menlo Park, and the USGS Pasadena have agreed to cooperate on a statewide basis, because of the obvious benefit to the state.

In the 2000-2001 Annual Report, we described the efforts to create this collaboration through the establishment of a memorandum of agreement and the development of the CISN strategic and implementation plans. Last year, we reported on the first steps toward establishing a statewide system with funding provided by the OES. This year we continued our efforts to move forward with the CISN.

2. CISN Background

2.1 Organization

The core CISN institutions (California Geological Survey, Berkeley Seismological Laboratory, Caltech, USGS Menlo Park, USGS Pasadena) and OES have signed a MOA (included in the 2000-2001 Annual Report) that describes the CISN organizational goals, products, management, and responsibilities of member organizations. To facilitate coordination of activities among institutions, the CISN has formed three management centers:

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

A goal of the CISN is for the Northern and Southern California Management Centers to operate as twin earthquake processing centers. The Engineering Management Center has the lead responsibility for producing engineering data products.

The Steering Committee oversees CISN projects and is comprised of two representatives from each core institution and a representative from OES. The position of chair rotates among the institutions; Barbara Romanowicz served as the first chair of the Steering Committee; the position has rotated to the California Geological Survey and Jim Davis served as chair from January 2003 until his retirement in the end of June. Mike Riechle is the new 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 Bruce Clark of the California Seismic Safety Commission. The Advisory Committee held its first meeting in July 2001 and met most recently in January of 2003.

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. 8 regions have been organized and the CISN represents the "California region". Over the last 4 years, ANSS funding in California has primarily been directed to the USGS Menlo Park to expand the strong-motion instrumentation in the San Francisco Bay Area. As a result, instruments at over 100 sites have been installed or upgraded, significantly improving the data available for ShakeMaps.

The CISN is currently developing plans for the FY03/04 ANSS program. As the ANSS moves forward, committees and working groups are being established to address issues of interest. Currently, Lind Gee and David Oppenheimer represent the CISN on an ANSS working group for business rules for earthquake reporting (developing figures of merit for selecting the "best" location, magnitude, and other earthquake products when multiple solutions are available).

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.

Despite the dire budget situation in the state of California in FY02/03, OES support led to the establishment of 3-year contracts to the BSL, Caltech, and the California Geological Survey for CISN activities. Although at a reduced level of support from the previous year, these funds are critical to continued efforts in statewide integration.

3. 2002-2003 Activities

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

3.1 Expanded Instrumentation

In 2001-2002, the BSL purchased equipment for 5 BDSN stations, including STS-2 seismometers, Episensors, and Q4120 data loggers and initiated efforts to identify potential sites, considering such factors as the current distribution of stations, private versus public property, location of power and telecommunications, and geologic materials. Two sites were permitted - McLaughlin Mine Natural Reserve and Alder Springs Conservation Camp.

In 2002-2003, the BSL permitted a 3rd site at Pacheco Peak with the California Department of Forestry and Fire. This site is located in south Santa Clara County. The BSL installed two sites during this year, at McLaughlin Reserve and Pacheco Peak, complementing the BDSN installations in the San Francisco Bay Area. The efforts for site preparation and installation are more fully described in Chapter 3.

Other areas under consideration for future installations include the Pt. Reyes area, the Santa Cruz Mountains (in collaboration with UC Santa Cruz), Placerville (in collaboration with Davey Jones and Lava Cap Winery), near Pinehurst (in collaboration with Peggy Hellweg), Hat Creek (in collaboration with UC Berkeley Department of Astronomy), and Carmel Valley (UC Berkeley Hastings Preserve). We hope to install two more sites in FY03/04.

3.2 Network Operations

As part of the CISN project, the BSL purchased a number of upgrade kits for their Q4120 data loggers with the goal of improving remote diagnostic capabilities last year. Three different kits were purchased – power board only, calibration board only, and combined power and calibration boards – in order to ensure that every Q4120 has a power board and that every 8-channel Q4120 also has a calibration board. The power boards provide the capability to monitor battery voltage, allowing staff to discriminate between power and telemetry problems remotely. The calibration boards provide the capability to monitor mass position as well as allow remote calibration of the seismic sensors. Both boards also record data logger temperature.

The boards were received in the winter of 2002. BSL staff, particularly Dave Rapkin, began to work on installing the upgrade kits. Of the 23 kits purchased, 11 have been installed as of June 30th and 9 of these dataloggers have been reinstalled in the field. In addition to the installation of these boards, the BSL staff must also prepare new cables in order to record these new channels. That effort is also underway.

3.3 Statewide Communications

One of the major accomplishments in FY01/02 was the design and initial implementation of a CISN 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 2.1) with dual routers at each node.

The implementation of the CISN ring was completed in early 2003, when the last problem (a bad wire in building

11 at the USGS Menlo Park) was resolved. All links are now fully operational and the ring is being used to push data among the CISN partners such as waveforms, picks, and ground motions. In addition, the CISN partners have migrated the transmission of ShakeMaps to OES to the ring. Use of the ring for sending ShakeMaps to OES has been a long-standing goal for the CISN but required coordination with OES personnel to configure machines. This effort was accelerated by the failure of the computer at OES that had been the recipient of ShakeMaps via the Internet. When the computer failed, BSL staff worked with OES and CISN partners to set up an interim system where ShakeMaps were transmitted to a UC Berkeley-maintained computer at OES. This stop-gap provided a local site within OES where the ShakeMaps could be retrieved while more permanent solutions were developed. OES replaced the failed computer and set up a new recipient system on the CISN ring. As of the end of May, ShakeMaps are being pushed to two separate OES machines, one on the CISN ring and one on the public Internet.

Early in 2003, Doug Neuhauser of the BSL installed the Multi Router Traffic Grapher (MRTG) software package to monitor the CISN ring. This package collects data for graphical display of traffic on the CISN router interface. More recently, Stan Schwartz of the USGS began using the Big Brother software to establish alarming capabilities - that is, to notify personnel when a problem with the ring is detected. The alarming system is running in Pasadena and will be installed at Berkeley soon. Two separate instances of the alarming software should provide reliable notification of problems with the ring.

The remaining outstanding issues with the ring include the connection of the OES routers to the Internet and the development of a security document.

3.4 Northern California Management Center

As part of this effort within the CISN, the BSL and the USGS Menlo Park have begun to plan for the next generation of the northern California joint notification system. Chapter 10 describes the operations of the existing Management Center and reports on design discussions.

Communications Infrastructure

In order to migrate to a design such as Figure 10.7, the BSL and the USGS Menlo Park need to enhance the communications infrastructure between their sites. Presently, data and information are shared on a dedicated connection, with fallback to the Internet.

Last year, the BSL commissioned Telecommunications Design Services, Inc. to perform a feasibility study for a microwave communication link between Berkeley and Menlo Park. The goal of the study was to evaluate options for a microwave communication link between the

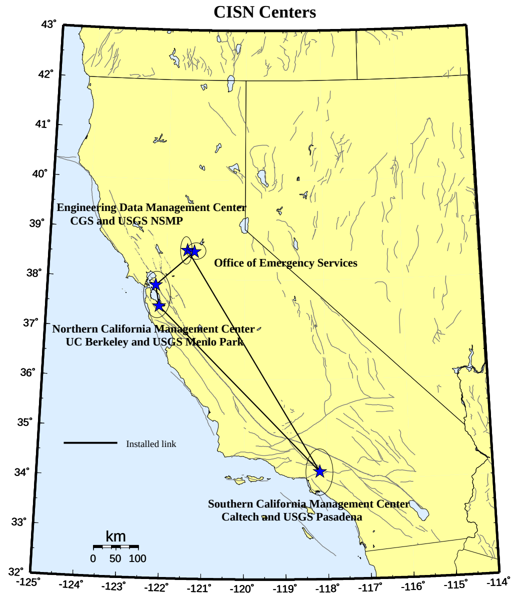


Figure 2.1: Map showing the geographical distribution of the CISN partners and centers. The communications "ring" is shown schematically with installed links (solid lines).

BSL and USGS elements of the Northern California Management Center. The report concludes that a repeater site will be required, given the length of the path and the obstructions (buildings, bridges, etc.). According to the report, the Space Sciences Laboratory at UC Berkeley will be a good site for the repeater.

Unfortunately, funding to establish this microwave link has not been identified. As a modest step to improve the communications links between the BSL and Menlo Park, the BSL installed a dedicated T1 connection this year, similar to the one established last year for the CISN ring. This dedicated T1 replaces the previous frame-relay connection as a more cost effective alternative. The second T1 provides the necessary bandwidth between the Berkeley and Menlo Park elements of the Northern California Management Center. The original frame-relay T1 will be reused by the BSL as a second link for connections to its seismic networks.

Computing Upgrade

The current data acquisition and processing computers used as part of the Northern California Management Center at the BSL are nearly 4 years old. As part of the OES project, the BSL purchased computers to replace these aging systems.

In the past year, the five Sun 280R computers have been brought online. Two of them were use to replace the data acquisition and processing computers. One is being used to generate ShakeMaps for northern California.

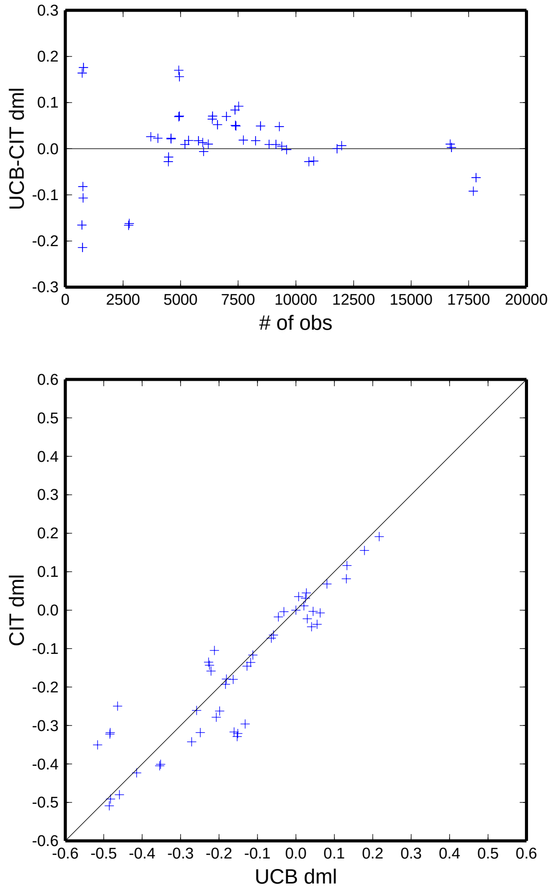


Figure 2.2: Comparison of M_L station adjustments estimated for BDSN stations from independent inversions of Wood Anderson amplitudes, using methodologies developed at UCB and Caltech (CIT).

And two are being setup as as pilot system for statewide earthquake processing. In addition to the 280R computers, the BSL purchased two Sun StorEdge RAID disk systems. The additional disk systems are required by the expanded waveform exchange among the centers.

3.5 Statewide Integration

BSL staff are involved in many elements of the statewide integration effort. In FY02/03, the Standards Committee of the CISN addressed a number of topics critical to this effort such as the software calibration issues discussed below. The Standards Committee continues to define and prioritize projects necessary to develop a prototype system and established working groups to address them (see the minutes from meetings and conference calls at `http://www.cisn.org/standards/meetings.html`).

Software Calibration

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 Northern and Southern California Management Centers is very different. Eventually, there may be standardization of software across the management centers, but in the short term, the focus is on calibrating the software to produce the same answers, given the same input data.

In the last year, effort was continued to focus on phase pickers, the association algorithm (binder), the location algorithm (hypoinverse), and magnitude estimation (various).

The CISN continued evaluation of data from a test system that is performing statewide earthquake notification using seismic data from all CISN partners. These tests are structured so that both northern and southern California are operating a statewide system in parallel with their current "regional" system. A recent 2-week evaluation of results from an exchange of data between northern and southern California networks showed that approximately 95% of the earthquakes were identical. Of the remaining 5%, most were "noise" associations on one system that were rejected on the other. The discrepant behavior can be attributed to differences in the order in which travel-time information is received by the two systems. This type of algorithm behavior may be difficult to eliminate without significant revision to the software design. We have identified several other issues and continue to improve the behavior of the statewide associator.

In parallel, the CISN has been working on issues related to magnitude. Here, the CISN is working in several areas. Pete Lombard of the BSL and Caltech staff have been working together to resolve issues in the original TriNet software that computes magnitude related to the selection of time windows and stations used in the estimation. Bugs in the codes that compute travel time have been identified and are being corrected. Once these issues have been resolved, then the Northern California Management Center will implement the magnitude codes for computing M_L and M_e. Similarly, the Southern California Management Center is working on the implementation of codes to estimate M_w and the seismic moment tensor that were developed in Northern California.

Also part of the magnitude calibration effort is the computation of station adjustments for M_L and M_e on a statewide basis. This effort is underway by BSL and Caltech staff. Figure 2.2 shows the results from two separate inversions of Wood Anderson amplitudes from the BDSN to estimate local magnitude adjustments. Bob Uhrhammer of the BSL and Jascha Polet of Caltech have been comparing their independent results as a first step to determine a common set of adjustments. The method Jascha employs estimates the adjustments and attenuation relationship simultaneously, while Bob's approach a differential approach while fixing the attenuation relationship. The good agreement between the estimates of the adjustments provides confidence in the first step of the process. The next step is a joint inversion of BDSN and TriNet data for magnitude adjustments and a unified statewide attenuation relationship. In parallel, the BSL has worked to develop a collection of energy magnitude estimates in order to determine M_e station adjustments.

A final component of the magnitude efforts is the designation of a magnitude reporting hierarchy. There is general agreement at the low end and at the high end, but the working group is still reviewing issues relation to transition points from one magnitude type to another. More details about the magnitude calibration effort are documented in Chapter 10.

Metadata Exchange

The CISN is also working on issues related to metadata exchange. This is an important component of CISN activities, as correct metadata are required to insure valid interpretation of data. A Standards Working Group has developed and initiated testing of a model for database replication of metadata, and is currently reviewing how much of the schema to exchange and how to address metadata from partners such as CGS, who do not currently maintain their metadata in a database.

The Metadata Working Group has 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 of their stations and other stations that enter into CISN processing through them. For example, Menlo Park is responsible for the NSMP, Tremor, and PG&E stations and Caltech is responsible for the Anza data. The Working Group believes that metadata exchange should proceed on a timely basis, not just when data are generated, and is testing an approach using database replication.

The core of the model is to have a master database at each organization and use multi-master replication to propagate the changes between the different data centers. Within a data center, it is proposed to use an interim database as the staging area. This database would contain snapshots of the master tables and the changes would be pushed manually to the master database by using snapshot replication. The use of such a staging area is particularly important because of the way Northern and Southern California currently load their databases. The current programs usually delete some or all the metadata before repopulating the updated data. This will introduce a latency period where the users will see inconsistent information in the database. The working group believes that this period should be relatively small and acceptable in our model. However, a longer term solution will certainly include the coding of new population programs. This model is currently being tested.

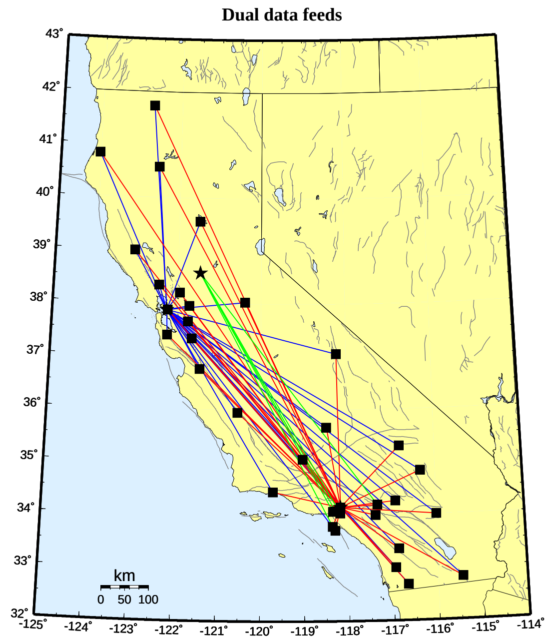


Figure 2.3: Map showing the 30 stations selected to send data directly to the Northern and Southern California processing centers, and the 5 stations that send data directly to the Engineering Data Center and the Southern California processing center.

Dual Station Feeds

One of the major accomplishments last year was the establishment of "dual station feeds" from 20 stations (10 in northern California and 10 in southern California). To achieve this, the BSL and Caltech both ordered the DLCIs (data link connection identifier) that allow the 2nd center to establish a PVC (permanent virtual circuit) to each station using the frame-relay network.

The Northern California Management Center is using data from the 10 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 more sensitive to the background noise level.

This initial set of 20 stations was expanded to 30 this year (Figure 2.3), providing a broad sampling of the state. The next step for the BSL is to test these stations in their automated processing system. This direct feed of data from the station to two processing centers is an important step to improving the robustness of earthquake monitoring statewide.

Data Exchange

Pick exchange was initiated between the Northern and Southern California Management Centers last year. Although the CISN has developed software to exchange the reduced amplitude timeseries, this aspect of data exchange has been delayed while certain problems in the codes that generate the time series are addressed. We hope to begin exchanging these timeseries in the fall of 2003.

The CISN partners completed the first stage of a system to exchange peak ground motion data this year. Using a common format, the CISN partners are exchanging observations with one another following an event or a trigger. This step increases the robustness of generating products such as ShakeMap, since all CISN partners are now exchanging data directly with one another. It also improves the quality of ShakeMaps on the boundary between northern and southern California, such as the recent events in Lompoc, by allowing all data to be combined in a single map. Finally, it is a necessary step toward the goal of generating statewide ShakeMaps.

3.6 Earthquake Information Distribution

In response to a request from the PMG, USGS and OES management established an *Ad Hoc* panel to develop specifications for an earthquake information system and to review existing systems as well as systems under development. Lind Gee of the BSL and David Oppenheimer of the USGS were asked to co-chair this panel and to provide a written report within 90 days. The panel was put together in May and a meeting took place on July 9-10th at the BSL. The report is due in early September.

3.7 Outreach

The CISN hosted an outreach workshop on ShakeMaps in January 2003, targeting the media. "ShakeMap for the News Media" was held at the USGS Menlo Park and attended by a number of print, radio, and television media in northern California. The purpose of the workshop was to raise awareness of ShakeMaps as an important tool in earthquake reporting. As part of the workshop, Lind Gee gave a talk on the CISN and its activities.

The CISN Web site `http://www.cisn.org` is continuing to develop. As part of the Web updating of the NCEDC and BSL this year, the CISN Web site was revamped and reorganized. In March, the Web site was updated to conform with USGS usage of their logo.

One of the major changes this year was the addition of "Seismology Data Reports". Both the Northern and Southern California Management Centers have generally produced special reports following earthquakes of note. These reports have generally provided tectonic and seismological context for the event and have included detailed maps showing background seismicity and figures showing waveforms of interest. We developed a prototype for a standard CISN report, and had the opportunity to try it out during the November 24, 2002 San Ramon swarm as well as the February 2, 2003 Dublin swarm and the February 22, 2003 Big Bear earthquake.

Plans are underway to expand the capabilities and services of CISN Web site. This year, the BSL purchased two computers for Web servers, in order to improve response. This upgrade is critical to insure that the CISN Web site can respond to post-earthquake traffic. Once the upgrade is complete, the BSL will migrate the recenteqs and ShakeMap pages from the NCEDC server to the CISN server. That will make these products available directly from cisn.org. In addition, we are working with Caltech to setup a system to mirror the CISN Web site in southern California in order to distribute the load.

We have also moved forward with the development of a "myCISN". The ability to personalize earthquake content on a Web site was suggested at an early CISN Advisory Committee meeting. This year, Ionut Iordache developed a prototype for myCISN and we have just started testing this feature.

4. Acknowledgements

CISN activities at the BSL are supported by funding from the Governor's Office of Emergency Services.

Barbara Romanowicz and Lind Gee are members of the CISN Steering Committee. Lind Gee is a member of the CISN Program Management Committee and she leads the CISN project at the BSL. Doug Neuhauser is chair of the CISN Standards Committee, which includes Lind Gee and Pete Lombard as members.

Because of the breadth of the CISN project, many BSL staff have been involved including: John Friday, Lind Gee, Ionut Iordache, Wade Johnson, Bill Karavas, Pete Lombard, Doug Neuhauser, Charley Paffenbarger, Dave Rapkin, Cathy Thomas, and Stephane Zuzlewski. Lind Gee contributed to this chapter. Additional information about the CISN is available through reports from the Program Management Committee (*Hauksson et al.*, 2002; 2003a; 2003b).

5. References

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Chapter 3

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 3.1 and Table 3.1). This 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.

The network upgrade and expansion initiated in 1991 has continued, and it has grown from the original 3 broadband stations installed in 1986-87 (BKS, SAO, MHC) to 28 stations in 2003, including the ocean-bottom seismometer in Monterey Bay. Two new stations were added in the past year (PACP and MNRC).

We take particular pride in high quality installations, which involves often 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 at existing stations.

Future expansion of our network 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.

2. BDSN Overview

Twenty-five of the BDSN sites are equipped with 3 component broadband seismometers and strong-motion accelerometers, and a 24-bit digital data acquisition system or data logger. Two additional sites (RFSB and SCCB) consist of a strong-motion accelerometer and a 24-bit digital data logger. Data from all BDSN stations 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 data loggers ensures that the BDSN has the capability to record the full range of earthquake motion for source and structure studies. Table 3.2 lists the instrumentation at each site.

Most BDSN stations have Streckeisen three-component broadband sensors (*Wielandt and Streckeisen*, 1982; *Wielandt and Steim*, 1986). Guralp CMG-3T downhole broadband sensors contributed by LLNL are deployed in post-hole installations at BRIB and FARB. 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 Q730, Q680, Q980 or Q4120 Quanterra data loggers, with 3, 6, 8, or 9 channel systems. The Quanterra data loggers employ FIR filters to extract data streams at a variety of sampling rates and these have been implemented as acausal filters in the BDSN. In general, the BDSN stations record continuous data at .01, 0.1, 1.0, and 20.0 samples per second and triggered data at either 80 or 100 samples per second using the Murdock, Hutt, and Halbert event detection algorithm (*Murdock and Hutt*, 1983) (Table 3.3). In addition to the 6-channels of seismic data, signals from thermometers and barometers are recorded at nearly every site (Figure 3.2).

In parallel with the upgrade of the broadband network, a grant from the CalREN (California Research and Education Network) Foundation enabled 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 data loggers, additional services such as FTP and telnet to the data loggers, data transmission to

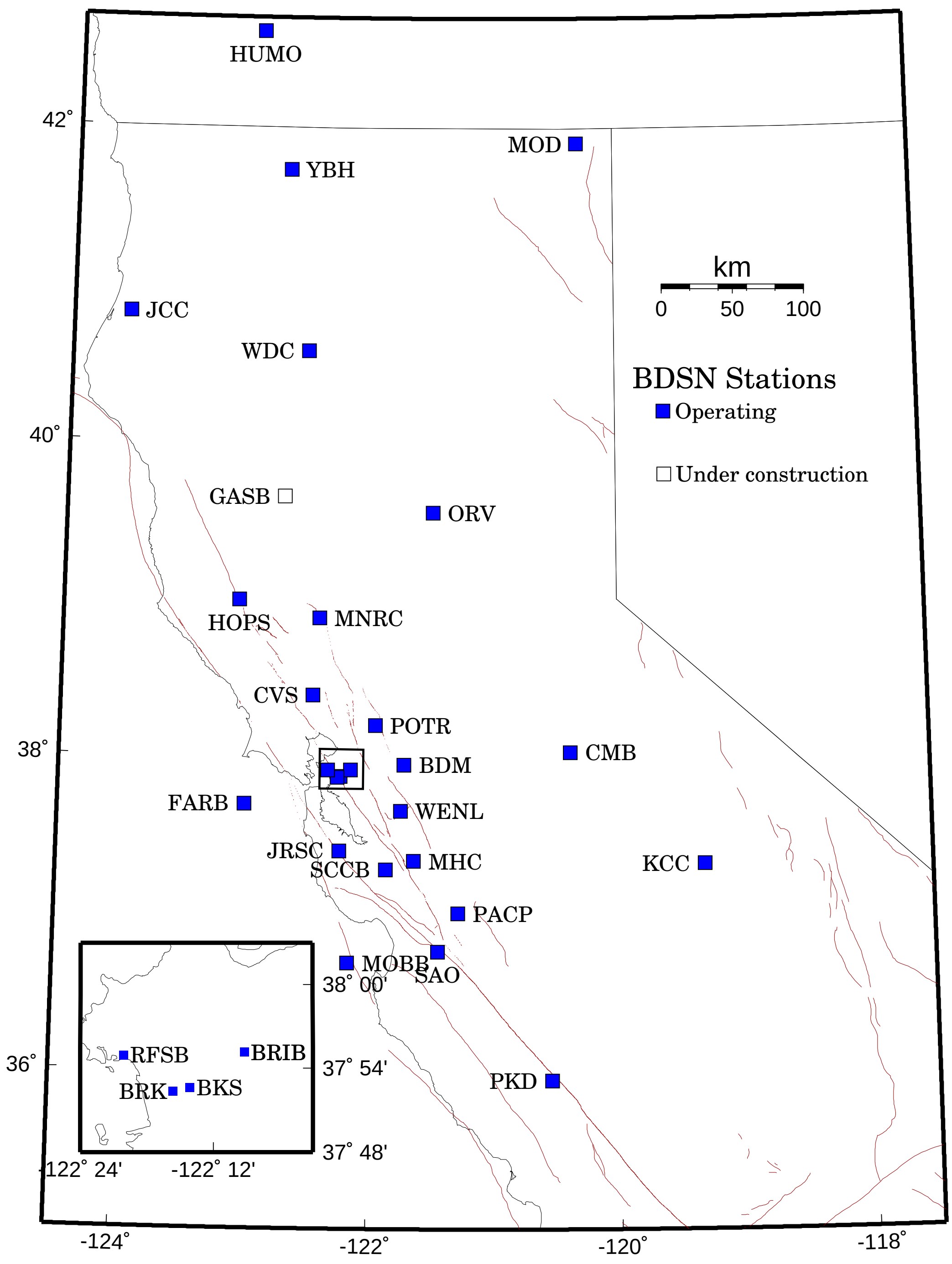

Figure 3.1: Map illustrating the distribution of operational (filled squares), planned (open squares), and closed (grey squares) BDSN stations in northern and central California.

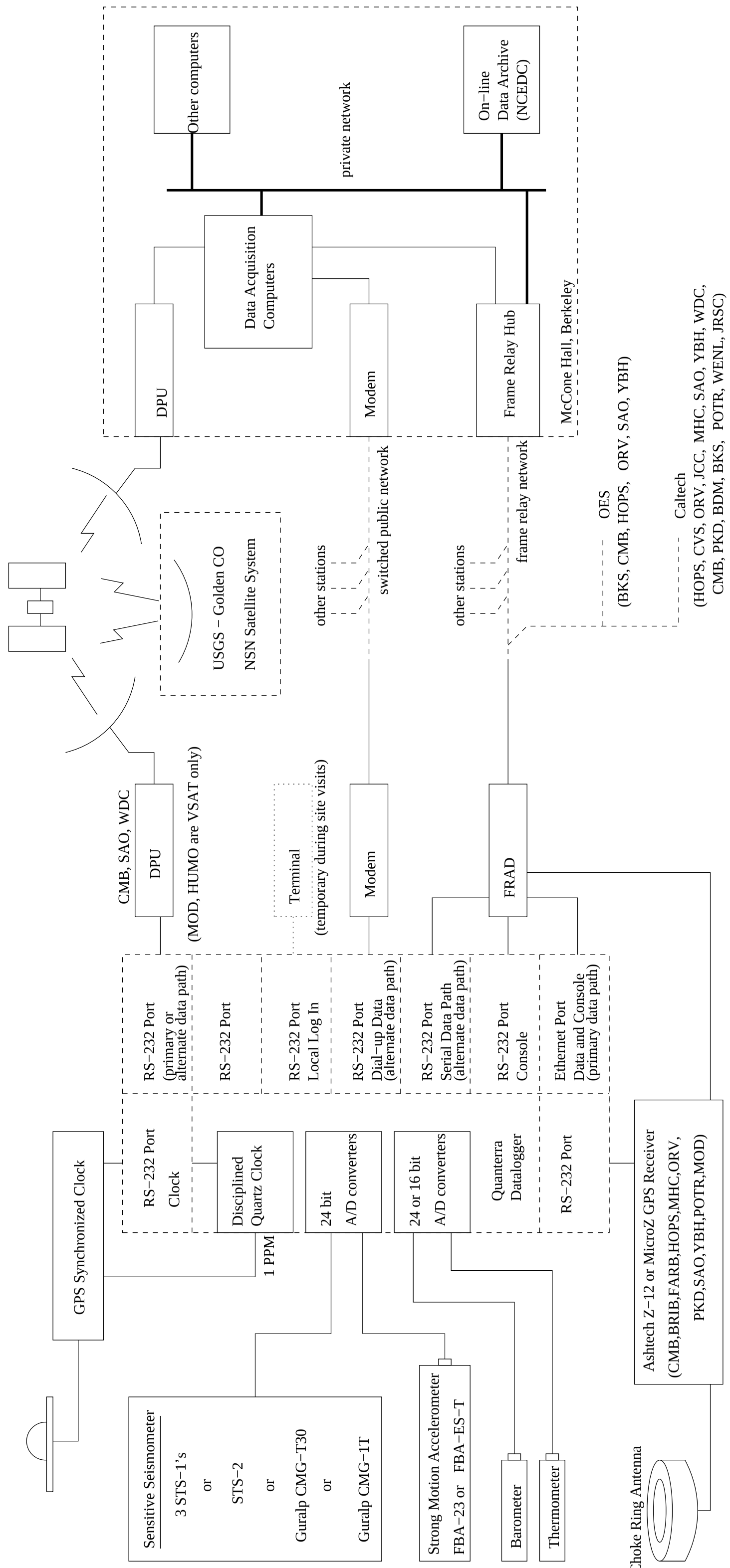

Figure 3.2: Schematic diagram showing the flow of data from the sensors through the data loggers to the central acquisition facilities of the BSL.

multiple sites, and the ability to communicate and transmit data from multiple instruments such as GPS receivers and/or multiple data loggers at a single site. Today, 20 of the BDSN sites use frame-relay telemetry for all or part of their communications system.

As described in Chapter 9, data from the BDSN are acquired centrally at the BSL. These data are used in the Rapid Earthquake Data Integration System as well as in routine earthquake analysis (Chapter 10). As part of routine quality control (Chapter 9), power spectral density analyses are performed weekly and Figure 3.3 shows a summary of the results for 2002-2003. The occurrence of a significant teleseism also provides the opportunity to review station health and calibration and Figure 3.8 displays the response of the BDSN to a M_w 7.3 deep focus earthquake in the Fiji Islands region.

BDSN data are archived at the Northern California Earthquake Data Center and this is described in detail in Chapter 11.

Sensor	Channel	Rate (sps)	Mode	FIR
Broadband	UH?	0.01	C	Ac
Broadband	VH?	0.1	C	Ac
Broadband	LH?	1.0	C	Ac
Broadband	BH?	20.0	C	Ac
Broadband	HH?	80.0/100.0	T	Ac
Strong-motion	LL?	1.0	C	Ac
Strong-motion	BL?	20.0	C	Ac
Strong-motion	HL?	80.0/100.0	C	Ac
Thermometer	LKS	1.0	C	Ac
Barometer	LDS	1.0	C	Ac

Table 3.3: Typical data streams acquired at BDSN stations, with channel name, sampling rate, sampling mode, and the FIR filter type. C indicates continuous; T triggered; Ac acausal. The LL and BL strong-motion channels are not transmitted over the continuous telemetry but are available on the Quanterra disk system if needed.

3. 2002-2003 Activities

3.1 Station Maintenance

Given the remoteness of the off-campus stations, BDSN data acquisition equipment and systems have been designed, configured, and installed for both cost effectiveness and reliability. As a result, the need for regular station visits has been reduced. Most station visits are necessitated by some catastrophic failure. The 2002-2003 fiscal year was no exception.

YBH Upgrades

The seismic vault at Yreka, CA (YBH) is sited in an abandoned hard rock mining drift in the Klamath National Forest in northern California. YBH was previously chosen as an alternative monitoring station by both IMS and DTRA. In collaboration with the IMS, BSL installed a VSAT data link, long-period microbarograph, separate battery back-up, a stand-alone data validation computer and door switch in 2001-2002.

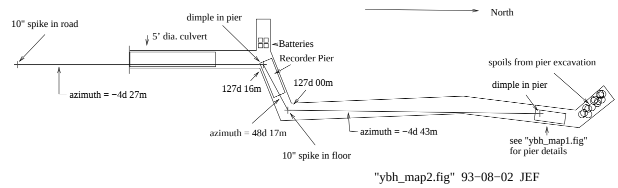

Figure 3.4: Map showing layout of YBH seismic vault. The location of the STS-2 seismic pier is shown in the right central part of the figure.

This year, an STS-2 seismometer was deployed, bringing YBH into compliance as an auxiliary station of the IMS. This seismometer (0.0083-50 Hz passband) joins the three-component set of Streckeisen STS-1 broadband seismometers (0.0027-5 Hz passband), a three-component Kinemetrics FBA-23 strong motion accelerometer (0-32 Hz passband; 2g full scale); an Ashtech Z-XII3 geodetic GPS receiver; a YSI 44031 thermistor (to sense seismic pier temperature); a Motorola MPX-2010 pressure transducer and a Druck PTX-1240 microbarograph (to sense atmospheric pressure); and a Quanterra GPS clock for an accurate time base. Additionally, the sensor temperature, data logger temperature, broadband sensor mass position, clock quality, and telemetry through-put are utilized for status of health monitoring.

The STS-2 became operational as a part of the BDSN and telemetry of the signals to CTBTO and to BSL commenced on 27 November 2002. The three-component STS-2 and STS-1 data are continuously telemetered at 80, 20, 1, 0.1 and 0.01 samples per second.

As one part of BSL routine testing, the vertical-component background noise levels observed by the STS-1 and STS-2 were compared (see Figure 3.5). From the manufacturers specifications, the self noise of the high-gain STS-2 is lower that of the STS-1 at frequencies above 1 Hz. Here the high-gain STS-2 noise floor rises above the background earth noise observed by the STS-1 at 0.5 Hz and there are also narrow band spectral peaks at 1 Hz and its harmonics present with amplitudes of up to 20 dB. We suspect that the abnormally high noise levels observed on the STS-2 signals are related to the installation of the IMS satellite transmitter and computer equipment in the YBH vault. We also need to track down the source of the 0.7-8 Hz frequency noise peaks on the STS-1 (see Figure 3.5) which we suspect are also related to the installation of the IMS equipment.

In the coming year, we need to trouble shoot and cure

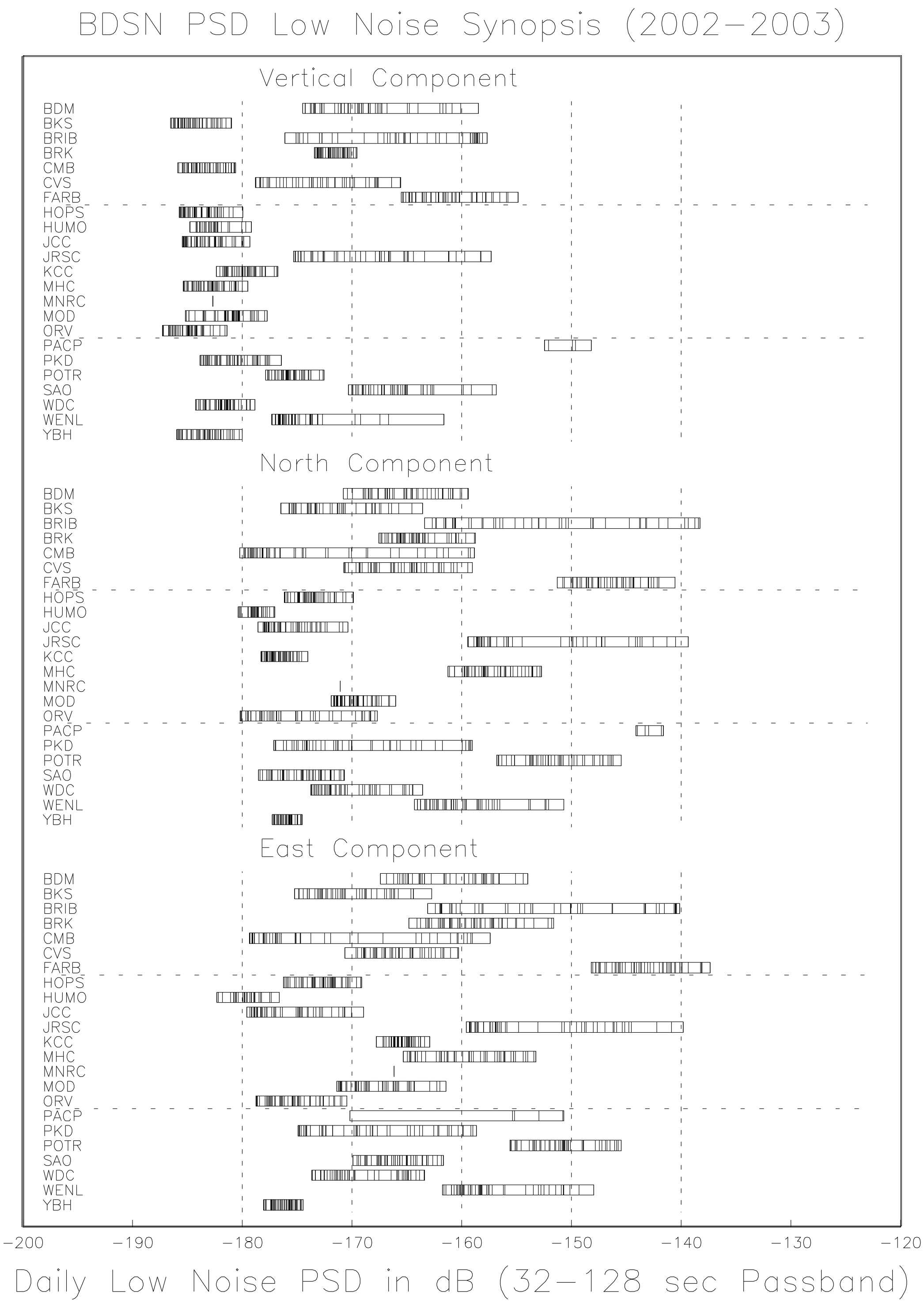

Figure 3.3: PSD noise analysis for BDSN stations, by channel, in the period range from 32-128 sec. PKD stands out in terms of its high noise level variation, which was caused by a problem in the sensor. FARB, sited on the Farallon Islands, stands out as the station with the highest average background noise level. BRIB, sited in a shallow borehole on a hillside prone to seasonal tilting, is also relatively noisy. YBH, sited in a remote and abandoned hard rock mining drift, stands out as exceptionally quiet site.

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
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
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
POTR	BK	38.2026	-121.9353	20.0	6.5	1998/02 -	Potrero Hill, Fairfield
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 3.1: 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.

the high-frequency noise observed on the STS-2 channels and on the STS-1 channels. The LD2 channel was configured to record the output from the Druck microbarograph in early January. We have experimented with installing opto-isolators in all digital signal lines at BSL in order to minimize the number of potential ground loop paths and the results are very encouraging. We will install opto-isolators in all digital signal lines at YBH, the next time the station is visited, to break the ground loop paths which are most likely contributing to the high noise level observed on the STS-2.

STS-1 Hinges

In November of 2001, Bob Uhrhammer reported observations of 1-sided steps on the STS-1 North component at station BKS. In January and early February of 2002, BSL staff replaced the electronics box and tested the baseplates, and concluded that rust on the sensor hinge was the source of the noise. Small rust spots were observed on another STS-1 sensor (both sensors had not been evacuated in their early history).

Since replacement hinges are not available from Streckeisen - and since as many as 20 BDSN sensors could develop this problem, BSL staff began efforts to manufacture replacement hinges. During a visit to BSL, Erhard Wielandt recommended replacing all 4 hinges simultaneously, using material similar to the original. BSL staff has spent time attempting to develop a reproducible recipe for the hinges, including laser cutting the edges for smoothness.

The first set of replacement hinges was tested and found to be too thin. In order to center the mass of the horizontal seismometers, the feet are adjusted such that the glass bell jar no longer clears the instrument itself. A second attempt at fabricating the hinges is ongoing.

Code	Broadband	Strong-motion	Data logger	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/NSN	X
CVS	STS-2	FBA-23	Q4120	X			FR	
FARB	CMG-3T	FBA-23	Q4120	X	X		R-FR/R	
HOPS	STS-1	FBA-23	Q980	X	X	Baseplates	FR	X
HUMO	STS-2	FBA-ES-T	Q4120	X			NSN	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
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	NSN	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
POTR	STS-2	FBA-ES-T	Q4120	X	X		FR	X
RFSB		FBA-ES-T	Q730				FR	
SAO	STS-1	FBA-23	Q980	X	X	Baseplates, EM	FR/NSN	X
SCCB		FBA-ES-T	Q730		X		FR	
WDC	STS-2	FBA-23	Q980	X			FR/NSN	X
WENL	STS-2	FBA-23	Q4120	X			FR	
YBH	STS-1 & STS-2	FBA-23	Q980	X	X	Baseplates	FR	X

Table 3.2: Instrumentation of the BDSN as of 06/30/2003. Every BDSN station consists of collocated broadband and strong-motion sensors, with the exception of PKD1, RFSB and SCCB which are strong-motion only, with a 24-bit Quanterra data logger and GPS timing. 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 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, NSN - USGS NSN satellite link, None - no telemetry at this time. An entry like R-Mi-FR indicates multiple telemetry links, in this case, radio to microwave to frame relay.

3.2 New Installations

In the past year, one installation was completed and two new sites were installed. At Pacheco Peak in south Santa Clara County, the BSL permitted and built an observatory at the site of a State of California radio tower and vault. North of the Bay Area, the BSL installed a site at the McLaughlin Mine Natural Reserve.

Hull Mountain, Oregon (HUMO)

In the fall of 2000, we began a search for a site to extend BDSN north of the California/Oregon border, as part of a collaboration with the USGS National Seismic Network and the Global Seismic Network of IRIS, to be located north of the midpoint between the existing sites at MOD and YBH.

During the fall of 2002, VSAT connection to the National Seismic Network VSAT was established. Because the equipment is underground and the site is located within a mature forest, it was necessary to locate the VSAT dish approximately 300 meters away from the data logger in a location with a view of the southern sky (where the NSN satellite is located). To achieve digital telemetry over this distance, power lines and fiber optic cable were trenched and buried. The fiber optic link connects the data logger with the VSAT hardware. Additionally, the station is accessible via a dial-up phone line.

HUMO is a collaborative effort; the USGS/NSN provided the STS-2 seismometer, the BSL supplied the Episensors and the Quanterra data logger, and IRIS provided additional installation funding. The US Bureau

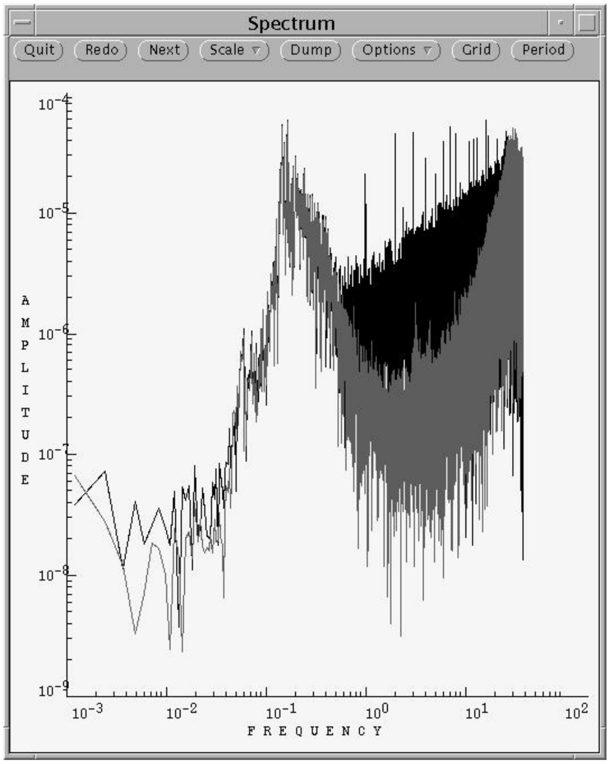

Figure 3.5: Comparison of the STS-1 (lower trace) and STS-2 (upper trace) derived background noise levels at YBH. The spectra are absolute ground acceleration (the respective instrument responses have been deconvolved). The nearly identical spectral amplitudes in the 0.05-0.5 Hz microseismic band indicates that the absolute calibrations of the two sensors are consistent with each other.

of Land Management assisted in locating the historical mine adit, and provides the site permit.

Pacheco Peak

During 2002-2003, BSL acquired a permit from the State of California, Department of Forestry and Fire Protection to install a broadband observatory at Pacheco Peak in south Santa Clara County. The mountain top site has two existing concrete radio vaults and 30 meter antenna towers. Police, fire, and state, and county communication equipment are housed there. Santa Clara County has furnished BSL a microwave channel from the site to transmit data back to their main facility in San Jose where the BSL station SCCB was previously installed in 2000. There data from both stations (PACP and SCCB) are aggregated with two BARD stations (LUTZ and SODA) onto a single digital data circuit.

Data from the Pacheco Peak station was first recorded in late June of 2003. At this time, additional efforts to minimize site, and thermally induced noise is being undertaken, such as the insulation over the seismometer.

The mutual cooperation of the State of California, Department of Forestry and Fire Protection (CDF), Santa Clara County Communications, together with BSL made this site possible.

McLaughlin Mine

The McLaughlin Mine site is on property owned and formerly operated by Homestake Mining Company as a surface gold mine. The geology of the area is extremely varied and complex. With the conclusion of mining operations, the property will be managed as a UC-Davis reserve for research. The seismographic vault is the first new research project on the reserve. The site is located approximately 20 kilometers east of the town of Lower Lake, California in an area of Franciscan sandstone.

A steel and concrete vault from a shipping container similar to those found at stations JCC, PKD, and HOPS was constructed. Power and telephone lines were trenched approximately 300 meters to the site. Because of the remoteness of the site, digital telephone data circuits are not available. To address our desire for continuous telemetry, BSL engineers have proposed and applied for permits to install a wireless radio bridge to a site 50 km away where digital phone service is offered. If and when permits are acquired, data would reach the Berkeley hub via a combination of land telco lines and spread spectrum radios. Continuous telemetry should be achieved in 2003-2004. In the meantime, data are being retrieved by dial-up access.

3.3 New Site Development

Alder Springs

At the Alder Springs site, located approximately 35 kilometers west of the central valley town of Williams, a short period observatory is operated by the California Department of Water Resources. Rocks are mostly serpentine in nature. Again, a seismographic vault similar to those at JCC, PKD, and HOPS will be built. The BSL vault will house the Department of Water Resources equipment presently installed in a fiberglass enclosure. This site has been named GASB by the BSL.

3.4 Ocean Floor Broadband Station

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 permanent 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). In this context, evaluating the possibility of a posteriori noise deconvolution using auxiliary data (e.g. current meter, differential pressure gauge) as well as comparison with land based recordings.

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 3.6). MOISE was a cooperative program sponsored by MBARI, UC Berkeley and the INSU, Paris, France (*Stakes et al.*, 1998; *Romanowicz et al.*, 1998; *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). In the future, it may be linked to the planned (and recently funded) MARS (Monterey Accelerated Research System; `http://www.mbari.org/mars/`) cable, or to the MBARI MOOS buoy, and provide real-time, continuous seismic data to be merged with the rest of the northern California real-time seismic system, although there are plans to eventually replace it by a quieter bore-hole installation.

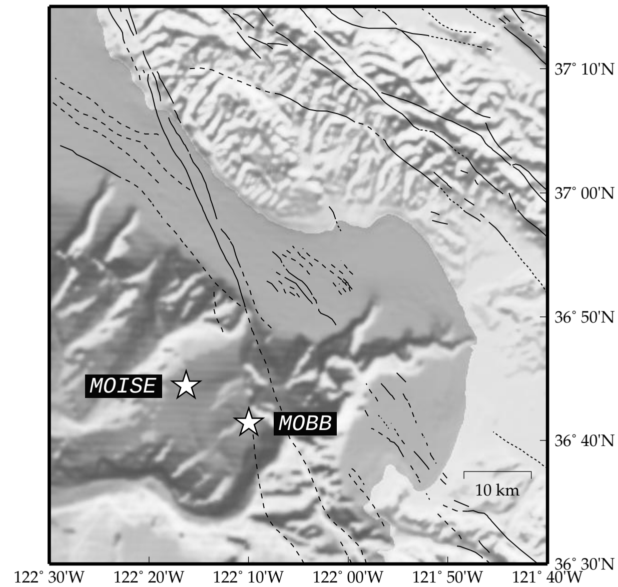

Figure 3.6: Location of the MOBB and MOIS stations in Monterey Bay, California, against seafloor and land topography. Fault lines are from the California Geological Survey database. MOBB is located at 1000 m below sea-level.

Instrumentation

The ocean-bottom MOBB station currently comprises a three-component seismometer package, a current-meter, and a recording and battery package. A differential pressure gauge (DPG) with autonomous recording (e.g. *Cox et al.*, 1984) was deployed in the vicinity of the seismometer package in December 2002.

The seismic package contains a low-power (2.2W), three-component CMG-1T broadband seismometer system, built by Guralp, Inc., with a three-component 24-bit digitizer, a leveling system, and a precision clock. The seismometer package is mounted on a cylindrical titanium pressure vessel 54 cm in height and 41 cm in diameter, custom built by the MBARI team and outfitted for underwater connection.

Because of the extreme sensitivity of the seismometer, air movement within the pressure vessel must be minimized. In order to achieve this, after extensive testing at BSL (Chapter 9), the top of the pressure vessel was thermally isolated with two inches of insulating foam and reflective Mylar. The sides were then insulated with multiple layers of reflective Mylar space blanket, and the vessel was filled with argon gas.

The current-meter is a Falmouth Scientific 2D-ACM acoustic current meter. It is held by a small standalone fixture and measures the magnitude and direction of the currents about 1 meter above the seafloor.

The recording system is a GEOSense LP1 data logger with custom software designed to acquire and log digital data from the Guralp system and digital data from the current meter over RS-232 serial interfaces. The seismic data are sampled at 20 Hz and current-meter data at 1 Hz, and stored on a 3 GB, 2.5 in disk drive. All the electronics, including the seismometer and the current meter, are powered by a single 10kWh lithium battery.

All installations were done using the MBARI ship Point Lobos and the ROV Ventana. Prior to the instrumentation deployment, the MBARI team manufactured and deployed a 1181 kg galvanized steel trawl-resistant bottom mount to house the recording and power systems (Figure 3.7), and installed a 53 cm diameter by 61 cm deep cylindrical PVC caisson to house the seismometer pressure vessel. The bottom mount for the recording system was placed about 11m away from the caisson to allow the future exchange of the recording and battery package without disturbing the seismometer. Prior to deployment, the seismometer package was tested extensively at BSL, then brought to MBARI where its internal clock drift was calibrated in the cold room against GPS time. The details of the deployment which took place on 04/09/02-04/11/02 were described in the 2001-2002 BSL Annual Report.

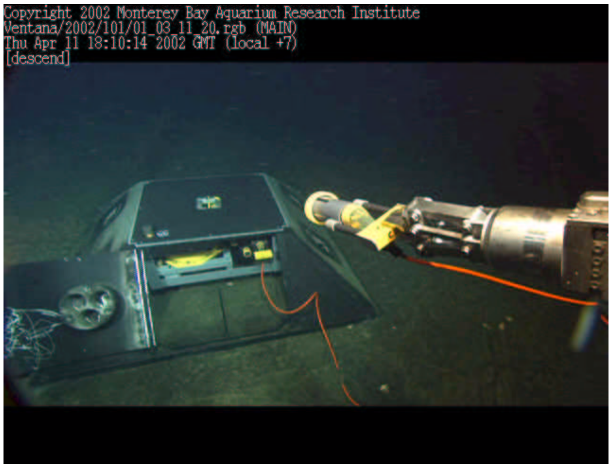

Figure 3.7: Snapshot showing underwater connection of cable from the seismometer system to the recording package inside the trawl-resistant mount. The robotic arm of the ROV is seen holding the connector from the right. Such an underwater connection was successfully performed for the first time during the MOISE experiment. The Point Lobos crew has now gained much experience, reducing the time it takes to successfully connect from over 2.5 hours to 10-15 mn at most.

Since the installation in April 2002, 5 data recovery dives have taken place (Jun 22, 2002; Sep 20, 2002; Jan 7, 2003; Mar 24, 2003; and Jun 9, 2003). Each time, the data recording and battery packages are exchanged for new ones, and the data transferred to BSL for analysis. While the seismometer package functioned well since installation, we have experienced several serious problems with malfunction of the data loggers, so that since that time, new seismic data are available only over short intervals. Both hardware and software problems appear to be involved, but BSL and MBARI staff are optimistic that the problems have been identified and corrected in the June 2003 deployment. We are hoping that the recovery dive scheduled for Sept 16th will result in augmenting our existing 2002 collection with 3 months of valuable uncorrupted MOBB seismic, DPG and current meter data.

Available MOBB data are being systematically analyzed assess the data quality and possible improvements, through post-processing and/or installation adjustments. We plan to evaluate the long term time evolution of background noise, as the system continues to settle and stabilize, and the shorter term noise fluctuations in relation to tides and currents as recorder by the current-meter as well as the DPG. Since the auxiliary data are sampled at sufficiently high rates (1 sps) compared to what was available for the MOISE experiment, we are investigating ways to reduce the background noise correlated with the pressure and current data at periods longer than 10 sec (see the Research contribution in Chapter III)

4. Acknowledgements

Under Barbara Romanowicz's general supervision, Lind Gee and Doug Neuhauser oversee the BDSN data acquisition operations and Bill Karavas is head of the engineering team. John Friday, Dave Rapkin, Cathy Thomas, and Bob Uhrhammer contribute to the operation of the BDSN. Bill Karavas, Bob Uhrhammer, and Lind Gee contributed to the preparation of this chapter.

Support for the installation of HUMO was provided by the USGS/NSN and IRIS. The California Governor's Office of Emergency Services provided funding toward the development of sites MNRC and PACP as part of the CISN.

MOBB is a collaboration between the BSL and MBARI, involving Barbara Romanowicz, Bob Uhrhammer, and Doug Neuhauser 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 funds from NSF/OCE and UC Berkeley.

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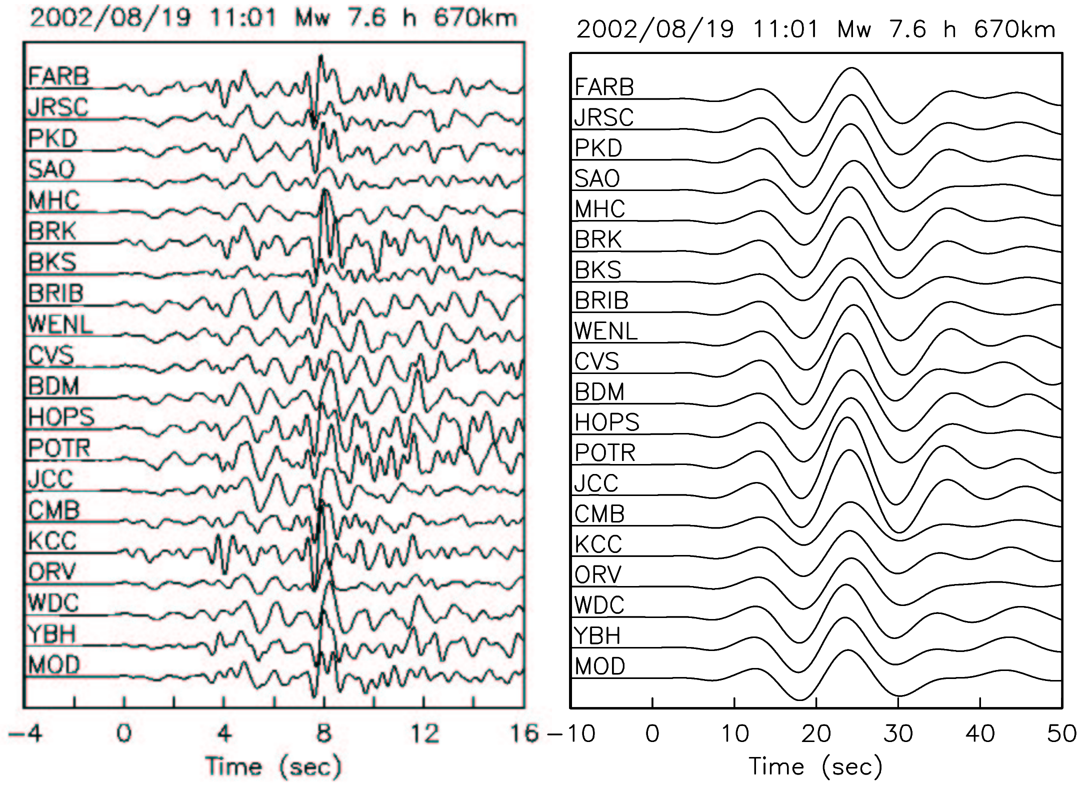

Figure 3.8: it Left: BDSN Z-component broadband recording of the P waveforms from a large deep focus teleseism the occurred in the Russia-northeast China border region (M_w 7.6; 2002.231,11:01; depth 670 km; 75°SW of Berkeley). The waveforms have been bandpass filtered (0.03-3.0 Hz), deconvolved to absolute ground acceleration, ordered by distance from the epicenter and aligned on the first peak in the P waveform (at 0 seconds). The differences in the waveforms in the BDSN broadband records are due primarily to differences in the response of the local crustal structure in the vicinity of each BDSN station. *Right*: Low-pass filtered version of the BDSN Z-component broadband P waveforms shown at left. The waveforms have been bandpass filtered (0.03-0.3 Hz), deconvolved to absolute ground acceleration, ordered by distance from the epicenter and aligned with 0 seconds the same absolute time. The similarities in the waveforms in the BDSN broadband records indicates that the sensors are all performing nominally within their specifications and that their calibrations are internally consistent. The variation in the waveforms correlates with variation in the crustal structure with generally larger amplitudes observed at BDSN stations in the Central Coast Ranges and smaller amplitudes observed at BDSN stations sited in the Sierra Nevada and elsewhere.

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Chapter 4

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 4.1 and Table 4.1). Efforts at ongoing development of the network have also recently been enhanced by through coordinated efforts with the Mini-PBO project (Chapter 8, 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 the surface sites of the NCSN; 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 Bay Area of California. 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 25 stations, 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 4.2). 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 4.1). During initial stages of the project, the NHFN sensors provided signals to on-site Quanterra Q730 and RefTek 72A-07 data loggers. In the current NHFN configuration on-line data logging is being done by on-site Quanterra Q4120 instrumentation. The SHFN sensors have been providing signals to Nanometrics HRD24 data loggers since initiation of data collection.

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.

Thirteen of the NHFN sites have Quanterra data loggers 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

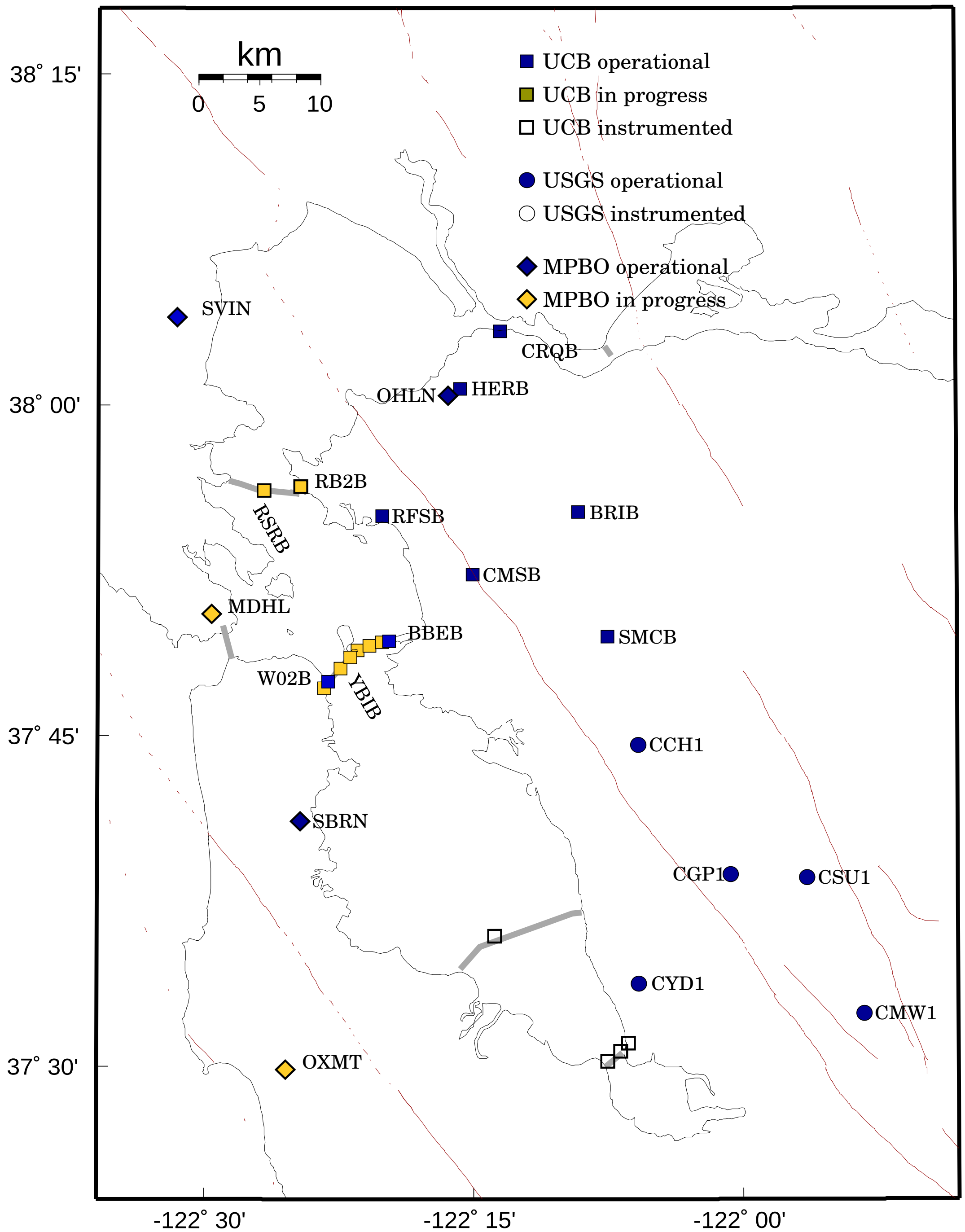

Figure 4.1: Map showing the locations of the HFN stations operated by the BSL (NHFN - squares) and the USGS (SHFN - circles) and Mini-PBO stations (diamonds) in the San Francisco Bay Area. Operational sites are filled, while sites in progress are grey. Other instrumented boreholes are indicated as open symbols.

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 4.3). In contrast to the BDSN implementation, the NHFN data loggers employ casual FIR filters at high data rates and acausal FIR filters at lower data rates. Because of limitations in telemetry bandwidth and disk storage, these 13 sites transmit triggered data at 500 sps, using the Murdock, Hutt, and Halbert (MHH) event detection algorithm (*Murdock and Hutt*, 1983), and continuous data at reduced rates (100, 20 and 1 sps) to the BSL.

The remaining 12 sites of the NHFN have in the past recorded data using RefTek data loggers. These sites do not have continuous telemetry for acquisition and required visits from BSL staff for data recovery. Collection of data from these sites has been discontinued, but efforts are underway to upgraded them with Quanterra Q4120 data loggers 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.

Experience has shown that the MHH detector does not provide uniform triggering across the NHFN on the smallest events of interest. In order to insure the recovery of 500 sps data for these earthquakes, a central-site controller has recently been implemented at the BSL using the 500 sps vertical component geophone data for event detection. Originally the 100 sps vertical component geophone data was used for event detection but the bandwidth proved to be inadequate for detection of the smaller events where most of the seismic wave energy was at frequencies above 40 Hz. Triggers from this controller are being used to recover the 500 sps data from the NHFN data loggers.

Data from the NHFN and SHFN are archived at the NCEDC. 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 (Chapter 11). However, the new central-site controller will provide the capability to both include SHFN data in the event detection and extract SHFN waveforms for these events in the future.

As originally planned, 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. This is not happening quickly, although west of the fault, Caltrans has provided sites along the Bay bridges. This important contribution to the Hayward Fault Network has doubled the number of sites with instrumentation. At times, Caltrans provides holes of opportunity away from the bridges (e.g., HERB), 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 fault.

Sensor	Channel	Rate (sps)	Mode	FIR
Accelerometer	CL?	500.0	T	Ca
Accelerometer	HL?	100.0	C	Ca
Accelerometer	BL?	20.0	C	Ac
Accelerometer	LL?	1.0	C	Ac
Geophone	DP?	500.0	T	Ca
Geophone	EP?	100.0	C	Ca
Geophone	BP?	20.0	C	Ac
Geophone	LP?	1.0	C	Ac

Table 4.3: 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. The 100 sps channels (EP & HL) are only archived when the 500 sps channels are not available.

As a check on the calibration and an example of the capabilities of a borehole installed network, we compare the bandpass filtered (0.3-2 Hz) ground velocity data recorded at HERB, RFSB, BBEB, CMSB, BRIB, and SMCB for a M 6.9 deep focus teleseism that occurred in the vicinity of the Rat Islands in the Aleutian Islands chain at a depth of 685 km. in Figure 4.2.

3. 2002-2003 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 assurance, performance enhancement and catalog development.

3.1 Station Maintenance

Shown in Figure 4.3 are power spectral density (PSD) distributions of background noise for a sample of 8 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 (Figure 5.3). 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 W02) 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 completed.

On average the MPBO NHFN sites are more consistent and quieter (Figure 8.6). This is due in large part to

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
CRQB	BK	38.05578	-122.22487	-25.0	38.4	1996/07 - current	CB
HERB	BK	38.01250	-122.26222	-25.0	217.9	2000/05 - current	Hercules
BRIB	BK	37.91886	-122.15179	219.7	108.8	1995/07 - 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	3.4	1997/12 - current	SMC, Moraga
SVIN	BK	38.03325	-122.52638		158.7	2003/08 - current	MPBO, St. Vincent's school
OHLN	BK	38.00742	-122.27371		196.7	2001/07 - current	MPBO, Ohlone Park
MDHL	BK	37.84227	-122.49374		160.6	in progress	MPBO, Marin Headlands
SBRN	BK	37.68562	-122.41127		157.5	2001/08 - current	MPBO, San Bruno Mtn.
OXMT	BK	37.498	-122.425		194.2	in progress	MPBO, Ox Mtn.
BBEB	BK	37.82167	-122.32867		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		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		36.3	1997/10 - current *	BB, Pier W5
W02B	BK	37.79120	-122.38525		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		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 4.1: 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 stations indicates that the stations are not currently recording data. RSRB is shut down while Caltrans is retrofitting the Richmond-San Rafael bridge (as of April 19, 2001) and YBIB has been off-line since August 24, 2000 when power cables to the site where shut down. Other off-line stations are in the process of being upgraded as funding for equipment becomes available. The table also includes 2 MPBO stations which became operational in the last 2 years, and 3 MPBO borehole sensors that have recently been installed.

Site	Geophone	Accelerometer	Z	H1	h2	Data logger	Notes	Telem.
CRQB	Oyo HS-1	Wilcoxon 731A	-90	251	341	Q4120		FR
HERB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Q4120		FR
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	Posthole	FR
SVIN	Mark L-22		-90	TBD	TBD	Q4120	Tensor.	FR/Rad.
OHLN	Mark L-22		-90	TBD	TBD	Q4120	Tensor.	FR
MDHL	Mark L-22		-90	TBD	TBD	None at present	Tensor.	
SBRN	Mark L-22		-90	TBD	TBD	Q4120	Tensor.	FR
OXMT	Mark L-22		-90	TBD	TBD	None at present	Tensor.	
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	Q4120	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	Q4120	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 4.2: Instrumentation of the HFN as of 06/30/2002. Every HFN downhole package consists of co-located geophones and accelerometers, with the exception of MPBO sites. 6 HFN sites also have dilatometers (Dilat.) and the 5 MPBO sites have tensor strainmeters (Tensor.) 12 NHFN sites have Quanterra data loggers with continuous telemetry to the BSL. The remaining sites are being upgraded to Quanterra data loggers. The 5 SHFN sites have Nanometrics data loggers 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).

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) in their borehole sensor packages.

One of the most pervasive problems at NHFN stations equipped with the new Q4120 data loggers 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.

Below is a synopsis of maintenance efforts performed over the past year for several NHFN stations that gives some idea of the ongoing maintenance and performance enhancing measures that we are continuing to implement.

NHFN Station Maintenance Synopsis

BBEB: Installed upgraded power system in July. Installed Q4120 data logger and started data acquisition on September 10, 2002. Replaced coaxial cable and connector between Cylink radio and antenna to fix problem with poor data flow.

BRIB: Vault flooded in December during heavy rains owing to failure of sump pump. A portable electric generator and sump pump were used to pump out the water. Wood platforms were installed to raise the batteries off of the floor so that they will not become submerged if the vault floods again. The Rule 2000 Sump pump, Sure Bail switch, associated wiring and battery were repaired in the lab and reinstalled in the vault.

CMSB: Replaced batteries with two new C & D Technologies UPS 12-310 batteries. Replaced Q4120 data logger and FRAD. Rodents had chewed on the data logger case but they did not penetrate the case. Replaced defective rodent repeller near the FRAD and installed a second repeller near the data logger. Replaced preamp when it was discovered that channel 4 was bad. Upgraded Q4120 with installation of Q730PWR board. Experienced some problems during year with clock quality owing to poor antenna sky visibility.

CRQB: Upgraded Q4120 data logger with installation of Q730PWR board. Disconnect DAT to fix multiple boot up messages and questionable EP counts problem when booting up the Q4120 data logger. The DAT drive is not used so this is not a problem.

HERB: Swapped in a new preamp to fix a channel gain problem. Spent some time troubleshooting problem with 60 Hz and its harmonics contaminating geophone channels and running a series of experiments and discovered that the 120 Hz signal is a 100 kHz spike which repeats at a 120 Hz rate. Installed damping resistor when it was discovered to be missing. Also installed shunt capacitors to reduce the high frequency spike noise. Replaced power supply when it was discovered to have periods of imperfect regulation.

RFSB: Upgraded Q4120 data logger with installation of Q730PWR board and new software.

SMCB: Station was down from August 28 through October 29 owing to construction at Moore Hall which provided power and telemetry. Q4120 digitizers failed due to a blown fuse. While Q4120 was in lab for fuse replacement a Q730PWR board was added to give input power monitoring capability.

W02B: Installed hardware (data logger, etc.) in utility boxes bolted to the NW face of the pier, just above water level. Began data acquisition and telemetry on June 17th.

Geophone Calibrations

Comparisons of the inferred ground accelerations generated by local earthquakes, from co-sited HFN geophone and accelerometer pairs, shows that the waveforms 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 and also 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 that 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 not accurate. *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 data logger 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 now performing the initial calibration tests and response adjustments for all NHFN stations as sites are visited for routine maintenance. We also plan a scheduled re-tests of all sites to monitor for sensor responses changes through time.

3.2 Combined Catalog

We are building a HF-specific data archive from the existing waveform data that have been collected by the heterogeneous set of recording systems in operation along the Hayward fault (i.e. the NHFN, SHFN, NCSN, and BDSN continuous and triggered waveforms). Recently we have taken the NHFN triggers collected during operations between 1995.248 and 1998.365 (recorded on portable RefTek recorders) and origin times from the NCSN and BDSN catalogs for this time period and undertaken a massive association of event and trigger times. The purpose of the effort is to compile a relatively uniform catalog of seismic data to low magnitudes and extending back in time to the beginning of reliable HFN data collection. The process has reduced nearly a million individual time segments to 316 real events along the Hayward fault during the period–an increase in the number of events of a factor of about 2.5 to 3 over the NCSN catalog alone in the same area.

3.3 Event Detection

As noted in the Introduction, one of the purposes of the HFN is to lower the threshold of microearthquake detection. Towards this goal, we have been developing new algorithms: a pattern recognition approach to identify small events; a phase onset time detector with sub-sample timing resolution, and; a phase coherency method for single component identification of highly similar events.

Pattern Recognition

In order to improve the detection and analysis of small events (down to $M_L \sim$-1.0) some specialized algorithms are being developed. 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. One solution is to use a pattern recognition approach to identify small events associated with the occurrence of an event which was flagged by the REDI system. Tests have indicated that the pattern recognition detection threshold is $M_L \sim$ -1.0 for events occurring within $\sim$10 km of a NHFN station. The basic idea is to use a quarter second of the initial P-wave waveform, say, as a master pattern to search for similar patterns that occur within $\pm$ one day, say, of the master event. Experimentally, up to six small CMSB recorded events, at the $M_L \sim$ -1.0 threshold and occurring within $\pm$ one day of a master pattern, have been identified.

The pattern recognition method is CPU intensive, however, and it will require a dedicated computer to handle the pattern recognition tasks. To expedite the auto-correlation processing of the master pattern, an integer arithmetic cross-correlation algorithm has been developed which speeds up the requisite processing by an order of magnitude.

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, say, 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 data loggers, be removed. The algorithm typically resolves P-wave onset times to one-fiftieth of the sample interval or better.

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 which occur months to years apart. The resolution of the complex spectral phase coherency methodology is an order of magnitude better that the cross correlation method which is commonly used to identify highly similar events with resolution of order a few meters. This method, originally developed using NHFN borehole data, is now being applied as well to data from another borehole network (the HRSN) to provide more rapid and objective identification of the large fraction (approx. 40%) of characteristically repeating microearthquakes that occur at Parkfield, CA.

3.4 New Installations

San Francisco-Oakland Bay Bridge

The infrastructure at seven stations along the San Francisco-Oakland Bay Bridge (SFAB, W02B, W05B, YBAB, E07B, E17B, and BBEB) was upgraded with the installation of weatherproof boxes, power, and telemetry in anticipation of installing Q4120 data loggers and telemetering the data back to Berkeley. BBEB was brought on-line in May of 2002, and W02B in June of 2003.

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. The hole is to be drilled by Caltrans as a hole of opportunity when the schedule of a Caltrans drilling crew has an opening. The site has been reviewed by UCB, Caltrans and St. Mary's college personnel, and we are now in the drilling queue. Depending on the geology at borehole depth, this site my either become a MPBO site (w/o accelerometers) or a standard land site installation including both geophones and accelerometers.

Caltrans has also provided funding for instrumentation of several other land sites which we will install as future Caltrans drill time becomes available. Currently we are considering sites for these additional holes-of-opportunity at Pt. Pinole, on Wildcat Mtn. in the north Bay.

Mini-PBO

The stations of the Mini-PBO project (Chapter 8) are equipped with borehole seismometers. As these stations have become operational, they augment HFN coverage (Figure 4.1). In the last year, SVIN and SBRN have added coverage to the north bay and east side of the south bay, respectively.

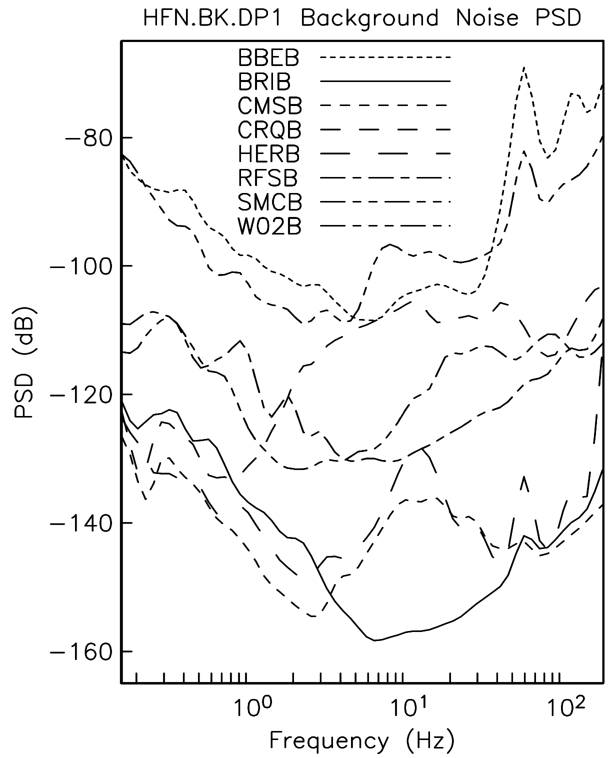

Figure 4.3: Plot showing the HFN.BK.DP1 background noise, PSD, for 8 of the NHFN stations. Plotted are the background low-noise PSD estimates. Ten minutes of .BK.DP1 data starting at 2003.225.0900 (2 AM PDT) were used in the analysis. Note that there is considerable variation in the general level and structure of the individual station background noise PSD estimates. Some of the stations show peaks at 60 Hz and its harmonics while others have a high average background level. The two bridge sites, BBEB and W02B are the noisiest while land site BRIB in Briones Regional Park (well away from the heavy cultural noise of the more populated region of the Bay Area) is the quietest. Two stations, CMSB and HERB show a peak in the 20-30 Hz range. The peak at CMSB is probably due to excitation of modes in the open bore hole and the peak at HERB is due to excitation of the local structure by the adjacent railway line and highways 4 and 80. The three stations in the middle of the group (RFSB, SMCB and CRQB) are responding to the local cultural noise. There are numerous ongoing experiments at the Richmond Field Station which are affecting the noise level at RFSB, CRQB is sited near a sewage treatment plant and the Carquinez bridge, and SMCB is currently only installed at post hole depth (3.5 m) on the St. Mary's campus.

4. Acknowledgements

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, Wade Johnson, Doug Neuhauser, Bill Karavas, John Friday, and Dave Rapkin all contribute to the operation of the NHFN. Bob Nadeau, Bob Uhrhammer and Lind Gee contributed to the preparation of this chapter.

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5. References

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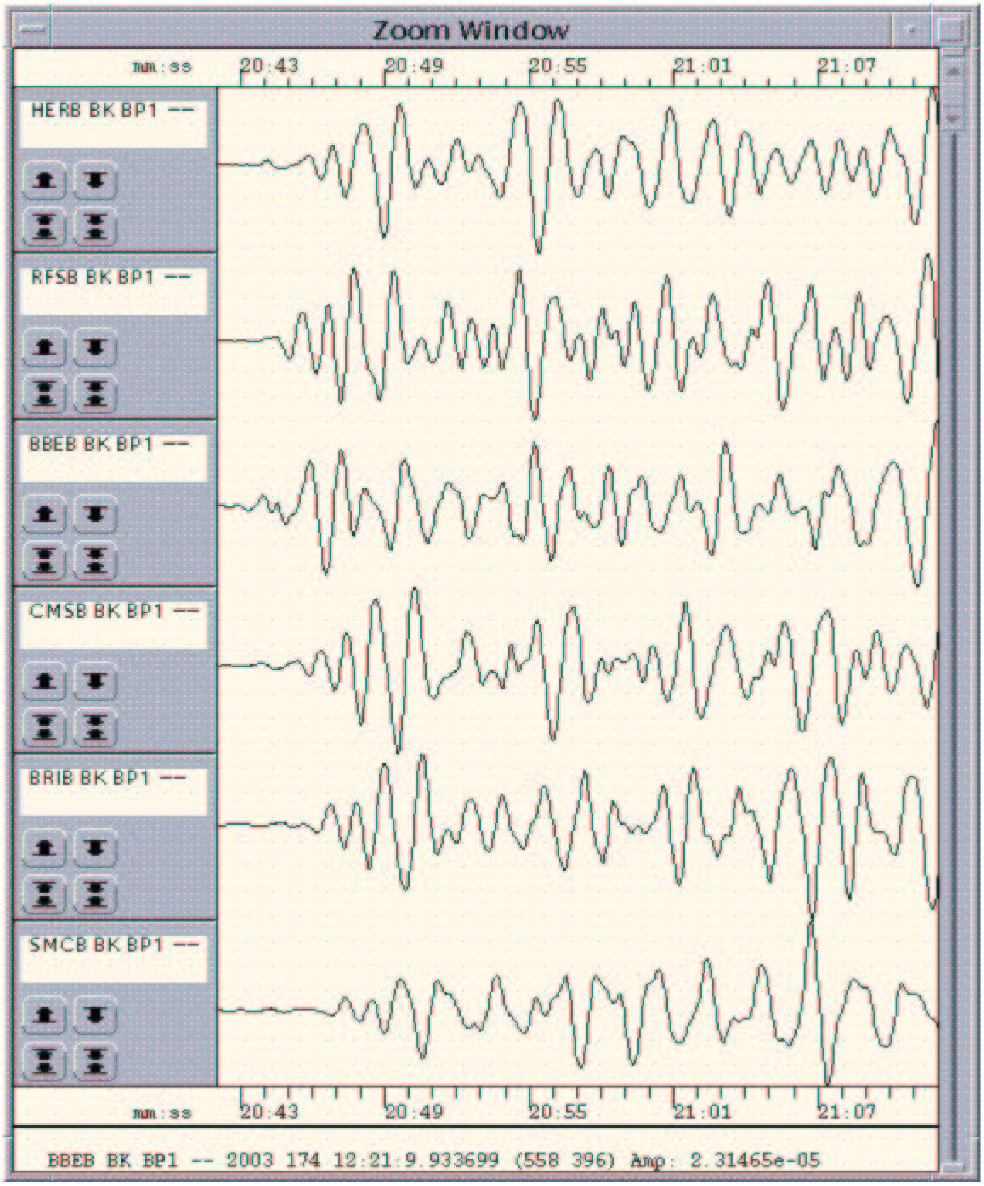

Figure 4.2: Displayed are 30 seconds of 0.5-2.0 Hz BP filtered ground velocity data for a M_w 6.9 deep focus teleseism which occurred 6/23/2003 at 12:12 UT at a depth of 685 km in the vicinity of the Rat Islands in the Aleutian Islands chain (51.44N,176.78E). The traces have been ordered by increasing distance (top to bottom). For reference, the great circle distance of the event from the NHFN is $\sim 44.2°$with an azimuth of $\sim 308°$. The NHFN waveforms are relative scaled. Absolute scaling of the plot has indicated that the transfer function gain for station BBEB may be too low, making the inferred filtered ground velocity too large for a true comparison of the ground velocity. By periodically analyzing the network-wide response to deep focus teleseisms, whose arrivals are of near vertical plane wave incidence of uniform amplitude, anomalous station response (indicating potential problems in the network) such as that seen for BBEB are easily identifiable and can be further investigated to ensure accurate station operation. The same teleseism may be seen in Figure 5.2, recorded on the HRSN.

Chapter 5

Parkfield Borehole Network

1. Introduction

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

Figure 5.1 shows the location of the network, its relationship to the San Andreas fault, sites of significance from previous and ongoing research using the HRSN, relocated earthquake locations from 1987-1998.5, routine locations of seismicity since August 2002, and the epicenter of the 1966 M6 earthquake that motivated the PPE. 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 (5.1)), its high-frequency wide bandwidth recordings (0-125 Hz), and its low magnitude detection threshold (recording events below magnitude -1.0).

Several aspects of the Parkfield region make it ideal for the study of small earthquakes and their relationship to tectonic processes. These include the fact that the network spans the expected nucleation region of a repeating magnitude 6 event 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), a 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, a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip), and the planned drilling zone and penetration and instrumentation site of the San Andreas Fault deep observatory at depth experiment (SAFOD) (see: `http://www.earthscope.org/safod/index.html` or `http://www.iris.iris.edu/HQ/EarthScope/EarthScope.saf.html`).

In a series of journal articles and Ph.D. theses, we have presented the cumulative, often unexpected, results of U.C. Berkeley's HRSN research efforts (see: `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.

2. HRSN Overview

2.1 1986 - 1998

The HRSN was installed in deep (200-300m) boreholes beginning in 1986. 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 network was completed to a ten station 3-component 500 sps set of stations telemetered into a central detection/recording system operating in triggered mode and incorporating a deep (572 m) sensor in the Varian well string into the network. The Varian system was slaved in 1988, 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 to M_L about 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, old batteries, and recording system outages of a week or more were not uncommon. In July of 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 (dis-

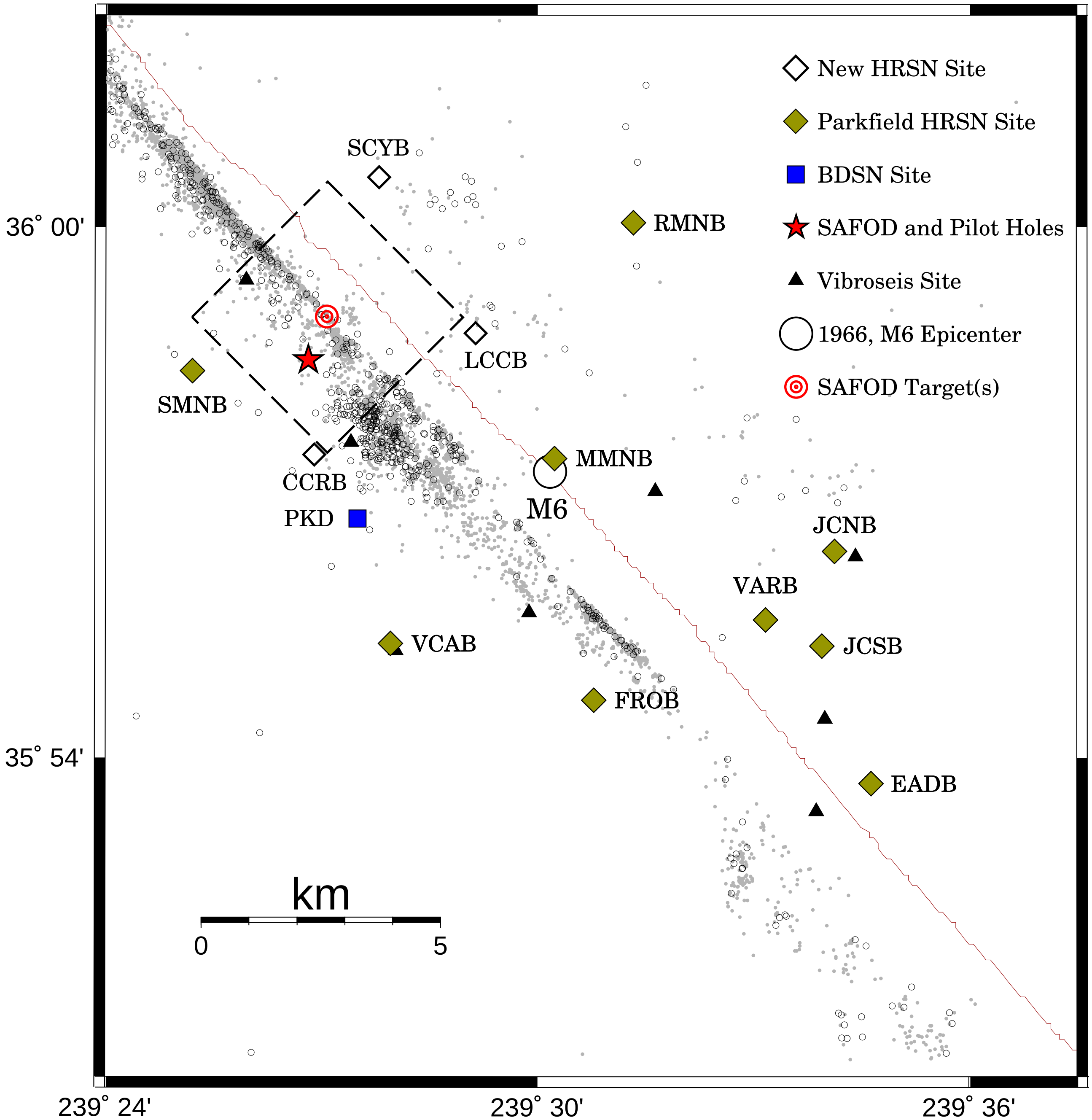

Figure 5.1: Map showing the San Andreas Fault trace, the location of the original 10 Parkfield HRSN stations (filled diamonds) and the 3 new sites installed to enhance coverage of the region containing the SAFOD facility (open diamonds), along with the BDSN station PKD (filled square). The locations of the 8 source points for the Vibroseis wave propagation monitoring experiment are represented by small black triangles. The epicenter of the 1966 M6 Parkfield main shock is located at the large open circle. The location of the pilot hole and SAFOD drill site is shown by the filled star, and the location of the 2 alternative M2 repeating earthquake targets (70 meters apart) are shown as concentric circles. Because of the SAFOD experiment, the 4 km by 4 km dashed box surrounding the SAFOD zone is a region of particular interest to BSL researchers. Routine locations of earthquakes recorded by the expanded and upgraded 13 station HRSN are shown as open black circles. Locations of events recorded by the earlier vintage 10 station HRSN, relocated using an advanced 3-D double-differencing algorithm applied to a cubic splines interpolated 3-D velocity model (*Michelini and McEvilly*, 1991), are shown as gray points. Station GHIB (Gold Hill, not shown) is located on the San Andreas Fault about 8 km to the Southeast of station EADB.

continued 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 of 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 was required, in order to identify the microearthquakes down to M = -1, 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 we had to reduce the network 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 5.2.

2.3 Upgrade and SAFOD Expansion

Thanks to emergency funding from the USGS NEHRP, we have 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). The new system is now online and recording data continuously at a central site located on the California Department of Forestry (CDF) fire station in Parkfield.

We have also added three new borehole stations at the NW end of the network as part of the SAFOD project, with NSF support, to improve resolution at the planned drilling target on the fault. Figure 5.1 illustrates the location of the proposed drill site (star), the new borehole sites, and locations of earthquakes recorded by the initial and the upgraded/expanded HRSN.

These three new stations use similar hardware to the main network, with the addition of an extra channel for electrical signals. Station descriptions and instrument properties are summarized in Tables 5.1 and 5.2. All HRSN Q730 data loggers employ FIR filters to extract data at 250 and 20 Hz (Table 5.3).

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

Table 5.3: 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.

The remoteness of the drill site and new stations require 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. A modified version of the REDI real-time system detects events from the HRSN data, creates event files with waveforms from the HRSN and sends the event data in near real-time to UC Berkeley. Currently the continuous data is being migrated to DLT tape when local disk space fills up, and the tapes are mailed to the BSL for long-term storage. Efforts are being made to acquire funding to make this data Internet accessible to the research community through the NCEDC.

The upgraded system is compatible with the data flow and archiving common to all the elements of the BDSN/NHFN and the NCEDC, and is providing remote access and control of the system. It is also providing data with better timing accuracy and longer records, which are to eventually flow seamlessly into NCEDC. The new system also solves the problems of timing resolution, dynamic range, and missed detections, in addition to providing the added advantage of conventional data flow (the old system recorded SEGY format).

3. 2002-2003 Activities

Over the past year, activities associated with the operation of the HRSN primarily involved three components: 1) routine operations and maintenance of the network, 2) enhancement of the network's performance for detection and recording of very low magnitude earthquakes, and 3) routine data processing and analysis.

3.1 Operations and Maintenance

In addition to the routine maintenance tasks required to keep the HRSN in operation, various refinements and adjustments to the networks infrastructure and opera-

Site	Net	Latitude	Longitude	Surf. (m)	Depth (m)	Date	Location
EADB	BP	35.89525	-120.42286	499	245	01/1988 -	Eade Ranch
FROB	BP	35.91078	-120.48722	542	284	01/1988 -	Froelich Ranch
GHIB	BP	35.83236	-120.34774	433	63	01/1988 -	Gold Hill
JCNB	BP	35.93911	-120.43083	559	224	01/1988 -	Joaquin Canyon North
JCSB	BP	35.92120	-120.43408	487	155	01/1988 -	Joaquin Canyon South
MMNB	BP	35.95654	-120.49586	731	221	01/1988 -	Middle Mountain
RMNB	BP	36.00086	-120.47772	1198	73	01/1988 -	Gastro Peak
SMNB	BP	35.97292	-120.58009	732	282	01/1988 -	Stockdale Mountain
VARB	BP	35.92614	-120.44707	511	572	01/1988 -	Varian Well
VCAB	BP	35.92177	-120.53424	790	200	01/1988 -	Vineyard Canyon
CCRB	BP	35.95716	-120.55161	601	251	05/2001 -	Cholame Creek
LCCB	BP	35.98006	-120.51423	637	252	08/2001 -	Little Cholame Creek
SCYB	BP	36.00942	-120.53661	947	252	08/2001 -	Stone Canyon

Table 5.1: 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 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 5.2: 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 in the near future.

tional parameters have been needed this year to correct for pathologies that continue to manifest themselves in the recently upgraded and expanded system.

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 data loggers 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, it can also be directly accessed. 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 data loggers to modify or restart processes when necessary.

The network connectivity allows analysts at the BSL to routinely perform checks on the system health of the HRSN and its data quality. One example of a technique used by BSL analysts involves the use of teleseismic arrivals from deep focus earthquakes. Since seismic waves from such events impose a near simultaneous and vertically incident plane wave of relatively uniform amplitude on all HRSN stations, seismograms from these events can be used to assess relative station responses across the network and help identify pathologies in station polarities, individual component failures and other response characteristics.

Figure 5.2 shows an example of a recent teleseism recorded on the DP1 (vertical) channel across the network. Not shown are recordings from stations MMNB and VARB. The initial display of seismograms from this teleseism showed these station components to be responding abnormally at the time of the earthquake. Based on this teleseismic result other remotely acquired information was uploaded from the HRSN and it was determined that these components were indeed malfunctioning. Subsequent field visits were then scheduled and the necessary repairs made.

The network connectivity also allows remote monitoring of the background noise levels being recorded by the HRSN stations. For example shown in Figure 5.3 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.

Triggered event data for the HRSN is also telemetered in near real time to the BSL, and this allows for rapid evaluation of the triggered data. This year we have implemented a semi-automated waveform and trigger review procedure using a graphical user interface (GUI). This procedure is now being used to review the triggered waveform data daily to discriminate between earthquake and non-earthquake events and to pick P and S phases of the local events. In the process, our analyst/field technician also makes note of obvious problems with station/component specific earthquake recording, and this malfunction information is used to identify maintenance needs for the HRSN.

3.2 Enhancing HRSN Performance

Over the past year significant efforts were made to identify and reduce noise problems arising from the new and expanded data acquisition system. Detection, monitoring, and high-resolution recording of earthquakes down to the smallest possible magnitudes with the highest possible signal-to-noise (especially in the region of the proposed SAFOD drilling) is a major objective of the HRSN data collection effort. Consequently, elimination of all sources of unnaturally occurring system noise is a primary goal. The minimization of data loss due to station outages and data-dropouts is also critical to this objective.

The sophisticated HRSN data acquisition involves integration of a number of distinct components at each station (i.e., sensor, preamp, solar panels, solar regulator, batteries, Freewave radio, antenna, lightening arresters, and associated cabling, connectors and grounds) and radio telemetry apparatus between the seismic stations, telemetry relay stations, and the central processing site on the CDF site in Parkfield.

This complex integration of station and communication components combined with a variety of associated concerns (e.g., ground loops, cable resistances, radio feedback into recording equipment at stations, radio interference between stations, marginal line of site paths, cloud cover and solar power, the integration of older (pre-upgrade) hardware components with new components, old component deterioration and failures, and malfunctioning and unexpected performance characteristics of newer components) all make identification of specific causes of network generated (i.e. artificial) noise difficult to identify.

Exhaustive and iterative testing of HRSN performance has identified two primary causes for observed artificial noise remaining in the system (i.e. solar regulator spiking and preamp self-noise generation). We have designed and have implemented or are in the process of implementing

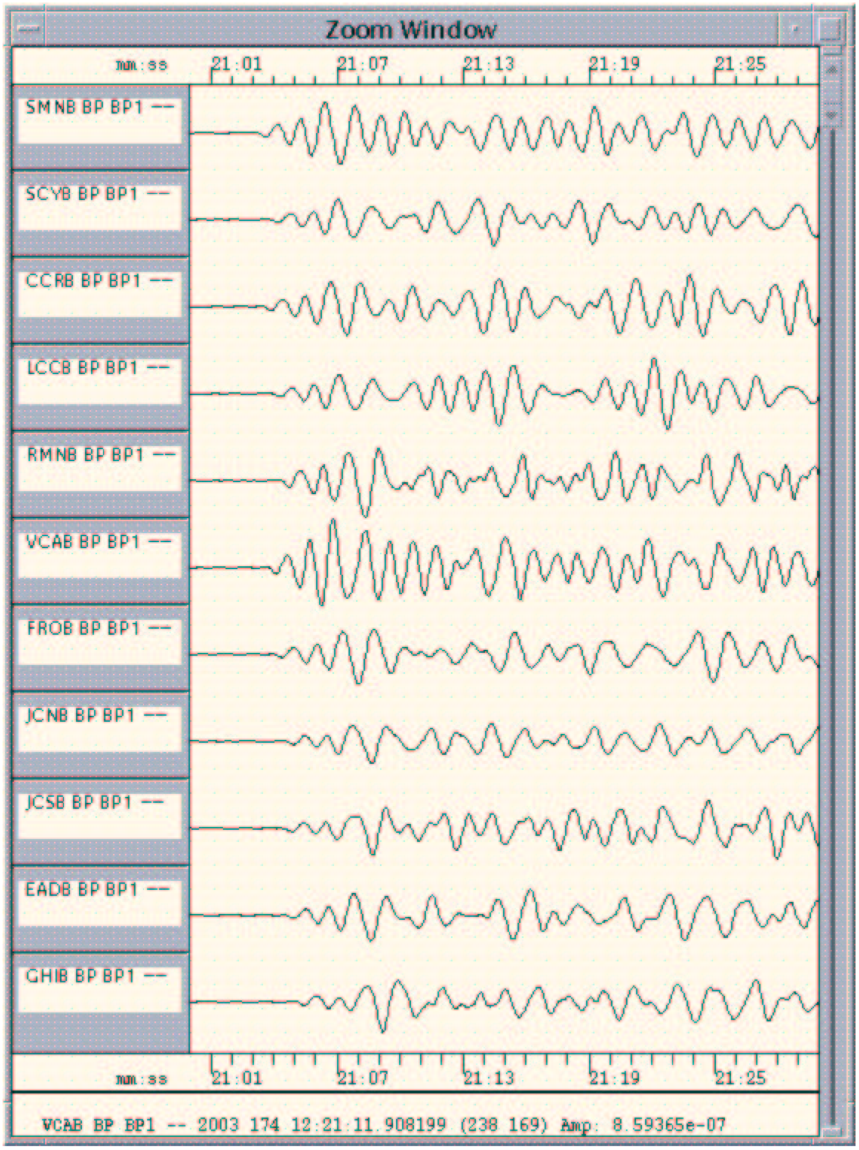

Figure 5.2: Displayed are 30 seconds of 0.5-2.0 Hz BP filtered vertical ground velocity data for a M_w 6.9 deep focus teleseism which occurred 6/23/2003 at 12:12 UT at a depth of 685 km in the vicinity of the Rat Islands in the Aleutian Islands chain (51.44N,176.78E). The traces have been ordered by increasing distance (top to bottom), their waveforms are absolute scaled to allow comparisons between the response functions between stations. The great circle distance to the HRSN is approximately 46.5 degrees with an azimuth of $\sim 310°$. The recording of this teleseism on the Northern Hayward Fault Network is show in Figure 4.2.

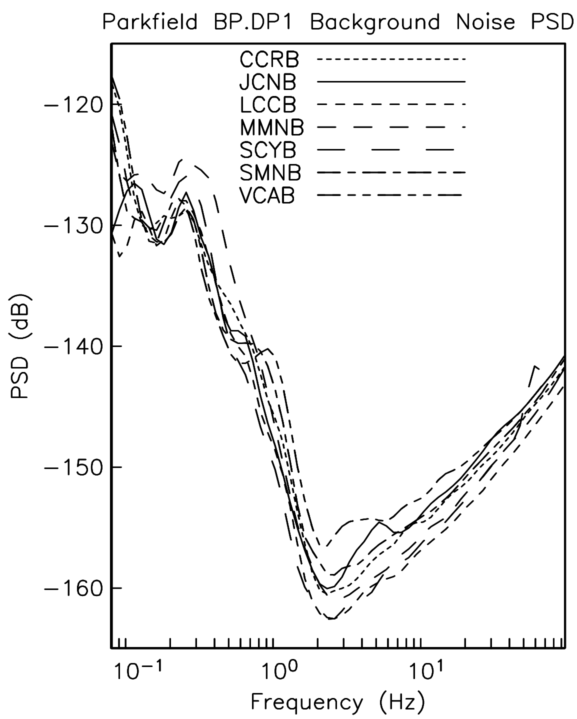

Figure 5.3: Background noise PSD plot for the seven continuously telemetered BP.DP1 data streams from Parkfield. The data are 20 minute samples starting at 2003.225.0900 (2 AM PDT). The plots show the background noise PSD as a function of frequency for the the highest available sampling rate (250 sps) vertical component data which are continuously telemetered to Berkeley. Note the relatively low PSD levels and the overall consistency for all the HRSN stations. By comparison, the PSD curves among the borehole Northern Hayward Fault Network (NHFN) land and bridge stations (Figure 4.3) are much more variable and show a generally higher background noise level. On the other hand, PSD curves for the MPBO stations of the NHFN are much more consistent with the HRSN PSD's (Figure 8.6). The differences among the various station PSD's can, in large part, be explained by the relative cultural noise levels at the various stations, by the depth of the borehole sensors, and by whether the boreholes remain open holes (noisier) or have been filled with cement. The 2 Hz minimum in the PSD plots for the HRSN sensor results from 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. In the 2 to 5 Hz range, VCAB and JCNB have historically shown higher background noise which is believed to result from excitation modes in the local structure. A small 60 Hz blip can be seen in the SCYB curve due to its close proximity to a power-line.

fixes for these problems. We are also continuing to improve the HRSN event detection sensitivity by refining the HRSN triggering scheme.

Solar Regulators

Regularly occurring spikes occurring during the daylight hours were observed in the continuous data streams and found to be due to the solar regulators. We have tested a variety of solar regulator designs and have identified the Prostar 30 as having the optimal cost-benefit. We have purchased and installed several of these devices at several of the HRSN sites with the ultimate goal of installing the Prostar's at all the HRSN stations as time and funding permit.

Pre-amplifier Noise

We found that a significant source of artificial noise was coming from the station pre-amplifiers. In the upgraded system, preamps from the older network were used. During integration of the older preamps with the increased dynamic range capabilities of the 24-bit Quanterra system, gain settings of the preamps were reduced from x10,000 to x80 in order to match signal sensitivity of the new system with the older one. While these lower preamp gain levels are still within the operational design of the preamps, they are no longer in their optimal range and a significant contribution of preamp's self-generated noise is present in the recorded seismograms. Initially, this was not expected to be a significant problem. However, we have subsequently found that even the small increase in preamp noise that results from the preamp gain reduction significantly impacts the sensitivity of the network for detecting and recording the smallest locatable events.

Figure 5.4 shows the preamp noise reduction effect observed on background noise signals at three vertical components of the HRSN when gains are raised from x80 to x1,000. Considerable signal hash is seen at gain levels of x80 (top waveform in each station pair), and significantly reduced when gains are increased to x1,000 (lower waveforms). Since we are also interested in recording large earthquakes on-scale, simply increasing gain levels on all stations is not the preferred solution, since doing so causes the recording system to saturate at much lower magnitudes. Instead we are attempting to redesign the preamps using modern components to reduce the noise levels at the lower gain levels. However our attempts at redesign have not yet yielded satisfactory results.

Since a primary objective of the HRSN is to monitor the evolving patterns of the numerous small earthquakes that occur at very low magnitudes, and since this objective also complements the scientific objectives of the recently funded SAFOD experiment, it is important to address the preamp noise problem in a timely manner. We have opted, therefore, to raise the gain levels for the

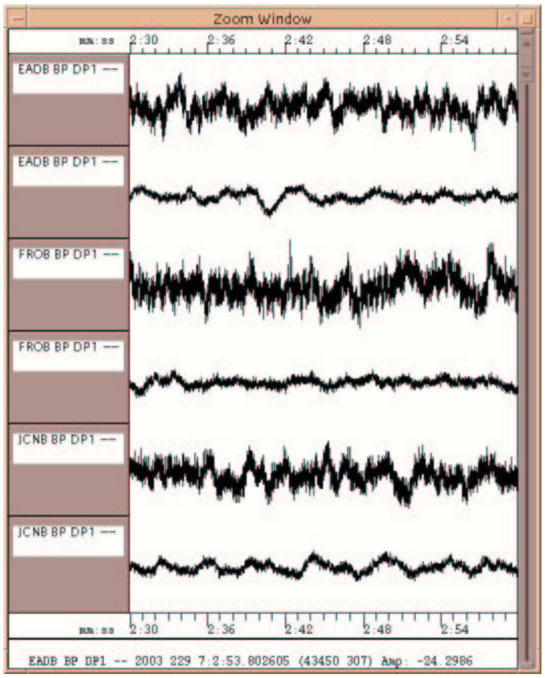

Figure 5.4: Preamp noise reduction test. Shown are 30 seconds of vertical background signal recorded at stations EADB, FROB and JCNB on day 229 of 2003 at 0700 UTC (top of station pairs, recorded at x80 gain and scaled up by 1000/80 for comparison to the x1000 preamp gain levels) and 0700 UTC on day 233 (bottom of station pairs, recorded at x1000 preamp gain). Note the substantial reduction in background noise, due primarily to the lower preamp generated noise at higher preamp gain.

near-term on all the station preamps from x80 to x1,000. These gain changes are currently (late August, 2003) being implemented, and we estimate that the number of small earthquakes we will detect will increase by a factor of 2 to 3. We will continue investigating preamp redesigns until a suitable alternative is found at which time we will install the new preamps and lower the preamp gain back to x80–allowing both the increased detection of small events and the on-scale recording of events up to about magnitude 4 to 4.5.

Triggering Refinement

Additional efforts underway to increase event detection sensitivity include: 1) development of a station specific filtering scheme for input into the triggering algorithm, 2) refinement of the multi-station trigger association algorithm to include subnet triggering, and 3) incorporation of the pilot hole array data into the network triggering scheme to capture the smallest events in the SAFOD drilling area.

3.3 Routine Data Analysis

Monitoring the evolution of microseismicity, particularly in the SAFOD drilling and target zone, is a primary objective of the HRSN project. In addition, the continued analysis of the HRSN data for determining detailed seismic structure, for the study of similar and characteristic microearthquake systematics, for estimation of deep fault slip rate evolution, and for various studies of fault zone and earthquake physics is also of great interest to seismologists. Before advanced studies of the Parkfield microseismicity can take place, however, initial processing, analysis and routine cataloging of the earthquake data must be done. An integral part of this process is quality control of the processed data, including a final check of the routine catalog results.

Initial Processing

At this time, continuous data streams on all 39 components are being recorded at 20 and 250 sps on disk on the local HRSN computer at the CDF facility and when the local disk space is full, the continuous data is migrated onto DLT tape. The 20 sps data are transmitted continuously to the BSL over the frame-relay linked and 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 to the BSL at 250 sps over the frame relay-circuit for purposes of quality control and fine tuning the triggering algorithm for the detection of the smallest possible events around SAFOD.

Shortly after being recorded to disk, 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 trigger, 30 second waveform segments are then collected for all stations and components, assigned a unique event identifier (compatible with the NCEDC classification scheme) and saved as an event gather. Event gathers are then periodically telemetered to BSL and included directly into the NCEDC earthquake database (dbms) for analysis and processing.

An ongoing effort has been the development of a new earthquake triggering scheme, with the goal of routinely detecting SAFOD area events to magnitudes below -1.0. A first cut version of the new scheme has been implemented and is already detecting earthquakes at an increased rate–nearly 3 times the number of earthquakes detected before the upgrade.

In order to facilitate the processing and archiving of this large number of events (approx. 150 per month), BSL personnel have recently developed a Graphical User Interface (GUI). The GUI is integrated with the NCEDC dbms and allows review of the waveforms from every triggered event. Initial analysis of the data using the GUI involves review of the waveforms and classification of the event as an earthquake or non-earthquake event. The GUI also allows the analyst to log potential network problems that become apparent from the seismograms. The HRSN analyst then classifies the event as a local, distant-local, regional, or teleseismic event and then systematically hand picks the P- and S-phases for the local and distant local events.

Picking of the numerous microearthquake events is no mean task. On average about 7 P-phases and 4 S-phases are picked for each event, putting the total number of annual phase picks for the HRSN data on the order of 19,000 to 20,000. We have experimented with algorithms that make initial auto-picks of the phase arrivals, but have so far found picking by hand to be an advantage since it forces the analyst to review each pick carefully while at the same time allowing him to assess the state of health of recording on each station-component in detail. In all our tests, repicked autopicks have also invariably resulted in catalog locations that are significantly more scattered and that have higher residuals than locations done with purely hand-picked data.

A peculiarity of processing very small earthquake data, is that multiple events commonly occur within a few seconds of one another (Figure 5.5). The close timing of these events does not allow the local triggering algorithm to recover from one event before another occurs. As a result, the central site processor often does not trigger uniquely for each event. In such cases only one, 30 sec waveform gather and one earthquake identifier will be created for all the events. These multiple earthquake records (MER) account for only 3 to 5% of the total seismicity recorded by the HRSN. However, there are times when this rate rises to over 10%. In order to assign each event in an MER a unique event identifier for the NCEDC dbms and to make picking and automated processing of these events more manageable an additional feature of the GUI was developed that allows the analyst to "clone" MER into separate gathers for each event.

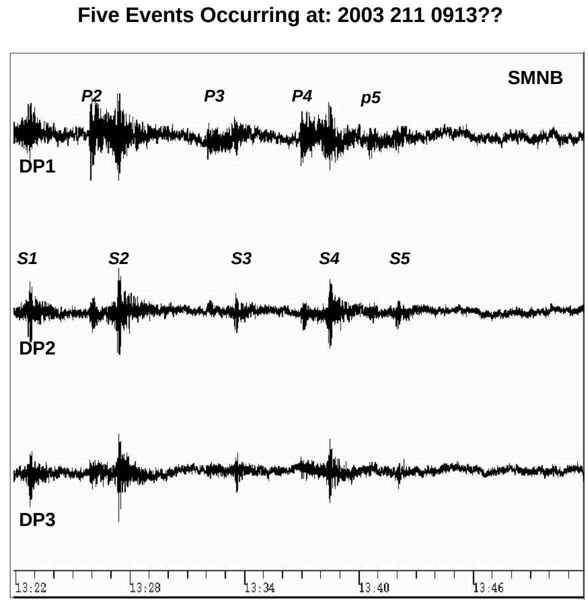

Figure 5.5: Five events occurring on the same MER. The P phase of the first event was not captured on this record. These five events occurred as part of a swarm of 47 small events recorded by the HRSN that occurred on day 211 of 2003. Of these 47 events, the NCSN catalog contains only 2. Events shown are all less than magnitude 0.

Quality Control

Once false triggers have been removed and picks for the events completed, quality control on the picks is made to ensure that all picks have phase and weights assigned, that extraneous characters have been removed from the pick files, that double station-phase picks have not inadvertently been made, and that no repicks of the same event had been accidentally made during any cloning that was performed.

Initial locations are then performed and phase residuals analyzed in order to determine whether severe pick outliers must be removed or adjusted. Unstable location solutions based on events with few picks are also assessed to see if the addition of marginal phases will improve the stability of the location determination.

After any required pick adjustments have been made, the events are then relocated, and combined with error information to allow ranking of the confidence of location quality.

These procedures have all been put in place and tested over the past year for the new HRSN configuration. Currently we have located 9 months of data recorded by the new HRSN (over 1300 events) and are staying current with ongoing seismicity and also moving backwards in time to pick and locate the earlier data collected since early 2001.

We now have enough data and are confident enough with the procedures to begin organizing the locations for formal inclusion into the NCEDC dbms and dissemination to the community. These efforts are now underway. We are also in the early stages of establishing a scalar seismic moment catalog for the new HRSN events that is also to be included in the NCEDC dbms.

Catalog Assessment

We continue to examine the ongoing earthquake data being collected by the HRSN in search of possible earthquake precursors. This includes quality control and evaluation of the routine earthquake catalog locations and analyses of the spatial and temporal distribution of the microseismicity in relation to the occurrence of larger earthquakes in the area and heightened alert levels declared as part of the Parkfield Prediction Experiment. Even before our planned enhancement of HRSN performance, the new central detection system that operates at the telemetry hub, along with real-time telemetry of selected high-sensitivity channels to Berkeley for monitoring, allows event detection below magnitude 0.0. As a result, the rate of earthquake detection by the HRSN exceeds that of the NCSN by about a factor of 3 in the 30 km stretch of the SAF centered at the location of the 1966 M6 Parkfield event (Figure 5.6). The additional rate of HRSN event detection significantly increases both the spatial and temporal coverage of the changing seismicity patterns and provide unique additional information on the earthquake pathology at very low magnitudes. With our planned noise reduction and triggering enhancement, we estimate the proportion of HRSN located events relative to the NCSN catalog to increase by an additional factor of 2. Differences between earthquake locations evident in Figure 5.6 are largely attributable to the more advanced 3-D P- and S- wave velocity model used in determining the HRSN locations and the more accurate hand-picked P- and S- phases made possible by the high sampling rate (250 sps) and horizontal component borehole recordings of the HRSN.

4. Acknowledgements

Thomas V. McEvilly, who passed away in February 2002, was the PI on the HRSN project for many years, and without his dedication and hard work the creation and continued operation of the HRSN would not have been possible. His contributions continue to be appreciated in the extreme and the fruits of his labor many-fold.

Under Bob Nadeau's and Doug Dreger's general supervision, Rich Clymer, Wade Johnson, Bob Uhrhammer, Doug Neuhauser, Don Lippert, Bill Karavas, John Friday, Pete Lombard, and Lane Johnson all contribute to the operation of the HRSN. Bob Nadeau prepared this chapter with the assistance of Bob Uhrhammer and Wade Johnson.

During the period of this report, the operation and maintenance of the HRSN and the processing and archiving of its data was supported in large part by the USGS, through the NEHRP External Grants Program (grants: 02HQGR0067 and 03HQGR0065). NSF also provided support for the expansion of the HRSN near the SAFOD drill site through grant EAR-9814605.

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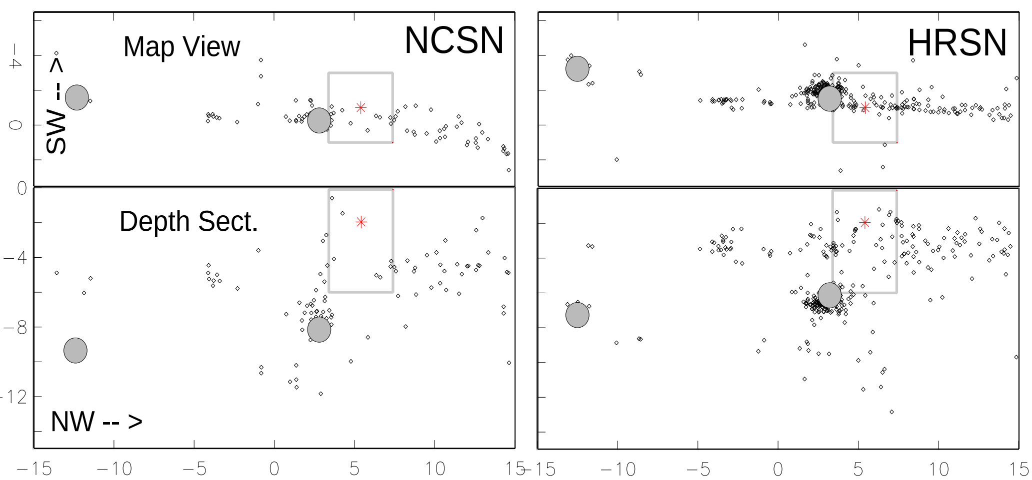

Figure 5.6: Comparison of NCSN and HRSN catalog locations for the period September through November of 2002. During this period, magnitude M3.8 and M4.2 earthquakes occurred at about −13 and +3 km NW, respectively (gray disks). The proposed SAFOD drilling target is shown as an asterisks and a 4x4 km gray box of 6km depth is shown surrounding the target (corresponding to the 4x4 km box in Figure 5.1). The region shown is centered on the hypocentral region of the 1966 Parkfield M6 earthquake that occurred at 0 km at about 9 km depth. The lower magnitude detection and greater rate of microearthquake detection by the HRSN provides increased spatial coverage and detail in the temporal pattern of the evolution of seismic activity in the region. Station coverage in the region is comparable for both networks, yet the more accurate S- phase picks possible on the horizontal HRSN component seismograms and the use of a 3-D P and S velocity model for hypocentral inversion provides a sharper picture of the fault zone structure. On average the current detection rate of locatable earthquakes by the HRSN is about 3 times that of the NCSN. Planned enhancements for the HRSN are expected to increase rate of locatable earthquakes by an additional factor of 2 to 3.

Chapter 6

Parkfield-Hollister Electromagnetic Monitoring Array

1. Introduction

The primary objective of the UC Berkeley electromagnetic (EM) monitoring array is to identify EM fields that might be associated with earthquakes. The array has consisted of up to three sites since 1995 at SAO, PKD, and PKD1, each of which measures three orthogonal components of the magnetic field and two orthogonal components of the electric field. Such an array is necessary in order to separate the fields of a local source (e.g., an earthquake signal) from the natural EM fields of the Earth. Our approach has been to determine the transfer function between fields at different sites for periods of normal background EM variations and then use this transfer function to predict fields between sites. Differences between the observed and predicted fields are used to search for anomalous local fields.

Analysis of the UCB array has shown that cultural noise from the San Francisco Bay Area (in particular BART) extends over surprisingly large areas, and that natural ionospheric sources may exhibit significant spatial complexity (Egbert et al., 2000). The fundamental MT assumption of spatially uniform sources is thus frequently violated in this area. These source complications are highly variable in time, reducing the effectiveness of a single remote site for EM noise cancellation. Multiple remote sites would allow significantly better cancellation of these more spatially complex EM noise fields, and would also reduce bias errors in the inter-station transfer function estimates. It was always the goal of the project to have three stations, but in 1999 the use permit at Haliburton Ranch was lost and PKD1 was removed just one month after PKD was installed. Analysis of data from this one month clearly demonstrates the value of three sites for improving the residual analysis, 2000 BSL Annual Report.

2. MT Overview

In 1995 we 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 6.1 and 6.2). 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 Parkfield (Figure 6.1). 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 data loggers, shared with the collocated BDSN stations, synchronized in time by GPS and sent to the BSL via dedicated communication links.

3. 2002-2003 Activities

Over the past year new electrodes have been installed at the PKD site, and automated quality control software has been implemented. Any failures of the UCB MT array are now immediately detected so that corrective

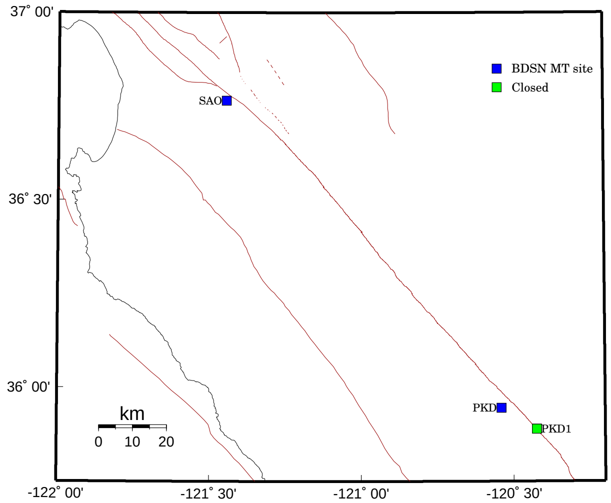

Figure 6.1: Map illustrating the location of operational (filled squares) and closed (grey squares) MT sites in central California.

action can be taken in a timely fashion. With these improvements in the system, nearly continuous high quality data have been collected.

This year time domain processing codes have been developed and tested on short segments of data. Karl Kappler is using a least squares Wiener filter, while Gary Egbert employs multivariate array transfer functions.

3.1 Station Maintenance

SAO

In January of this year the Q4120 datalogger was replaced. In February, the Hx coil was replaced.

PKD

Last September, lead-lead chloride electrodes from John Booker were installed in the 200 m dipoles. They require less maintenance than the copper-copper sulfate electrodes used in the 100 m dipoles. The addition of bentonite has significantly improved water retention in the electrode holes, increasing electrode longevity. In December the vertical coil was replaced, and in May and June 2003, the batteries powering the electric field preamplifiers were replaced.

Instrument Responses

Sierra Boyd ensures the transfer function information at the NCEDC is correct and current.

3.2 Data Quality Control

During this year, BSL staff worked in collaboration with Gary Egbert to install his software for automated data processing. The software provides the capability of identifying problems and alerting staff. There is a daily printout of the signal to noise ratios (SNR) in dB for each channel of the array. Currently, SNR's below 10 dB are flagged for inspection or repair by the array operators.

4. Data Processing

An effort has been made to do residual analysis purely in the time domain. The data used are the MT measurements on all five channels sampled at 1Hz. Since the station mostly sees noise originating by large sheet currents in the ionosphere, and the distance between sites is only a few hundred km, the input EM signal at each station should be roughly the same. Thus, a transfer function (TF) between two sites should be approximately constant. The relationship between the two sites is determined at a time when no significant seismic activity (SSA) is occurring near the arrays. On a day when SSA is present at one site, we can examine the residuals for anomalous activity.

4.1 Residuals

In this section we use an impulse response operator (IRO) rather than a TF as we are working in the time domain. The current IRO is a Wiener filter computed using least squares. The operator is computed using a days worth of data (86400 observations). Before computing the operator, the data must be despiked. For this, an automated despiking algorithm has been employed. Time series data are scanned for anomalies which lie more than a user specified number of standard deviations from the sample mean (default is 10). When an outlier is observed, the corresponding channel at the other station is examined within a two minute window about the time of the outlier. If a similar event took place, the anomaly is considered signal. Otherwise it is considered anomalous noise and is replaced. Currently a two minute window about the spike is replaced with a linear fit. Substituting with an ARMA (AutoRegressive Moving Average) model prediction has also been used, but is not yet the standard.

After despiking, the data are detrended using a first order polynomial. Then the IRO is computed. To predict a given channel we use all five channels at the other site. Denoting the channel to be predicted as the time series $\{X_t\}$ we obtain the formula

$$X_t = \sum_{ch=1}^{5} \Psi_{ch} * T_{ch} \tag{6.1}$$

where ch denotes that the sum is over each channel, and each channel has its own convolution operator. The * then denotes the convolution between the filter and T, the time series.

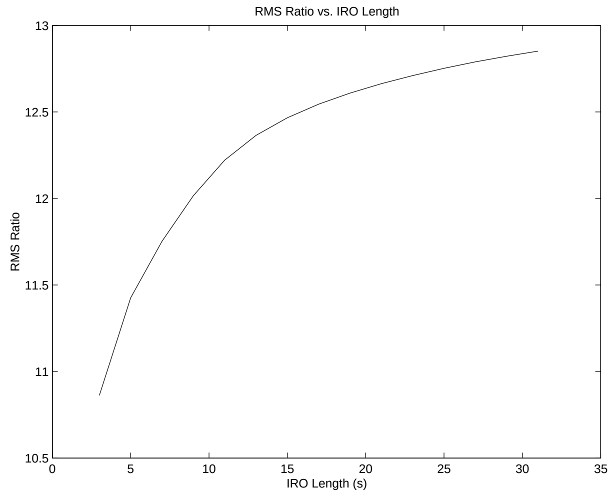

Figure 6.2: As the filter gets longer, the fit is better.

The length of the IRO can be any odd number. It has been observed that by using a longer IRO, predictions improve. With a long enough operator the least squares fit can be made arbitrarily fine (RMS(signal-fit)-¿0), but such a fine fit is also fitting noise unique to the data segment used to compute the IRO. We choose an IRO length which gives a fit roughly as good as it gives a prediction of future signal. The following chart (Figure 6.2) shows the ratio of the RMS signal to residuals as a function of IRO length.

Due to the computing power needed for this approach (inverting a matrix of dimension 5 times the filter length, and multiplying two matrices of dimension [number of seconds of data, 5xfilter length]), we can see that the number of calculations rises quadratically with filter length. For day long time segments (86400 rows) it is difficult to compute an IRO much longer than 35. An optimization can be performed for a given time segment length to determine the best IRO length. These may include a constrained least squares inversion using support vector machines, or ARMA approaches. For simply reducing one channel to residuals through modeling, invertible ARMA methods yield reduction as good or better. The disadvantage to this type of modeling, however, is that it is difficult to use in predicting one station from another. Furthermore, the method is expensive on computing power and can only model short segments, say of order one hour, with the current computing system and software.

Figure 6.3a shows the result of five 11-point Wiener filters applied to the five channels of Parkfield on day 228 in 1996. This day was chosen for its good signal to noise ratios in the raw data, and the fact that a M4.0 quake occurred one month later near the Parkfield array. The IRO was computed using this day's data, so this is

Sensor	Channel	Rate (sps)	Mode	FIR
Magnetic	VT?	0.1	C	Ac
Magnetic	LT?	1.0	C	Ac
Magnetic	BT?	40.0	C	Ac
Electric	VQ?	0.1	C	Ac
Electric	LQ?	1.0	C	Ac
Electric	BQ?	40.0	C	Ac

Table 6.2: Typical data streams acquired at each MT site, with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous; T triggered; Ac acausal.

essentially a least squares fit. The edges are imperfect, but the fit is generally excellent. The RMS ratio is around 12.2; however, if we neglect the edges (5000 s to either side), the RMS is 14.

In Figure 6.3b, the day 228 filters are used for prediction of day 230. We can see that the shape of the fit is again excellent, but there are some long period effects, which leave the prediction higher than the signal in some places and lower than the signal in others.

In the raw data there have been some long period instrument related diurnal effects in the magnetic data. A high pass filter has been designed for this job. Care is required in filtering out the long period signals, as the MT precursors we are looking for could be low frequency.

4.2 The Future

The residual analysis in time domain is free of the frequency domain inherent errors. The Gibbs phenomenon and effects due to discrete modeling are non existent. The time domain residuals can be computed and scanned for anomalous activity. Bandpass filtering of the raw data will likely remove some of the prediction misfit. Also, cutting the data into smaller parcels (one-three hours) and detrending each of these segments individually may reduce some of the long period noise. High frequency noise also leads to misfits in data. Low pass filters need to be employed to decimate signal to about 0.03 Hz, as we are looking for signals with duration greater than half a minute. Cleaning out this high frequency noise will likely improve predictions. The code is in place to begin the filtering this fall. Experiments with other prediction methods (such as constrained LS and ARMAs mentioned earlier) will continue as well. The plan is to have an automated system which reads in data from the array, despikes, computes residuals, and then scans the residuals for RMS anomalies in place over the next 4 months.

5. Acknowledgements

Frank Morrison directs the MT program, and collaborates closely with Gary Egbert of Oregon State University and Steve Park of UC Riverside. Sierra Boyd, John Friday, Lind Gee, and Doug Neuhauser also contribute to the operation of the MT observatories. Karl Kappler, Sierra Boyd, Gary Egbert, and Lind Gee contributed to the preparation of this chapter.

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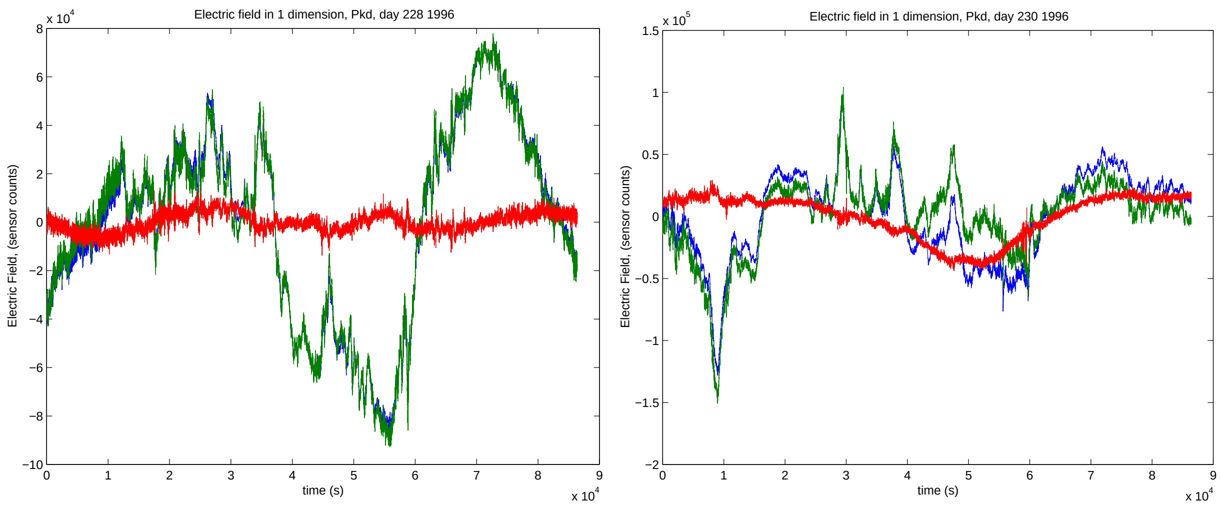

Figure 6.3: it a): A least squares fit (green) to the signal (blue), and the residuals (red), using an 11 point filter to the PKD data of day 228 in 1996. *b)*: Signal(blue), prediction (green), and residual(red) from using the day 228 filters to predict day 230. Note the change in scale from figure a.

Site	Net	Latitude	Longitude	Elev (m)	Date	Location
PKD	BK	35.945171	-120.541603	583	1999/02/05 -	Bear Valley Ranch, Parkfield
PKD1	BK	35.8894	-120.426109	431.6	1995/06/06 - 1999/03/08	Haliburton House, Parkfield
SAO	BK	36.76403	-121.44722	317.2	1995/08/15 -	San Andreas Obs., Hollister

Table 6.1: Sites of MT observatories

Chapter 7

Bay Area Regional Deformation Network

1. Introduction

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.,* 1998). It is a cooperative effort of the BSL, the USGS, and several other academic, commercial, and governmental institutions. Started by the USGS in 1991 with 2 stations spanning the Hayward fault (*King et al.,* 1995), BARD now includes 70 permanent stations (Figure 7.1). The principal goals of the BARD network are: 1) to determine the distribution of deformation in northern California across the wide Pacific–North America plate boundary from the Sierras to the Farallon Islands; 2) to estimate three-dimensional interseismic strain accumulation along the San Andreas fault (SAF) system in the Bay Area to assess seismic hazards; 3) to monitor hazardous faults and volcanoes for emergency response management; and 4) to provide infrastructure for geodetic data management and processing in northern California in support of related efforts within the surveying and other interested communities.

BARD currently includes 38 continuously operating stations in the Bay Area and northern California (Table 7.1), 14 near Parkfield along the central San Andreas fault, and 18 near the Long Valley caldera near Mammoth (Table 7.2). The BSL maintains 22 stations (including 2 with equipment provided by Lawrence Livermore National Laboratory (LLNL) and UC Santa Cruz). Other stations are maintained by the USGS (Menlo Park and Cascade Volcano Observatory), LLNL, Stanford University, UC Davis, UC Santa Cruz, and East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, Thales, Inc., and the Jet Propulsion Laboratory. Many of these stations are part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation.

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 7.1). Five more of the BSL receivers will be installed next year, 2 along the southern Hayward fault, and 3 as part of the NSF-funded Mini-PBO project establishing collocated GPS, and borehole strainmeter and seismometer observatories in the Bay Area (see Chapter 8).

The number of continuous GPS stations in northern California will dramatically increase over the next 5 years, with over 250 new site installations planned as part of the Plate Boundary Observatory (PBO) component of the NSF-funded Earthscope project. The BARD network will form the initial core of the northern California array, and the BSL recently received NSF funding to maintain 40 stations for an 18-month period. During this period, BARD and the other regional networks, such as SCIGN, BARGEN, and PANGA, will be developing plans to fold operation and maintenance of portions the existing networks into the PBO array at the end of 5 years. We are working closely with UNAVCO, Inc., who has primary responsibility for implementation of PBO, to facilitate this transition and are acting in an advisory role on siting issues for the new installations.

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

Many of the BARD sites are classified as CORS stations by the NGS, which are used as reference stations by the surveying community. We coordinate efforts with surveying community at meetings of the Northern California GPS Users Group and the California Spatial Reference Center, and are currently developing plans to use the

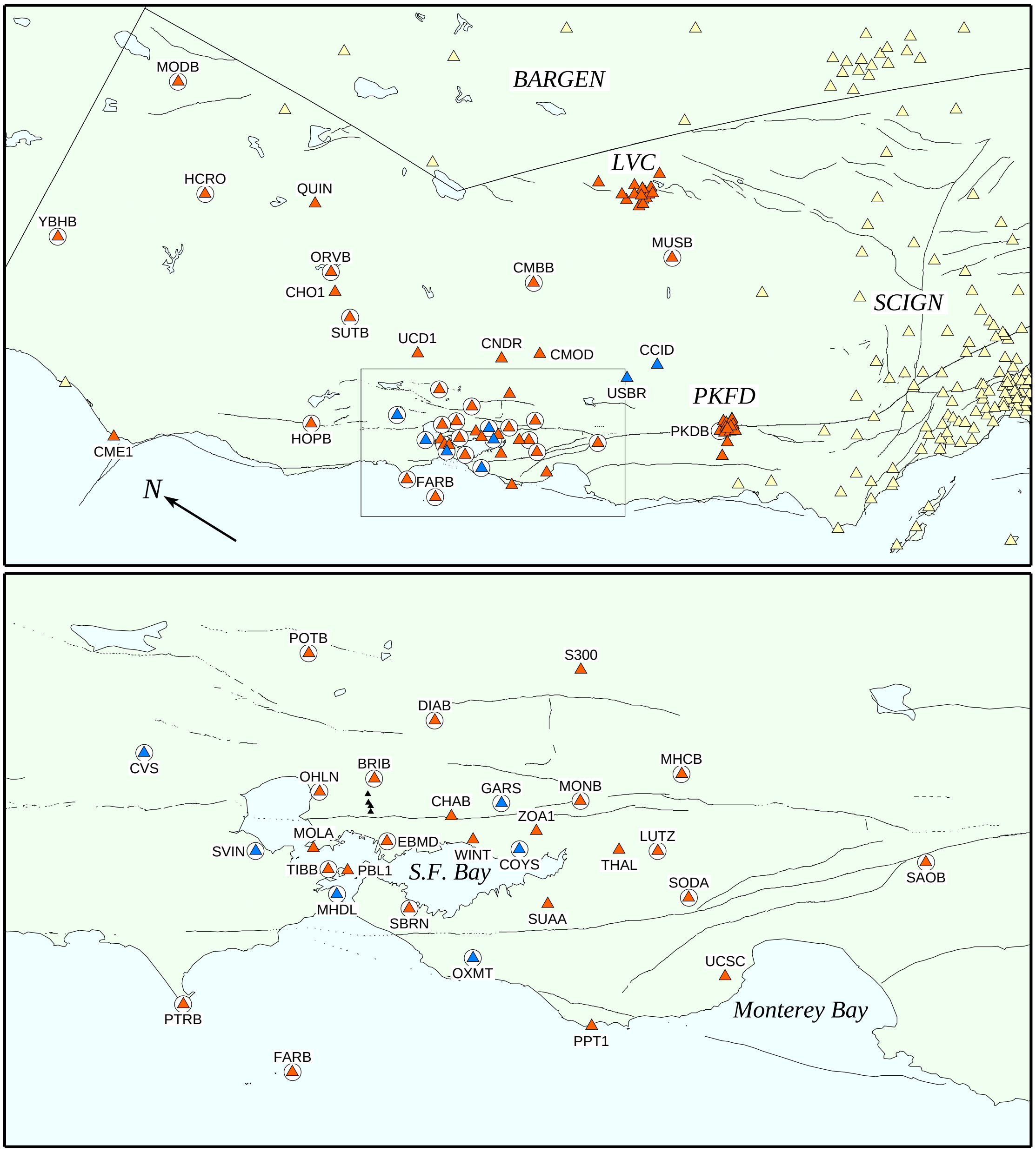

Figure 7.1: Operational (red) and planned (blue) BARD stations in northern California (top) and in the San Francisco Bay area (bottom). In the oblique Mercator projection expected Pacific–North America relative plate motion is parallel to the horizontal. Circled stations use continuous real-time telemetry. The 18 station Long Valley Caldera (LVC) network and 15 station Parkfield (PKFD) networks are also part of BARD. The small black triangles near BRIB are the experimental L1 stations. Mini-PBO stations are OHLN and SBRN (existing), and MHDL, OXMT, and SVIN (planned), all located along the northern Hayward and San Andreas fault. We plan to install 3 other stations at CVS, GARS, and COYS. The 2 Central Valley sites (USBR and CCID) are being installed in cooperation with the CSRC. Other nearby networks (open triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

Code	Latitude	Longitude	Start	Receiver	Maint.	Telem.	Location
BRIB	37.91940	-122.15255	1993.58	A-Z12	BSL	FR	Briones Reservation, Orinda
CMBB	38.03418	-120.38604	1993.92	A-Z12	BSL	FR	Columbia College, Columbia
DIAB	37.87858	-121.91563	1998.33	A-Z12	BSL	FR	Mt. Diablo
FARB	37.69721	-123.00076	1994.00	A-Z12	BSL	R-FR/R	Farallon Island
HOPB	38.99518	-123.07472	1995.58	A-Z12	BSL	FR	Hopland Field Station, Hopland
LUTZ	37.28685	-121.86522	1996.33	A-Z12	BSL	FR	SCC Comm., Santa Clara
MHCB	37.34153	-121.64258	1996.33	A-Z12	BSL	FR	Lick Obs., Mt. Hamilton
MODB	41.90233	-120.30283	1999.83	A-Z12	BSL	NSN	Modoc Plateau
MOLA	37.94657	-122.41992	1993.75	T-SSE	BSL		Pt. Molate, Richmond
MONB	37.49892	-121.87131	1998.50	A-Z12	BSL	FR	Monument Peak, Milpitas
MUSB	37.16994	-119.30935	1997.83	A-Z12	BSL	R-Mi-FR	Musick Mt.
OHLN	38.00742	-122.27371	2001.83	A-uZ	BSL	FR	Ohlone Park, Hercules
ORVB	39.55463	-121.50029	1996.83	A-Z12	BSL	FR	Oroville
PKDB	35.94524	-120.54155	1996.67	A-Z12	BSL	FR	Bear Valley Ranch, Parkfield
POTB	38.20258	-121.95560	1998.92	A-Z12	BSL	FR	Potrero Hill, Fairfield
PTRB	37.99640	-123.01490	1998.58	A-Z12	BSL	R-FR	Point Reyes Lighthouse
SAOB	36.76530	-121.44718	1997.58	A-Z12	BSL	FR	San Andreas Obs., Hollister
SBRN	37.68622	-122.41044	2003.18	A-uZ	BSL	FR	San Bruno Mt., Brisbane
SODB	37.16640	-121.92552	1996.33	A-Z12	BSL	R-FR	Soda Springs, Los Gatos
SUTB	39.20584	-121.82060	1997.33	A-Z12	BSL	R-FR	Sutter Buttes
TIBB	37.89087	-122.44760	1994.42	A-Z12	BSL	R	Tiburon
YBHB	41.73166	-122.71073	1996.75	A-Z12	BSL	FR	Yreka Blue Horn Mine, Yreka
CHAB	37.72412	-122.11931	1992.00	A-Z12	USGS		Chabot, San Leandro
WINT	37.65264	-122.14056	1992.00	A-Z12	USGS		Winton, Hayward
EBMD	37.81501	-122.28380	1999.18	T-SSi	EBMUD		EBMUD, Oakland
QUIN	39.97455	-120.94443	1992.68	Rogue	JPL		Quincy
S300	37.66642	-121.55815	1998.48	T-SSi	LLNL		Site 300, Livermore
HCRO	40.81563	-121.46915	2003.50	T-SSi	HCRO		Hat Creek Radio Obs.
CHO1	39.43264	-121.66496	1999.50	A-Z12	NGS		Chico
CME1	40.44177	-124.39633	1995.74	A-Z12	NGS		Cape Mendocino
CMOD	37.64130	-121.99997	2000.76	T-SSi	City		Modesto
CNDR	37.89641	-121.27849	1999.27	A-Z12	NGS		Condor, Stockton
PBL1	37.85306	-122.41944	1995.50	A-Z12	NGS		Point Blunt, Angel Island
PPT1	37.18167	-122.39333	1996.00	A-Z12	NGS		Pigeon Point
SUAA	37.42691	-122.17328	1994.30	A-Z12	SU		Stanford University
THAL	37.35149	-121.93549	2003.00	A-uZ	Thales		Thales, Inc., Santa Clara
UCD1	38.53624	-121.75123	1996.38	T-SSi	UCD		UC Davis
UCSC	36.99279	-122.05219	2000.31	T-SSi	UCSC		UC Santa Cruz
ZOA1	37.54305	-122.01594	2002.50	Novatel	FAA		Fremont

Table 7.1: Currently operating stations of the BARD GPS network maintained by the BSL or by other agencies except in the Parkfield and Long Valley caldera regions. Other agencies include: EBMUD = East Bay Mun. Util. Dist., UCD = UC Davis, SU = Stanford Univ., UCSC = UC Santa Cruz, City = City of Modesto (see also Table 1.1). Receivers: A = Ashtech, T = Trimble. See Table 3.2 for telemetry codes and for BSL sites collocated with seismic stations. Data from other agencies retrieved or pushed by FTP or from the Web.

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

Code	Latitude	Longitude	Start	Receiver	Maint.	Location
CAND	35.93935	-120.43370	1999.33	A-Z12	USGS	Cann, Parkfield
CARH	35.88838	-120.43082	2001.58	A-Z12	USGS	Carr Hill 2, Parkfield
CARR	35.88835	-120.43084	1989.00-2003.31	A-Z12	JPL	Carr Hill, Parkfield
CRBT	35.79161	-120.75075	2001.67	A-Z12	USGS	Camp Roberts, Parkfield
HOGS	35.86671	-120.47949	2001.50	A-Z12	USGS	Hogs, Parkfield
HUNT	35.88081	-120.40238	2001.58	A-Z12	USGS	Hunt, Parkfield
LAND	35.89979	-120.47328	1999.33	A-Z12	USGS	Lang, Parkfield
LOWS	35.82871	-120.59428	2001.58	A-Z12	USGS	Lowes, Parkfield
MASW	35.83260	-120.44306	2001.58	A-Z12	USGS	Mason West, Parkfield
MIDA	35.92191	-120.45883	1999.75	A-Z12	USGS	Mida, Parkfield
MNMC	35.96947	-120.43405	2001.58	A-Z12	USGS	Mine Mt., Parkfield
POMM	35.91991	-120.47843	1999.75	A-Z12	USGS	Pomm, Parkfield
RNCH	35.89999	-120.52482	2001.58	A-Z12	USGS	Ranchita, Parkfield
TBLP	35.91741	-120.36034	2001.67	A-Z12	USGS	Table, Parkfield
BALD	37.78330	-118.90130	1999.67	A-ZFX	CVO	Bald Mt., LVC
CA99	37.64460	-118.89670	1999.67	A-ZFX	CVO	Casa 1999, LVC
CASA	37.64464	-118.89666	1993.00	Rogue	JPL	Casa Diablo, LVC
DDMN	37.74430	-118.98120	1999.67	A-ZFX	CVO	Deadman Creek, LVC
DECH	38.05150	-119.09060	2001.58	A-ZFX	CVO	Dechambeau Ranch, LVC
HOTK	37.65860	-118.82130	2001.67	A-Z12	CVO	Hot Creek, LVC
JNPR	37.77170	-119.08470	1997.81	A-Z12	USGS	Juniper, LVC
KNOL	37.65912	-118.97917	1998.58	A-ZFX	CVO	Knolls, LVC
KRAC	37.71330	-118.88050	2001.67	A-Z12	CVO	Krakatoa-USGS, LVC
KRAK	37.71313	-118.88114	1994.73	Rogue	JPL	Krakatoa, LVC
LINC	37.63719	-119.01729	1998.67	A-Z12	CVO	Lincoln, LVC
MINS	37.65376	-119.06090	1995.92	A-Z12	USGS	Minaret Summit, LVC
MWTP	37.64052	-118.94473	1998.58	A-ZFX	CVO	Mammoth Water Treat Plant, LVC
PMTN	37.83130	-119.05690	1999.67	A-Z12	CVO	Panorama Mt., LVC
RDOM	37.67707	-118.89794	1998.58	A-ZFX	CVO	Resurgent Dome, LVC
SAWC	37.68990	-118.95310	2000.65	A-ZFX	CVO	Saw, LVC
TILC	37.61890	-118.86280	2000.65	A-Z12	CVO	Tilla, LVC
WATC	37.66440	-118.65390	2001.67	A-Z12	CVO	Waterson, LVC

Table 7.2: Currently operating stations of the BARD GPS network maintained by other agencies in the Parkfield and Long Valley caldera regions. Other agencies include: CVO = USGS Cascade Volcano Observatory (see also Table 1.1). Receivers: A = Ashtech. Data from other agencies retrieved or pushed by FTP or from the Web.

2. 2002-2003 Activities

The typical configuration of a BSL continuous GPS station installation has been described in detail in previous annual reports. We here provide a brief description and highlight some of the recent changes. During July 2002–June 2003, we performed maintenance on existing BARD stations, installed a new station, assisted collaborators with the installation of two new stations, and prepared for new stations near the Hayward fault, on the San Francisco peninsula, and north Bay area regions.

2.1 BARD Stations

Each BSL BARD station uses a low-multipath chokering 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 programmed to record data once every 30 seconds, observing 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 phenomenon, and to minimize differential radio propagation delays.

Data from most BSL-maintained stations are collected at 30-second intervals and transmitted continuously over serial connections (Table 7.1). Station TIBB uses a direct radio link to Berkeley, and MODB uses VSAT satellite telemetry. Nineteen stations use frame relay technology, either alone or in combination with radio telemetry. Thirteen GPS stations are collocated with broadband seismometers and Quanterra data collectors (Table 3.2). 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 and MONB in the Bay Area, and 13 stations in the Parkfield regional (all but PKDB), are now being collected at 1 second intervals. Collecting at such high-frequency (for GPS) allows dynamic displacements due to large earthquakes to be better measured, such as was demonstrated by several studies following the 2002 Denali fault earthquake. However, this 30-fold increase in data can be limited by telemetry bandwidth issues. Data from the Parkfield stations are collected on an onsite computer, written to removable disk once per month, and sent to SOPAC for long-term archiving (decimated 30-sec data is acquired daily via the BSL frame relay circuit). In the Bay Area, we have converted the two stations that have sufficient bandwidth and are not collocated with seismic instrumentation. We are currently assessing bandwidth issues at other stations and are planning to convert to 1-second sampling where possible, such as the Mini-PBO stations, in the next year.

The BSL acquired 7 Ashtech MicroZ-CGRS (uZ) receivers with NSF funding for the Mini-PBO project. These receivers, designed for continuous station applications, use less power (5.6 W) than the Z-12 receivers due to the lack of an interactive screen, provide better remote receiver control, and can support serial telemetry in both native raw format and the receiver independent BINEX format. We installed a uZ at SBRN and replaced the Z-12 at OHLN with a uZ in May 2003 after the clock chip on Z-12 at the site began to malfunction. We are currently considering switching to the more compact BINEX format where possible, as this will reduce some of the bandwidth limitations and allow us to convert more stations to 1-second sampling.

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

2.2 Station Maintenance

In February 2003, telemetry flow of GPS data stopped at MUSB. Access to the site was initially limited by the winter snowpack, and then by the need to coordinate the visit with Southern California Edison engineers. During a visit to the site in August 2003 continuity tests revealed that the hardline antenna cable had apparently failed. This 70 m cable may have been damaged by repeated water freezing in the PVC conduit that houses it. We intend to replace the antenna cable and improve the drainage of the conduit in September 2003.

As part of the Plate Boundary Deformation project (Chapter 8), nine new continuous GPS sites were installed in the Parkfield area (see Table 7.2) in Summer 2001 by the USGS and SIO. These sites span about 25 km on either side of the San Andreas fault and are designed to link the BARD network in central and northern California to the SCIGN network in southern California. As part of this upgrade, the new station CARH was installed at Carr Hill near the original CARR station, which had been running since 1989. After allowing both stations to run side-by-side for nearly 2 years, CARR was turned off in April 2003. In February 2003, the NCEDC assumed responsibility from the USGS Pasadena for the telemetry download of these stations over their existing frame relay circuit at Parkfield. We installed an onsite LINUX computer that controlled the sequential download of data. In June 2003, the stations were upgraded to real-time streaming using Wi-Lan radios by SIO and the USGS.

2.3 New Installations

Throughout the year, we have continued installations for the NSF-funded mini-PBO project establishing collocated GPS, and borehole strainmeter and seismometer observatories in the Bay Area. Completion of these sites have been hampered by problems with the original permitting at Ox Mt and Marin Headlands, and by the need to redesign the GPS antenna mount. The GPS system at the Mini-PBO site SBRN was installed in early March 2003. Two major changes were made since the installation of the first Mini-PBO site at OHLN. We increased the diameter of the upper part of the steel shroud, which protects the borehole casing, from 10 to 14 inches to ensure that the casing remains decoupled from the surface. We also used a new borehole adapter for the GPS mount that was machined from two stainless steel flanges. Should borehole access be needed, this adapter allows a very high level of horizontal accuracy when reinstalling the antenna. These GPS mounts will be installed at the remaining 3 sites in Fall 2003 after rainfall lessens the fire hazards posed by the required welding of the lower flange onto the casing. For more details about the Mini-PBO station installations, see Chapter 8).

We assisted Hat Creek Radio Observatory (HCRO), located in northeastern California near Mt Lassen (Figure 7.1), in designing and installing a continuous GPS station. The HCRO is installing the new Allen Telescope Array (ATA), which will consist of approximately 350 6.1-meter radio telescope dishes arrayed at the site, for both astrophysical and Search for Extraterrestrial Intelligence (SETI) studies. We previously assisted UC Berkeley astrophysicists in conducting an RTK survey of the HCRO site to determine the optimal locations for the 350 dishes using Trimble RTK equipment purchased for the project. After completion of the RTK survey, the base receiver was converted into the continuous station. The site is set amidst and underlain by extensive lava fields. After extensive reconnaissance of the site, we chose a monument location that is close to the main laboratory buildings, unlikely to be affected by future ATA dish placement, and on a reasonably stable lava flow. In June 2003, we assisted with the construction of a 12"-diameter concrete pier that is anchored to the lava flow outcrop. The Trimble Zephyr antenna was attached using a SCIGN adapter. We are currently establishing data acquisition procedures with the HCRO to archive the data at the NCEDC.

We also assisted Thales, Inc. (formerly Ashtech, Inc.) to establish a continuous GPS station on the roof of their Santa Clara office building. The chokering antenna is attached to a metal pin that was drilled and cemented into a corner of the roof's concrete parapet. Data is currently acquired daily by FTP from a server located at Thales, and we are investigating methods to acquire the data more rapidly using some of the TCP/IP capabilities of the recently developed Ashtech iCGRS receiver. Other agencies have also installed new continuous stations in the Bay Area, including an FAA site in Fremont (ZOA1) that will be used for Wide Area Augmentation System (WAAS) navigation control.

2.4 L1-System Profile

The BSL staff is evaluating the performance of the UNAVCO-designed L1 system in an urban setting. This single-frequency receiver is relatively inexpensive but is less accurate than dual-frequency receiver systems that can completely eliminate first-order ionospheric effects. Hence we expect the L1 system to be most useful for short baseline measurements where ionospheric effects tend to cancel due to similar propagation paths. The systems are self-contained, using solar power and integrated radio modems.

In April 2002, we installed 4 sites in a 10-km profile extending normal to the Hayward fault between the UC Berkeley campus and BARD station BRIB (Figure 7.2).

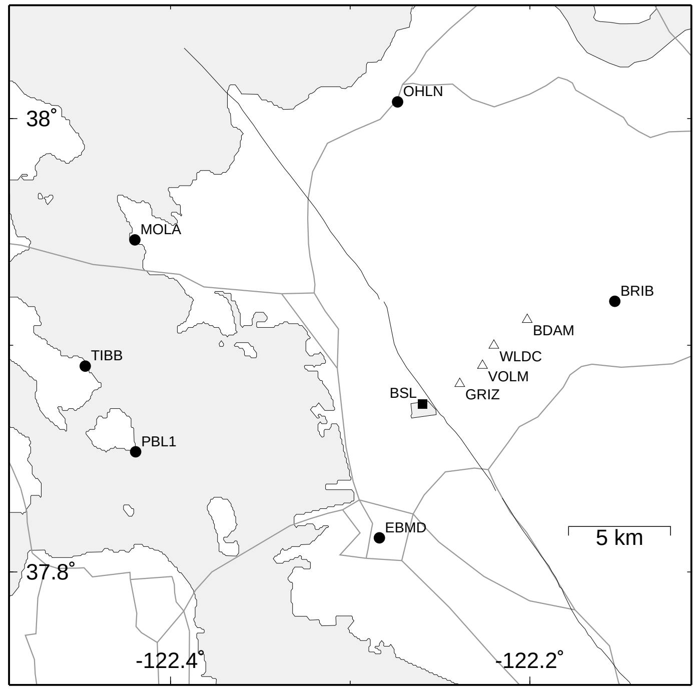

Figure 7.2: Location of L1-system (open triangles) and BARD (closed circles) stations. BSL, just southwest of the Hayward fault, is the location of the Berkeley Seismological Laboratory, where data from the 4 L1-system receivers northeast of the Hayward are telemetered.

Due to the topography of the East Bay hills, each site acts as a repeater for other sites. Data from WLDC passes through all the other stations, with its relay path being (in order) BDAM, VOLM, GRIZ, a repeater on the UC Berkeley Space Sciences Building, and then finally the master radio on the roof of McCone Hall where the BSL is located on campus. This profile, complemented by BRIB and EBMD to the west of the fault, will be most sensitive to variations in locking at 2–8 km depth. We expect that these systems will provide useful constraints on relative displacements near the Hayward fault in 3–5 years, and should help to resolve variations in creeping and locked portions of the fault (e.g., *Bürgmann et al,* 2000).

Between April 2002 and January 2003, the L1 system operated reasonably well, although problems with faulty batteries solar power regulators caused some loss of data. The Freewave radio at the repeater site SPSC was replaced with an Intuicom system. The original radio was sent in for routine maintenance and was found to have a frequency crystal that was beyond its normal operating range. In mid-January 2003, the solar panel at GRIZ was stolen, which resulted in damage to the cables located outside of the protective metal enclosure. The replacement solar panel was installed in a steel channel frame

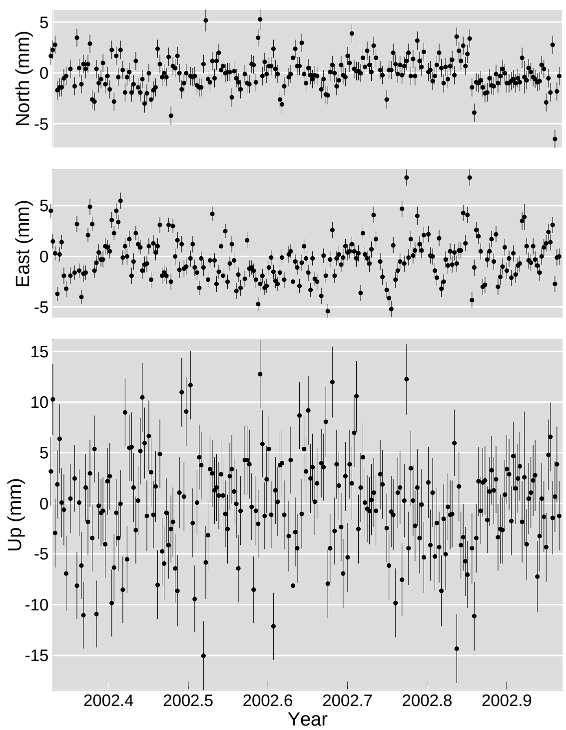

Figure 7.3: Daily estimates of the north, east, and vertical components of the BRIB to BDAM 3-km baseline. Daily repeatabilities are about 1, 2, and 5 mm, respectively.

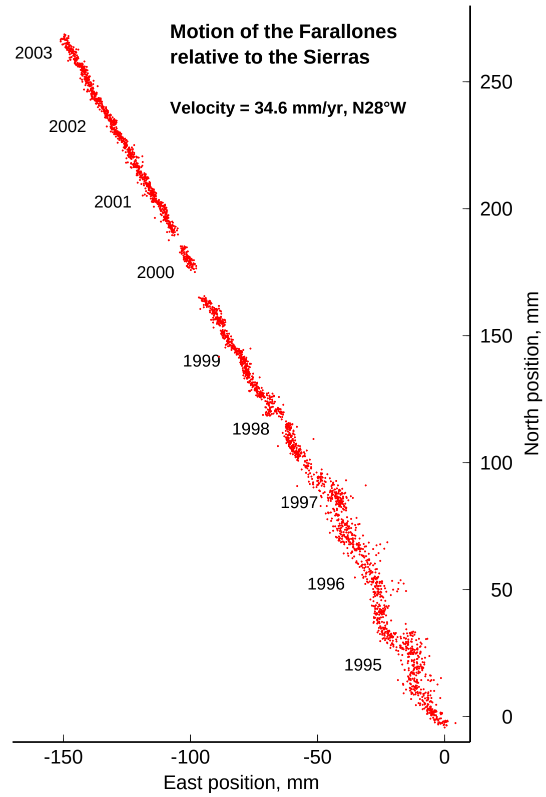

Figure 7.4: Daily position of FARB on the Farallon Islands west of San Francisco relative to CMBB at Columbia College in the Sierran foothills. The greater scatter in the 1994-1998 interval is due primarily to reference frame effects resulting from the weaker fiducial network available at that time.

welded to the vertical steel post that forms the monument base. A 0.5"-thick Plexiglas layer was inserted to protect the surface of the solar panel. Acquisition of all data failed not long after this repair. Initial tests suggested a problem at the repeater site SPSC, but subsequent efforts failed to resolve the problem. In August 2003 we isolated the problem to bad cable connections at the GRIZ sites and re-established operations of the network.

We are processing the data using the GAMIT/GLOBK analysis package, which required modifications to handle L1-only observations. We corrected software provided by UNAVCO to synchronize the phase, pseudorange, and clock offset observables, which allows the data to be cleaned in an automatic fashion. Preliminary results suggest that repeatabilities of 1–2 mm in daily horizontal relative positions and 5 mm in the vertical on the shortest (several km) baselines can be achieved (Figure 7.3), but these degrade to 3–4 mm on the longer (10 km) baselines. We are investigating ways to simultaneously process the dual-frequency data from nearby BARD stations (e.g., BRIB, OHLN), with the single-frequency L1 data to improve these results. Currently data from second frequency on the BARD stations is not used, which degrades the definition of the local reference frame and repeatability of the baselines.

3. Data Analysis and Results

We use the GAMIT/GLOBK software developed at MIT and SIO to process data from the BARD and other nearby continuous GPS networks. We have recently modified our processing strategies to take better advantage of recent enhancements to the GAMIT software and automated scripts. These improvements include better accounting of ocean-tide effects, estimating gradients in atmospheric variations, and applying elevation-dependent weighting to the data observables. We process data from more than 70 stations within hours of the completion of the day using rapid or predicted orbits and are reprocessing older data from the present to 1991 using improved orbits, which we expect to be completed by Fall 2003. Data from 5 primary IGS fiducial sites located in North

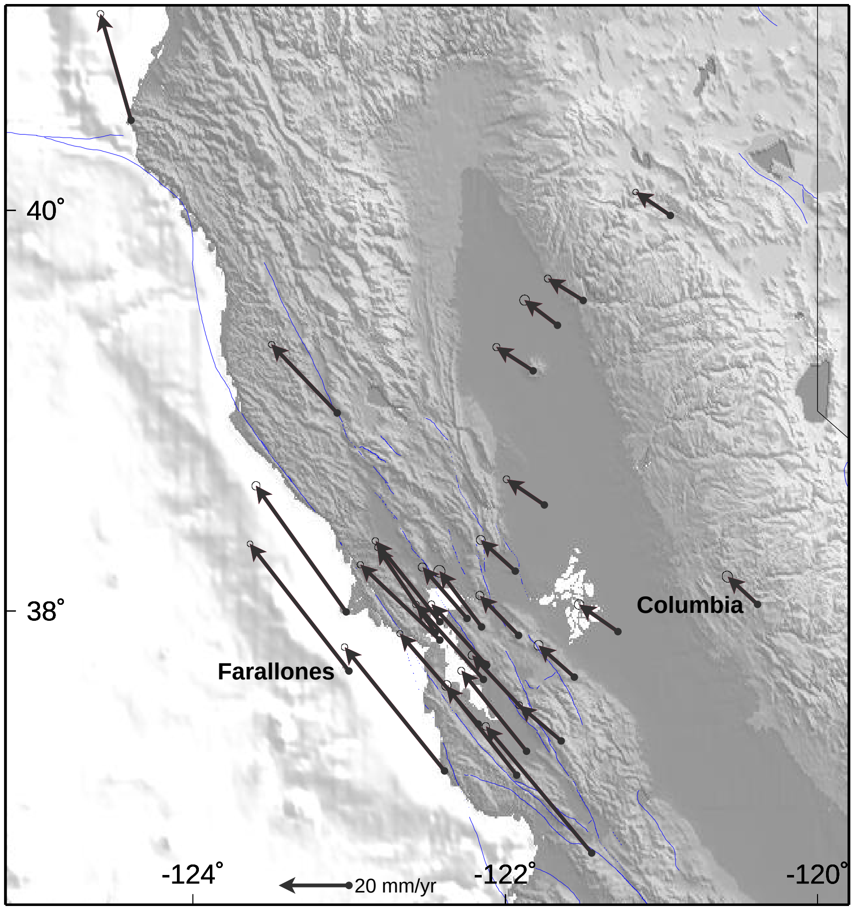

Figure 7.5: Velocities relative to stable North America for the BARD stations derived from 1993–2003 data. Ellipses show 95% confidence regions, assuming white noise only. The 35 mm/yr motion between Columbia and the Farallones is primarily due to shear across the San Andreas fault system.

America and Hawaii are included in the solutions to help define a global reference frame. For long-term velocity estimates, we combine these solutions with global and regional solutions provided by SOPAC to better define a stable North America reference frame.

The estimated relative baseline determinations typically have 2–4 mm long-term scatter in the horizontal components (Figure 7.4) and the 10–20 mm scatter in the vertical. Average velocities for the longest running BARD stations during 1993–2003 are shown in Figure 7.5, with 95% confidence regions assuming only white noise. The velocities are relative to stable North America, as defined by the IGS and CORS fiducial stations. 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 continuous GPS solutions into a self-consistent velocity field for northern California.

Most of the Sierra Nevada sites (CMBB, QUIN, and ORVB), as well as SUTB in the Central Valley, show little relative motion, indicating that the northern Sierra Nevada–Central Valley is tectonically stable. The motion of these sites relative to North America differs from the inferred motion of the western Basin and Range Province, suggesting 3 mm/yr right-lateral shear across the Walker Lane-Mt. Shasta seismicity trend. Deformation along the coast in central California is dominated by the active SAF system, which accommodates about 35 mm/yr of right-lateral shear. The Farallon Island site (FARB) off the coast of San Francisco is moving at nearly the rate predicted by the NUVEL-1A Pacific–North America Euler pole. Two-dimensional modeling of the observed fault-parallel strain accumulation (*Murray and Segall,* 2001) predicts deep slip rates for the San Andreas, Hayward, and Calaveras/Concord faults are 19.3±1.8, 11.3±1.9, and 7.4±1.6 mm/yr, respectively, in good agreement with estimated geologic rates (17±4, 9±2, and 5±3 mm/yr, respectively). Most of the 46 mm/yr of relative motion is accommodated within a 100-wide zone centered on the SAF system and a broader zone in the Basin and Range Province in Nevada.

4. Real-Time Processing

We are developing real-time analysis techniques that will enable rapid determinations (within minutes) of deformation following major earthquakes to complement seismological information. We use GAMIT/GLOBK processing techniques to estimate independent hourly solutions at the several cm-level horizontal precision and during the past year established an extension of the REDI system where estimates of postseismic positions are attempted when 10 minutes of data become available following an earthquake (*Murray et al.,* 2002).

We currently process 1 hour data batches available within 20 minutes of measurement from more than 20 continuously telemetered BSL and other stations providing hourly data. The hourly solutions have higher scatter than the 24-hour solutions (3–10 mm in the horizontal and 10–30 mm in the vertical), but our simulations suggest that displacements 3–5 times these levels should be reliably detected, and that the current network should be able to resolve the finite dimensions and slip magnitude of a M7 earthquake on the Hayward fault. Due to the poor ability of GAMIT to resolve ambiguities from short data spans, estimates of coseismic displacements within minutes of an event have high (decimeter-level) uncertainty. We are testing a relatively new component of GAMIT that uses Kalman filtering techniques and improved ambiguity resolution methods to provide higher-precision kinematic positions. This method works well for networks with small interstation distances (e.g., near the 1999 Hector Mine earthquake), which aids ambiguity resolution, but has less success on more widely spaced networks, such as the continuous GPS stations in the vicinity of the 2002 Denali earthquake. The August 1998 M=5.1 San Juan Bautista earthquake (*Uhrhammer et al.,* 1999) is the only event to have produced a detectable earthquake displacement signal (of 4 mm) at a BARD GPS receiver.

5. Acknowledgements

Mark Murray oversees the BARD program. André Basset, Bill Karavas, John Friday, Dave Rapkin, and Doug Neuhauser contribute to the operation of the BARD and L1 networks. Mark Murray and André Basset contributed to the preparation of this chapter.

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Chapter 8

Plate Boundary Deformation Project

1. Introduction

The Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation, commonly referred to as “Mini-PBO”, is a joint project of the BSL, the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the IGPP at UC San Diego (UCSD), and the U.S. Geological Survey (USGS) at Menlo Park, Calif. It augments existing infrastructure in central California to form an integrated pilot system of instrumentation for the study of plate boundary deformation, with special emphasis on its relation to earthquakes. This project is partially funded through the EAR NSF/IF program with matching funds from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN).

Because the time scales for plate boundary deformation range over at least 8 orders of magnitude, from seconds to decades, no single technique is adequate. We have initiated an integrated approach that makes use of three complementary and mature geodetic technologies: continuous GPS, borehole tensor strainmeters, and interferometric synthetic aperture radar (InSAR), to characterize broadband surface deformation. Also, ultrasensitive borehole seismometers monitor microearthquake activity related to subsurface deformation.

The project has three components: 1) the installation of broadband deformation stations in the San Francisco Bay area; 2) the installation of GPS stations in the Parkfield region; and 3) support for skeletal operations of a 5-m X-band SAR downlink facility in San Diego to collect and archive radar data, and develop an online SAR database for WInSAR users. The BSL has participated in the first two of these components. Additional details about the Parkfield GPS stations, installed in 2001 to link the BARD network in central and northern California to the SCIGN network in southern California and currently operating in real-time streaming mode with instantaneous position analysis, are provided in the BARD chapter of this report. The remainder of this chapter describes San Francisco Bay area broadband deformation station component of this project.

The broadband deformation stations augment existing instrumentation along the Hayward and San Andreas faults in the San Francisco Bay area (Figure 8.1). During July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers (Table 8.1). The strainmeters were recently developed by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. All of the stations include pore pressure sensors and 2-component tiltmeters. Three of the stations now are equipped with Quanterra recording systems that provide 100-Hz seismic and strainmeter data, and two of the stations now include a GPS receiver. The GPS antennas at these stations are mounted at the top of the borehole casings in an experimental approach to achieve stable compact monuments. The GPS stations complement existing Bay Area stations of the BARD continuous network.

The 30-second GPS, and 100-Hz strainmeter and seismometer data is acquired on Quanterra data loggers and continuously telemetered by frame relay to the BSL. Low frequency (600 second) data (including strainmeters, for redundancy) is telemetered using the GOES system to the USGS. All data is available to the community through the Northern California Earthquake Data Center (NCEDC) in SEED format, using procedures developed by the BSL and USGS to archive similar data from 139 sites of the USGS ultra-low-frequency (UL) geophysical network, including data from strainmeters, tiltmeters, creep meters, magnetometers, and water well levels.

2. New Site Installations

During the period July 2002–June 2003, the BSL and USGS began the installation of the broadband deformation stations at Marin Headlands (MHDL) in the Golden Gate National Recreation Area near Pt. Reyes, and at St. Vincent’s School for Boys (SVIN) near San Rafael. Additional equipment installation and maintenance was performed at the first three stations, including the installation of tiltmeters at all stations, and the GPS monu-

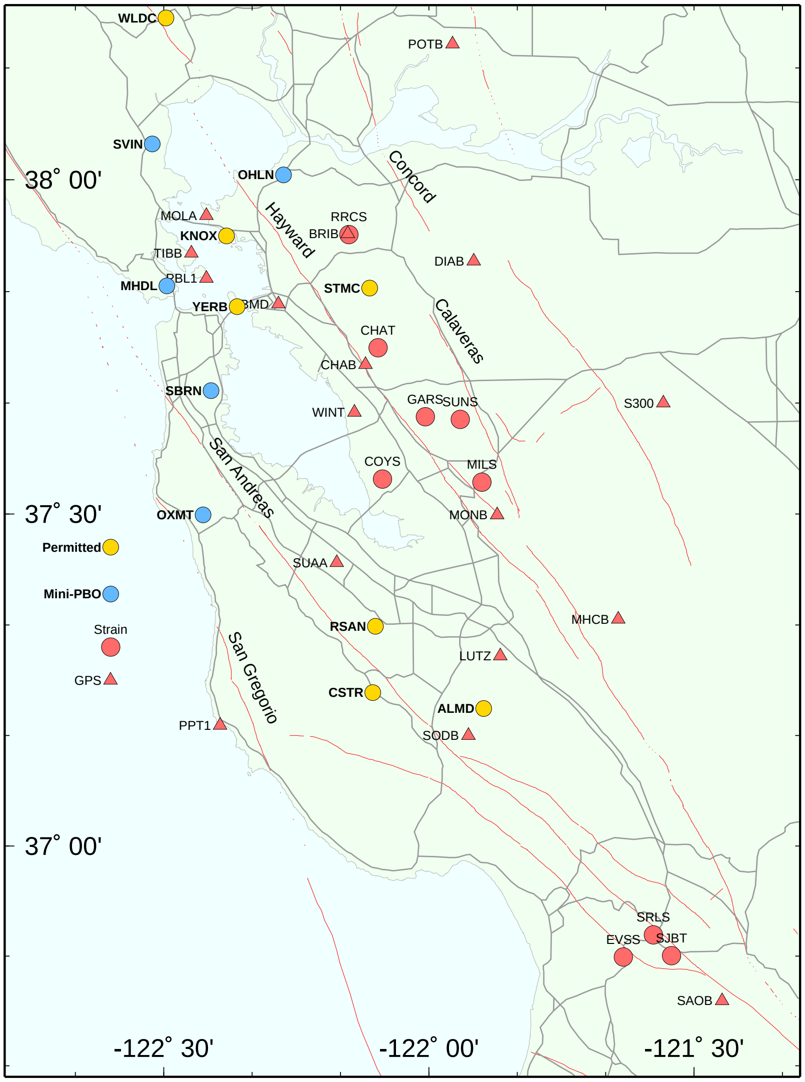

Figure 8.1: Location of existing (red), in preparation (yellow), and pending (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations. Blue triangles are other pending BARD stations. Black triangles are L1-system profile sites near the Hayward fault and the UC Berkeley campus.

Code	Latitude	Longitude	Installed	Strainmeter depth (ft)	Seismometer depth (ft)	Location
OHLN	38.00742	-122.27371	2001/07/16	670.5	645.5	Ohlone Park, Hercules
SBRN	37.68562	-122.41127	2001/08/06	551.5	530.0	San Bruno Mtn. SP, Brisbane
OXMT	37.49795	-122.42488	2002/02/06	662.7	637.3	Ox Mtn., Half Moon Bay
MHDL	37.84227	-122.49374	2002/08/06	520.6	489.2	Golden Gate NRA, Sausalito
SVIN	38.03325	-122.52638	2002/08/29	527.0	500.0	St. Vincent CYO School, San Rafael
SMCB	37.83881	-122.11159				St. Mary's College, Moraga
WDCB	38.24088	-122.49628				Wildcat Mt., Sears Pt.

Table 8.1: Currently operating and planned stations of the Mini-PBO network. Strainmeter installation date is given. Depth to tensor strainmeter and 3-component seismometers in feet.

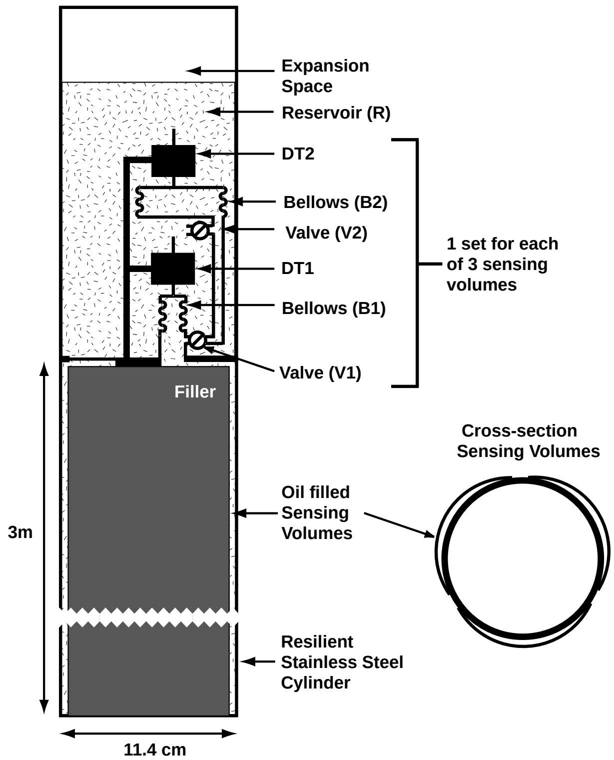

Figure 8.2: Tensor strainmeter diagram. These instruments are a modification of the Sacks- Evertson dilatometers that use a hydraulic sensing technique to achieve a volume strain sensitivity of 10**(- 12) with constant frequency response from 0 to more than 10 Hz and a dynamic range of about 130 dB. The design incorporates a second bellows- DT- valve sub- system which provides extended dynamic range, complete preservation of baseline during required instrumental resets, and redundant sensing electronics. Figure courtesy A. Linde (USGS).

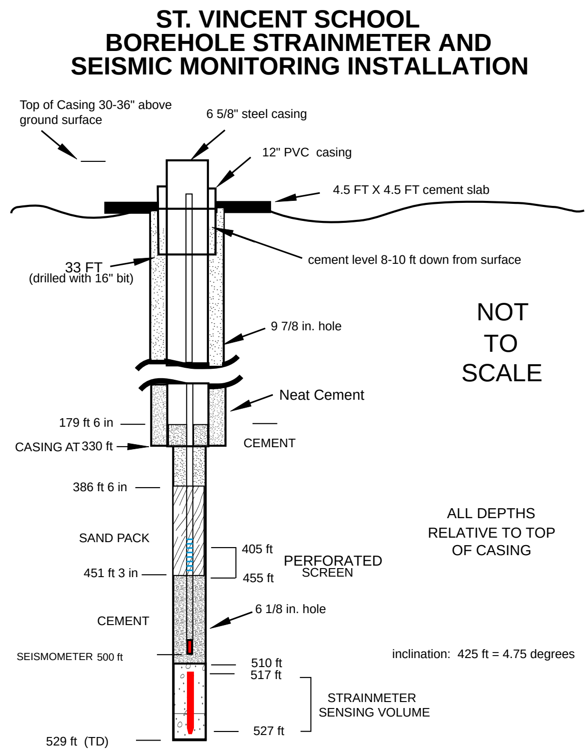

Figure 8.3: The Mini-PBO borehole configuration at St. Vincents, showing the emplacement of the strainmeter and seismometer instruments downhole. The GPS receiver is mounted on the top. Figure courtesy B. Mueller (USGS).

ment and receiver at San Bruno (SBRN).

The BSL directly supervised the drilling operations at St. Vincents during the August 2002. The boreholes were drilled by the USGS Water Resources Division using a relatively new rig that experienced numerous problems (hydraulics, stuck bits, etc.), which delayed the drilling considerably at several of the sites and significantly increased the costs of the project. At St. Vincents, the first hole had to be abandoned after some tungsten grinding buttons from a defective bit dislodged and could not be retrieved from the bottom of the hole. Hammer drilling through the very hard graywacke encountered throughout the hole also proved difficult due to the lack of proper stabilization on the drill string. Rotary drilling, although relatively slow, enabled penetration to 528' in the limited time available. A video log showed a promising region devoid of open fractures near the bottom of the hole where the strainmeter and seismometer packages were installed without any further difficulties.

The USGS supervised the drilling at the Marin Headlands (MHDL) site. The drilling in October 2001 encountered hard greenstone with some fractures and clay layers between 410-608' and red and green chert below to 659'. Coring at around 545' was slow and poorly recovered. A video log of the hole showed several promising strainmeter installation regions at 500-550' depths. However, containment of high volumes of artesianing fluids from the well became increasing problematic. The hole was cased to 278', sand filled on the bottom, and cemented and plugged at the top in mid-October. In August 2002, the cement and sand were rapidly drilled out, without any artesianing problems, allowing the strainmeter and seismometer packages to be successfully installed.

Figure 8.3 shows the typical configuration of the borehole instrument installation. A 6.625" steel casing was cemented into a 10.75" hole to 500-650' depth to prevent the upper, most unconsolidated materials from collapsing into the hole. Below this depth a 6" uncased hole was drilled to the target region for the strainmeter and seismometer packages. Coring, in order to identify the region with the most compentent rock for the strainmeter, was

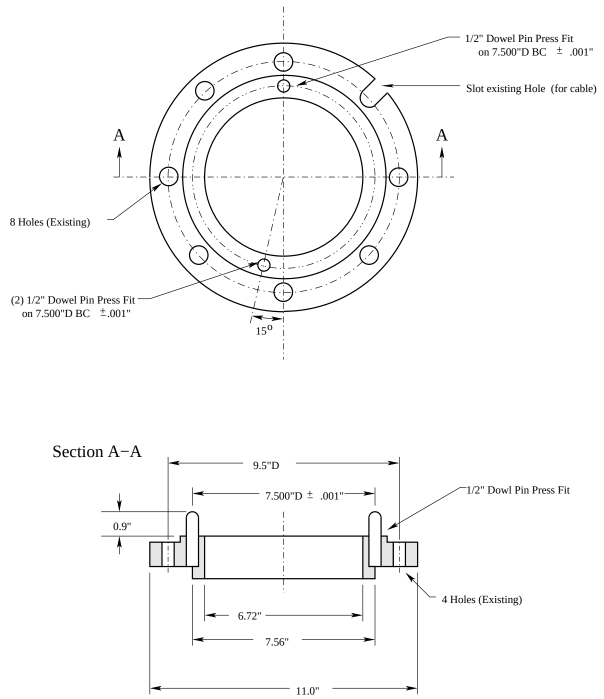

Figure 8.4: Design of the bottom flange of GPS antenna mount, which is welded to the top of the casing.

Figure 8.5: GPS antenna mount. The bottom flange is welded to the top of the borehole casing. The upper flange can be removed and replaced with sub-0.1 mm repeatability to provide access to the interior of the casing.

attempted with only moderate success at a few of the holes and was not attempted at St. Vincents. We found that video logs provided a reasonable substitute. The target region of each hole was filled with a non-shrink grout into which the strainmeter was lowered, allowing the grout to completely fill the inner cavity of the strainmeter within the annulus formed by the sensing volumes to ensure good coupling to the surrounding rock.

The 3-component seismometer package was then lowered to just above the strainmeter, on a 2" PVC pipe, and neat cement was used to fill the hole and PVC pipe to entirely enclose the package. The pipe above this depth was left open for later installation of the pore pressure sensor. To allow water to circulate into the pipe from the surrounding rock for the pore pressure measurements, the the steel casing was perforated, a sand/gravel pack was emplaced, and a PVC screen was used at this depth. At each hole, the casing was then cemented inside to about 200', and outside to about 20' depth. A 12" PVC conductor casing was cemented on the outside from the surface to 20' to stabilize the hole for drilling and to provide an environmental health seal for shallow groundwater flow. The annulus between the 12" conductor casing and the 6.625" steel casing was cemented to about 10' depth and above was left decoupled from the upper surface to help minimize monument instability for the GPS antenna mounted on top of the steel casing.

Due to the unexpectedly high costs of drilling, only 5 boreholes could be completed under the NSF/IF grant, although additional instrumentation was purchased in anticipation of acquiring more sites. Caltrans intends to drill boreholes at several locations for the HFN project in the coming year that might be suitable for Mini-PBO installations, depending on the quality of the rock encountered at about 600' depth. Two of the already permitted potential sites, St. Mary's College (SMCB) and Wildcat Mt. (WDCB) (Figure 8.1 and Table 8.1), would nicely complement existing instrumentation, providing additional monitoring of the northern Hayward fault and initiating monitoring of the southern Rodgers Creek fault north of San Pablo Bay.

The BSL is supervising GPS, power, frame relay telemetry, and Quanterra 4120 datalogger installation at all the broadband deformation stations. Power, telemetry, and dataloggers are currently installed at OHLN, SBRN, and SVIN. The frame relay circuit at OXMT is also installed, but the power hookup has been delayed due to permitting complications that should be resolved in Fall 2003. Permitting complications have also delayed the establishment of power and telemetry at MHDL. Our original plans and permitting to use phone line connections became prohibitively expensive, so we are currently seeking permits to establish radio telemetry from the site either to a nearby telephone pole where a frame relay circuit can be installed or from the site directly to the BSL via a radio repeater on the ridge above the station. The USGS has installed solar panels at OXMT and MHDL to collect the low-frequency strainmeter data prior to establishing DC power at the sites. Telemetry at SVIN was established in June 2003 using Wi-LAN radios, a new type of radio that the BSL is currently beginning to adopt. These radios act as ethernet bridges, providing superior access to console control on the Quanterras. The radios can also provide a spanning tree network structure for a regional wireless network, which allows greater flexibility for future network installations.

The BSL is developing an experimental GPS mount for the top of the borehole casings to create a stable, compact monument (Figure 8.4). The antennas, using standard SCIGN adapters and domes for protection, are attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level is cemented fully to the surrounding rock. Our original mount design used at OHLN, which consists of a metal pipe symmetrically centered with respect to the casing that is welded to a cross beam and bolted inside the top of the casing, was found to have too much play in the area where the bolts are attached to ensure long-term stability of the monument.

We therefore redesigned the mount to minimize such non-tectonic motions. The current GPS mount design (Figures 8.4 and 8.5) consists of two 11- inch diameter stainless steel flanges. The lower slip- and- weld type flange is welded onto the top of the 6 5/ 8”- inch borehole casing providing a level surface for the second flange . The upper blind-type flange, to which the 1 1/ 4” stainless steel pipe used to connect to the SCIGN DC3 adaptor is attached, is bolted to the lower flange using four 3/ 4” by 3” stainless steel bolts. Two half- inch stainless steel dowels are press fit with high location precision (radius 7.500” +/- 0.001”) into the lower flange. Two matching holes are machined into the upper flange with a high location precision (radius 7.500” +/- 0.001”) and hole diameter precision (between +0.005” and -0. 000”). One of the dowels is offset to insure unique directional alignment. This mount was installed at SBRN in March 2003, and we are preparing to install this mount at the other broadband deformation stations in Fall 2003, after rainfall lessens the fire hazards that result from the welding.

Analysis of GPS observations at OHLN and SBRN shows that the short-term daily repeatabilities in the horizontal components are about 0.5-1 mm. These values are similar to those obtained with more typical monuments, such as concrete piers or braced monuments, but it is too early to assess the long-term stability of the borehole casing monument, which might also be affected by annual thermal expansion effects on the casing.

Two-component tiltmeters were installed at all the stations by the USGS in Spring 2003. Data from these sensors are recorded at 10-minute intervals and telemetered using the GOES system. Pore pressure sensors are also installed at all the stations and data are recorded at 1 Hz on the Quanterra dataloggers, except at Marin Headlands, where 10-minute interval data are also recorded on the Zeno datalogger. After the server for the pore pressure channels was initiated in Spring 2003, the Quanterra data loggers have occasionally encountered memory overwrite problems that cause them to cease operating. We believe the problem is due to the server, which Quanterra is currently investigating. We currently are running the pore pressure sensors on a trial basis on the system at Ohlone, which seems to behave more robustly than the system at San Bruno.

We are addressing minor problems at several of the stations. Highly correlated low-amplitude noise is contaminating the seismic and strain channels at the recently installed SVIN station. We are still in the process of investigating the source of this noise, which we believe is due to deficiencies in the power grid at the maintenance yard at the school where the data loggers are housed. The vertical seismic channel at OHLN also shows poor long-period characteristics compared to the other channels, and recently displayed a non-linear response to a local earthquake. The source of this problem is probably in the Quanterra electronics, which we intend to swap out in the near future. The USGS and CIW are also investigating anomalies in the strainmeter channels, including unusual steps in the SBRN instrument and a poor long-period response of one of the channels at OXMT, both of which are probably due to electical grounding problems.

3. Broadband Deformation Data

We are in the initial stages of assessing the data quality of the broadband deformation instrumentation. The borehole seismic packages provide good signal to noise characteristics compared to the NHFN stations due to their relatively deep installation. The systems have the best signal to noise near their 2-Hz characteristic frequency, but typical microseismic noise around 0.1 Hz is not evident (Figure 8.6). It is possible that the microseismic noise could be resolved if the systems included a pre-amplifier. We are planning to test this at OXMT and MHDL when the power and telemetry issues at those sites are resolved. These stations currently sample at 100-Hz, so they miss some of the seismic energy at high frequencies that are observed on the 500-Hz Parkfield borehole stations.

The newly designed tensor strainmeters appear to faithfully record strain signals over a broad frequency range. During the 2 years that the strainmeter at OHLN has been providing high-frequency data, the strain has

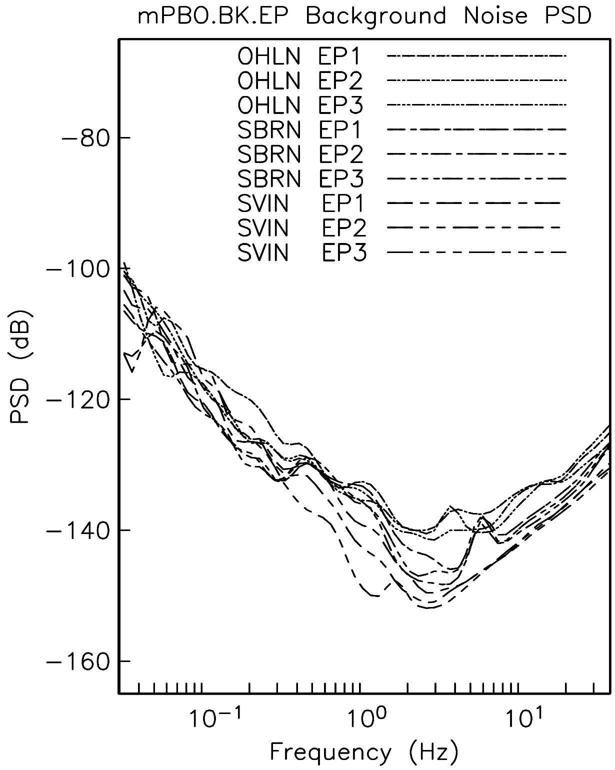

Figure 8.6: Background noise measured by the borehole seismic packages at OHLN, SBRN, and SVIN. Component 1 is vertical. The systems have the best signal to noise ratio near their 2-Hz characteristic frequency. Typical microseismic noise around 0.1 Hz is not evident.

a long-term exponential signal (Figure 8.7). This large signal is most likely due to cement hardening effects and re-equilibration of stresses in the surrounding rock in response to the sudden appearance of the borehole. These effects can last for many years and are the principal reason that borehole strainmeters can not reliably measure strain at periods greater than a few months. We are currently developing techniques to automatically clean the outliers and step offsets (due usually to valve resetting operations) seen in the raw data.

At periods around 1 day, tidally induced strains are the dominant strain signal, about 3 orders of magnitude smaller than the long-term exponential signal (Figure 8.8). Since the response of the strainmeter volumes is difficult to estimate independently, theoretically predicted Earth tides are typically used to calibrate the strainmeters. Figure 8.8 shows the approximate microstrain of the OHLN strainmeter over a several month period interval, and some of the steps required to clean the data, including removing the tides and atmospheric pressure effects. The remaining signal is highly correlated with rainfall, indicating the extent that hydrologic events can affect strain.

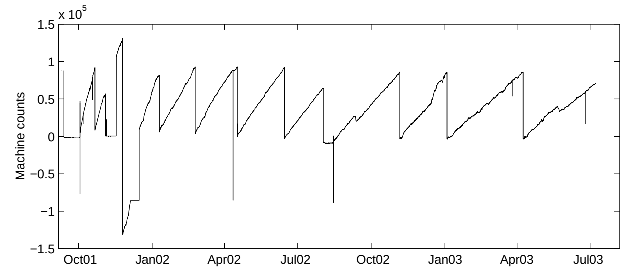

Figure 8.7: Two-year raw data time series from OHLN tensor strainmeter (component 1, flagged bad data removed) showing outliers, valve resetting offsets, and instrumental effects, such as faulty electronics in the strainmeter during the flat section in August 2002. Between the vertical offsets, the slope becomes less steep with time and shows the long-term exponentially decaying strain signal caused by grout curing and re-equilibration of stresses in the surrounding rock following the introduction of the borehole. This non-tectonic signal limits the ability of these strainmeters to reliably measure tectonic strain at periods greater than a few months.

At higher frequencies, strains due to seismic events are also evident. Figure 8.9 shows borehole strain measurements with clear seismic phases at OHLN for the M7.9 Denali Fault, Alaska earthquake on November 3, 2002. This figure also shows measurements of pore pressure, which responds to variations in volumetric strain although not necessarily in a linear fashion. Thus pore pressure provides both an independent check on the strainmeter observations and complementary information about the surrounding rock that will aid in determining the true tectonic strains. We are beginning to examine the strain data for other types of transient behavior, such as episodic creep or slow earthquake displacements.

4. Acknowledgements

This project is sponsored by the National Science Foundation under the Major Research Instrumentation (MRI) program with matching funds from the participating institutions and the Southern California Earthquake Center (SCEC).

Under Mark Murray's supervision, André Basset, Bill Karavas, John Friday, Dave Rapkin, Doug Neuhauser, Tom McEvilly, Wade Johnson, and Rich Clymer have contributed to the development of the BSL component of the Mini-PBO project. Several USGS colleagues, especially Malcolm Johnston, Bob Mueller, and Doug Myren, played critical roles in the drilling and instrument installation phases. Mark Murray and Barbara Romanowicz contributed to the preparation of this chapter.

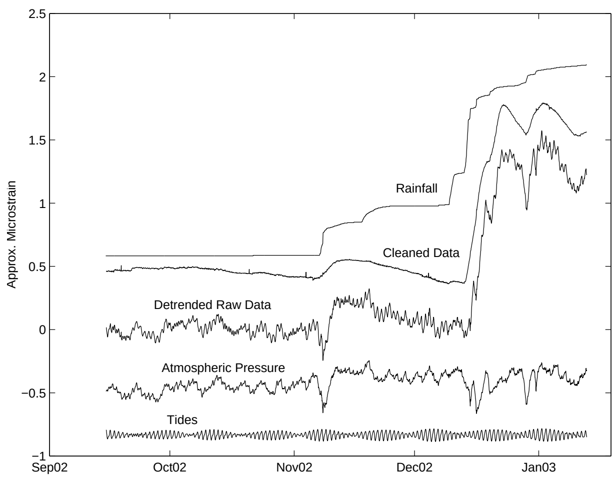

Figure 8.8: Four-month subset of OHLN data, detrended to flatten the first 50 days (middle trace), separated using BAYTAP-G (Tamura et al., 1991) into tidal, atmospheric pressure, and "cleaned" data components (with arbitrary vertical offsets). The atmospheric pressure time series measured at the site was also used for this decomposition. Approximate microstrain values are based on peak-to-peak tidal amplitude. The remaining large strain signals in the cleaned data are highly correlated with rainfall measured at an instrument located about 5 km from the site (40 cm total cumulative rainfall during this interval), and therefore are probably not geophysically interesting.

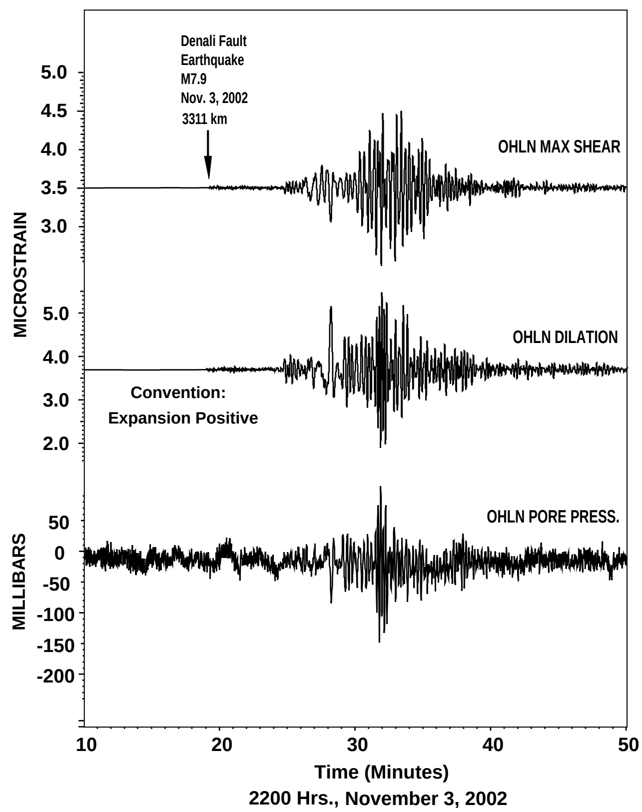

Figure 8.9: Borehole tensor strain and pore pressure monitor measurements of earthquake dynamic strains from the M7.9 Denali Fault, Alaska earthquake on November 3, 2002 observed at the Mini-PBO station OHLN. The strainmeter data have been converted to dilation and shear components based on preliminary calibrations of the sensors. Courtesy M. Johnston.

Chapter 9

Data Acquisition and Quality Control

1. Introduction

Stations from nearly all 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 cross-cut the individual networks described in Chapters 3 - 8, including the facilities in McCone Hall, procedures for data acquisition and quality control, sensor testing capabilities and procedures, and a collaborative experiment in early warning.

While some of these activities are continuous from year to year, we have identified changes or activities which are specific to 2002-2003.

2. McCone Hall Facilities

The routine data acquisition, processing, and archiving activities of the BSL are carried out in McCone Hall. The BSL facilities in McCone are designed to provide air conditioning, 100-bit switched network, and reliable power with UPS and generator.

Because of the mission-critical nature of the automated earthquake processing, most computer systems operated by the BSL run on circuits with both UPS and generator power. Air conditioning is provided through both "building air" and a separate room AC unit.

2.1 Power

Over the years, the BSL has experienced problems with the McCone generator system, including a failure in 1999 due to a combination of a weakened power system and a leak in the water pump. In last year's Annual Report, we described the failure of the McCone and Byerly generators in the March 7, 2002 campus-wide power outage.

While the failure of the generator at Byerly Vault was traced to PPCS human error (the generator had been left in a mode where it would not automatically start when power was lost), the failure of the McCone generator was due to poor maintenance. Similar to the situation in 1999, it failed due to problems in the power system combined with a leak in the water pump.

Last fall, BSL staff met with Eric Haemer, Sara Shirazi, and several others from PPCS to discuss maintenance and routine load testing of the McCone generator. As a result, the McCone generator is scheduled for quarterly load tests and bi-monthly run tests.

These quarterly load tests have proven extremely valuable. In January 31st, 2003 test, the generator failed. The failure was due to a problem with the thermostat (since replaced), but the test also revealed that the BSL is drawing more AC power than desirable from the generator, largely from the growth of the computing facilities.

In order to reduce the load on generator and UPS, BSL staff were forced to remove computer systems to building power. Mission-critical systems (communications, data acquisition, data processing, and archiving) were kept on the generator and UPS circuits, which research-specific systems were migrated to building power. To accomplish this, building power circuits were added to the computer server room (the room had originally been designed with only generator and generator/UPS circuits).

This change has meant that BSL researchers have had to address the impact on their programs with long runtimes. Without UPS power, the servers and workstations will immediately shut off during a power failure, causing all active programs to terminate. BSL researchers have been asked to build or modify their programs to save incremental results to disk, in order to minimize the loss of work.

2.2 Air Conditioning

In parallel with power problems, the BSL has faced cooling problems in room 237 in the past year. As with power, the growth of the computing systems in the past year has led to an increased heat load. This came to a crisis during the fall of 2002, with peak temperatures in the computer room exceeded 85deg when the AC unit failed. After consideration of several options, the BSL decided to add an additional AC unit to room 237. The new unit (which is not supported by UPS/generator power) has helped keep systems running this spring and summer, although the real test will be this fall.

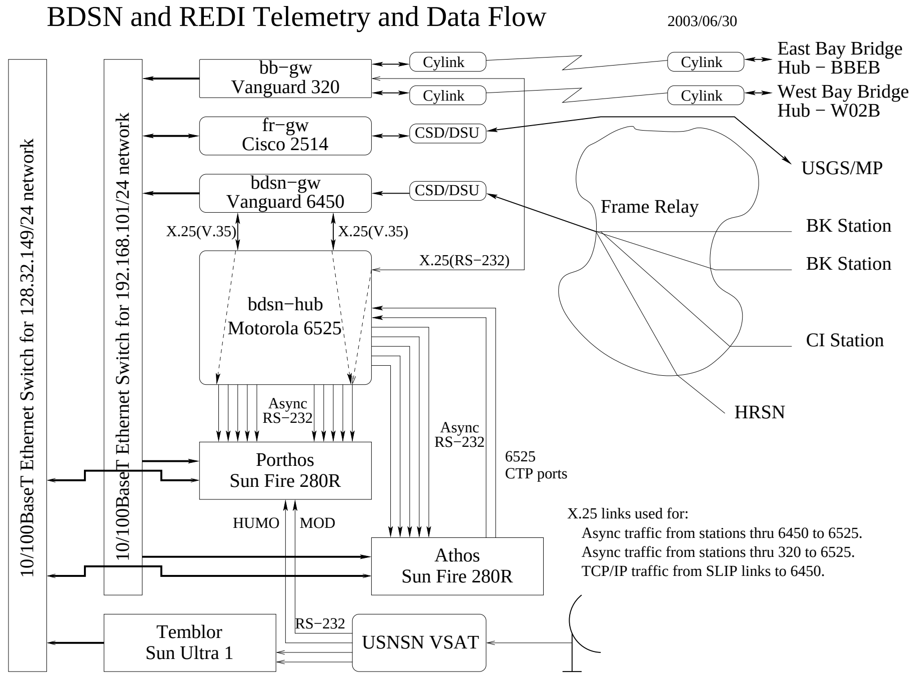

Figure 9.1: Data flow from the BDSN, NHFN, MPBO, HRSN, and BARD network into the BSL central processing facility.

In addition, the BSL staff set up a temperature monitoring system for room 237. For several years, we have relied on a temperature sensor within one our disk drives to notify us of excessive heat. In the last year, we purchased two temperature probes and a simple digitizing system that allows us to monitor temperature in several locations within the room. Complementing our pager notification, we can now monitor the temperature through real-time graphs accessible through the BSL Web site.

2.3 New Facilities

The BSL is actively working with the campus to relocate the critical operations of data acquisition, processing, archiving, and distribution to a more robust facility. With assistance from the Office of the Vice Chancellor for Research, the BSL has been granted space in a building currently under construction. The building is designed to current codes and has been given special attention for post-earthquake operations. Anticipated occupancy is in FY 2004-2005.

3. Data Acquisition

Central-site data acquisition for the BDSN/NHFN/MPBO is performed by two computer systems located at the BSL (Figure 9.1). These acquisition systems are also used for the Parkfield-Hollister electromagnetic array and for the BARD network. A third system s used primarily as data exchange system with the USNSN receives a feed from CMB, HUMO, MOD, SAO, and WDC from the the NSN VSAT. This system transmits data to the USNSN from HOPS, CMB, SAO, WDC, and YBH. Data acquisition for the HRSN follows a more complicated path, as described in Chapter 5.

Data acquisition and communication with the Quanterra data loggers depends both on the software on the recording systems and at the central site.

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 9.2).

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 sys-

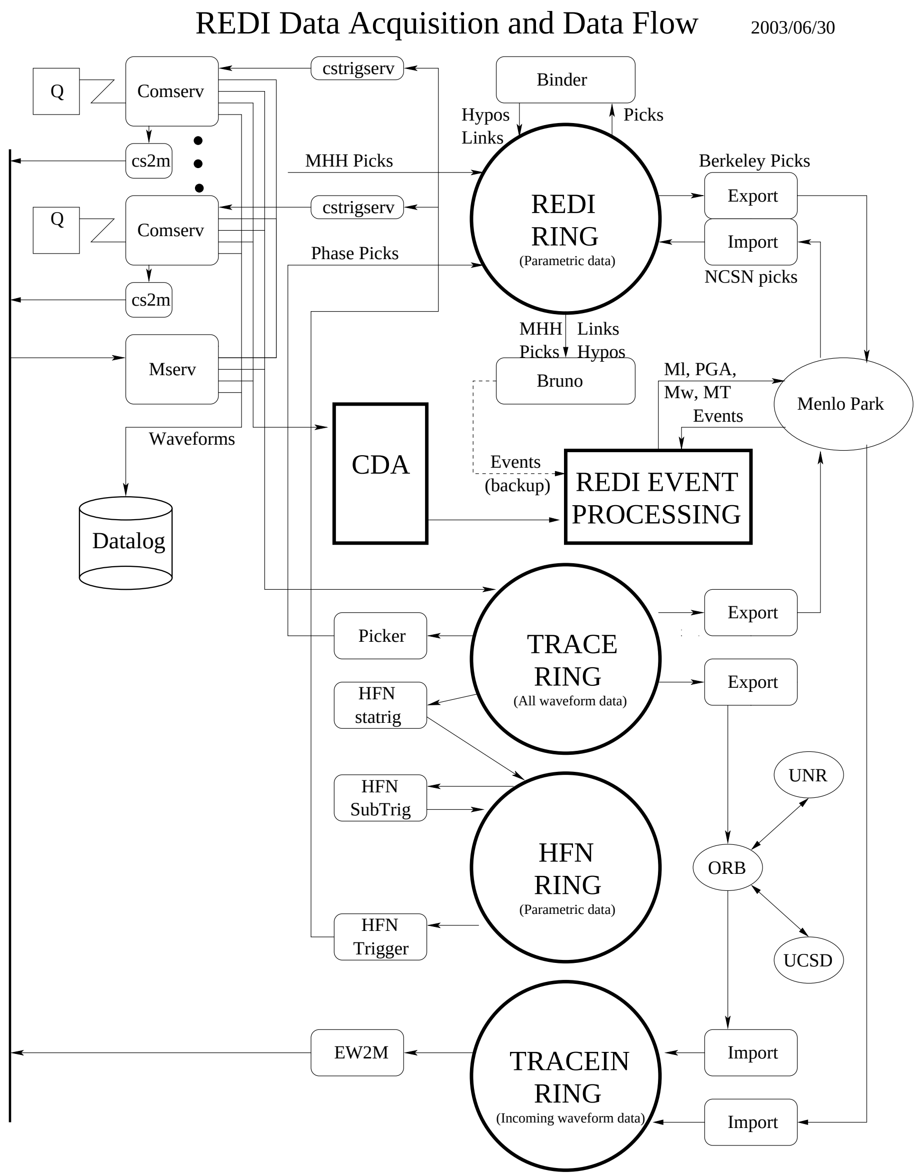

Figure 9.2: Dataflow in the REDI processing environment, showing waveform data coming in from the Quanterra data loggers (Q) into `comserv`. From comserv, data are logged to disk (via `datalog`), distributed to other computers (`mserv`), fed into the CDA for REDI processing, and spooled into a trace ring for export.

tem. 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.

Most stations transmit data to only one or the other of the two REDI systems. 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.

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.

3.2 FIR Filter Changes

At 5:00 PM PST June 30th (July 1, 00:00 UTC), 2003, the BDSN and MiniPBO Q4120 Quanterras were reconfigured and rebooted to change the FIR filter for the 100 Hz channels from acausal to causal. The affected stations are: BDM, CVS, FARB, HUMO, OHLN, PACP, POTR, SBRN, and WENL. The new BDSN Q4120 station MNRC was upgraded on the 29th, since it is a new station and continuous telemetry has not yet been installed.

This change means that all Q4120/Q730 dataloggers operated by the BSL will use causal filters for sampling rates of 100 Hz and higher (the HRSN and NHFN have traditionally used causal filters for the higher sampling rates). Lower data rates will continue to use the acausal filters. This change does NOT apply to the BDSN sites with Q680/980 dataloggers, as the FIR filters are set in firmware and are not readily changed.

This change is motivated by the desire to improve phase picking on the 100 Hz channels. A detailed comparison of casual and acausal FIR filters and their effect on the data is available by Bob Uhrhammer and Bob Nadeau is available at `http://quake.geo.berkeley.edu/bdsn/FIR_FILTRATION.pdf`.

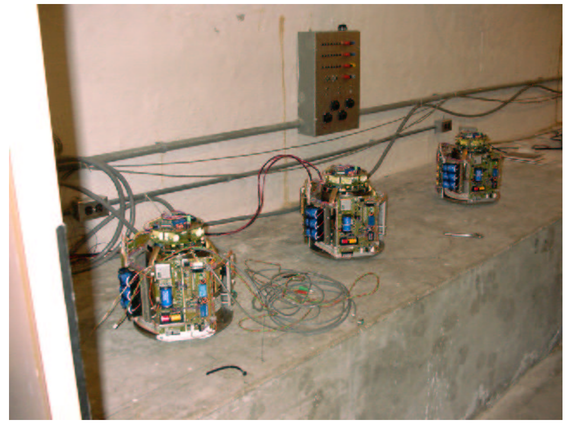

Figure 9.3: Photo of the three Guralp CMG-1TD OBS units (serial numbers T1046, T1047 and T1055 seismometers in the Byerly Vault (BKS). Shown are the various circuit boards on the sides and the top of the sensor package. Three of the nine batteries used by the leveling system are on the left side, the system clock is on the circuit board on the front, the power board is on the right, and the 24-bit digitizer is on the top of each seismometer. The seismometers are in the mu metal shielded container mounted on leveling gimbals in the center.

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 2002-2003 is displayed in Figure 3.3.

Three 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.

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. 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 access the linearity of a seismic sensor.

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

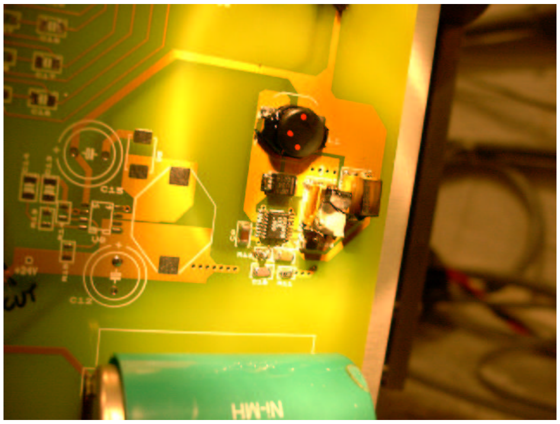

Figure 9.4: Closeup of the portion of the power board containing the failed capacitor (just to the right of center).

Figure 9.5: Custom made titanium pressure spheres which are designed for deployment at depths of up to 3.5 km. The hemispheres were made using an injection molding process. There are two access ports drilled into the flat top of each sphere, one for the penetrator containing the wiring cable and one for purging with argon gas (and for relieving any pressure differences so that the hemispheres can be separated). The handle on top is designed for the Remote Operated Vehicle (ROV) which deploys the sphere on the sea floor.

6. Sensor Testing in 2002-2003

6.1 CMG-1T Ocean Bottom Seismometers

Prior to the scheduled deployment of three CMG-1TD OBS sensor packages (Figure 9.3) on the ocean floor off of Washington State, beginning in the summer of 2003, we did extensive testing to verify the operation of the seismometers and the wide range leveling system, to verify the calibration of the seismometer and to characterize the background noise PSD performance of the seismometers. The following paragraphs provide a synopsis of the various problems we encountered when testing the three OBS systems. These problems significantly delayed the testing of the sensors and the lab personnel consequently spent more time on this project than was initially anticipated.

The testing of the OBS system in the Byerly Seismographic Vault (BKS) started on January 14, 2003 with the arrival, unpacking and installation of the three CMG-1TD seismometers (serial numbers T1046, T1047 and T1055) on the seismic pier in the Byerly Seismographic Vault (BKS). We installed a V200 FRAD in order to have sufficient serial ports to telemeter data the three sensors under test back to the lab. The next day we installed four 12 volt batteries (UPS12-310 type) to provide separate power for each of the three OBS systems and to the GPS clock. When we powered up T1047, a capacitor on the power input board caught fire and burned up with a spectacular flash and smoke within a second of applying power (see Figure 9.4). We confirmed that the power polarity was correct and we suspected that the polarized power capacitor was installed backwards. T1046 powered up without problems and responded to commands. T1055 was left unpowered pending inspection by Digital Technology Associates (DTA) (the US distributor for Guralp). DTA replaced the defective power board on T1047 we tested the unit and found it to be within specifications. The three GPS clock modules associated, one for each OBS system, were tested one at a time on the front of the BKS vault. All three GPS clocks tested good so we installed one of the clocks on top of the entrance to the vault and ran cabling back to provide time to the three OBS sensors. DTA replaced the defective power board on T1047 we tested the unit and found it to be within specifications. Plastic bags were placed over the OBS units to to keep dust and breezes off of the exposed sensors and electronics.

We encountered problems in telemetering data back to the lab so we set up a laptop with the SCREAM software provided by Guralp to locally log data from the sensors and troubleshoot the systems. We encountered no errors that would indicate telemetry problems when logging the data locally. When the three OBS's recorded a local earthquake, we discovered that horizontals on T1047 have half gain and inverted polarity. This was raw data so software and transfer functions errors are excluded. We found that the onboard rechargeable batteries on T1047 and T1055 were not charged enough to lock the seismometers. We moved the good power board from T1046 in order to lock the T1047 and T1055 seismometers. All three power boards were then removed and sent back to Guralp for repair with an expected turnaround time of three weeks.

On March 24th the "improved" power boards were in-

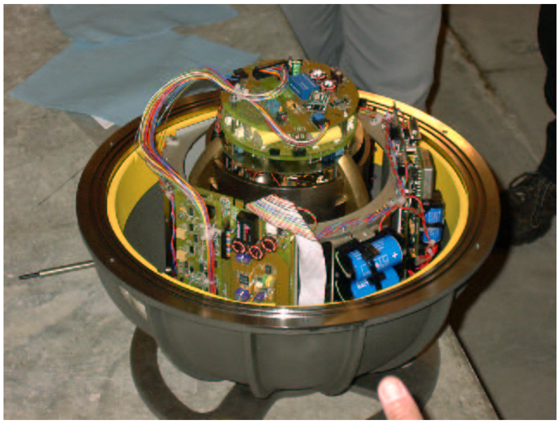

Figure 9.6: Closeup of the OBS installed in the lower hemisphere of the pressure vessel. Shown are the various circuit boards on the sides and the top of the sensor package. The thumb is pointing towards the rechargeable batteries which are used to to supply the extra current required by the two high torque motors used in the leveling system. On the right side of the sensor is the circuit board containing the internal clock. On the left front is the the I/O circuit board and on top is the 24-bit digitizer. The seismometers are in the mu metal shielded container mounted on leveling bowl. Also visible around the inside of the hemisphere, and just below the flange, is the high density foam insulation.

stalled on the three OBS units and the revised firmware was successfully uploaded to the onboard digitizers. During the initial simultaneous testing of all three OBS sensors, we found that the power management has improved and seems to work properly and also that the traces from all three sensors, as recorded on a local laptop computer, looked coherent in amplitude and phase. We then connected the three OBS units to the telemetry link back to the lab for further testing. The azimuth command was tested on T1055 by locking the sensors, rotating it 90 degrees counter clockwise and then using the azimuth command to reconfigure for NS/EW orientation. However, we found that T1055 would not re-level. Subsequently T1946 was removed for testing and evaluation by DTA. T1046 had some gaps in the telemetered data so we swapped its telemetry to a different serial port on the FRAD to see if a good OBS system produces data gaps through the same serial port.

On April 18th, T1046 was returned from Guralp and reinstalled in the BKS vault. Over the next couple of weeks, the OBS sensors were sequentially tested with local recording on the laptop computer. All three OBS units are operating nominally within specifications and we await the arrival of the titanium pressure vessels from MBARI to complete the testing.

On June 20th, the MBARI crew arrived with the pressure vessels (Figure 9.5) and we spent most of the day installing the OBS units within the pressure vessels (Figure 9.6). The MBARI crew had installed ∼0.5 inch thick high density foam insulation in the upper titanium hemisphere and ∼4 inches into the lower hemisphere to inhibit convection within the enclosed pressure vessel. Additionally, each pressure vessel was purged with argon gas to further inhibit convection within the titanium pressure vessels. T1046 and T1055 were reconnected to the telemetry back to the lab and T1047 was taken to MBARI for testing in their cold room to determine whether or not the internal clock on the OBS unit met the factory specifications when operated at 4 degrees Celsius (the nominal temperature of the water on the ocean floor).

Subsequent testing indicated that T1055 had a high Z-component noise level and we suspected that it had drifted off center. We successfully recentered both OBS units via the laptop computer. T1046 was now operating nominally within specifications but T1055 remains noisy (Figure 9.7) so it will require further testing. The OBS units we picked up by the MBARI crew for transporting to the University of Washington on July 15th.

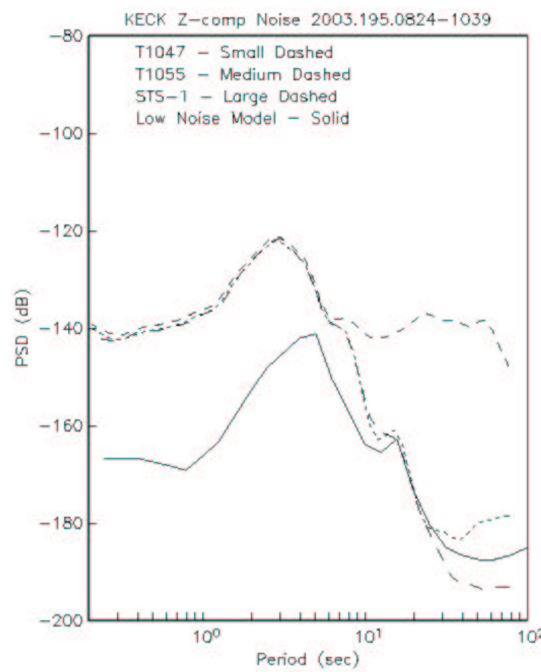

Figure 9.7: Power Spectral Density (PSD) plot of the background and instrumental noise levels in dB as a function of period. Shown are the PSD's for T1047 and T1055. The PSD for the co-sited STS-1 Z and the low seismic noise model are shown for reference. Note that the PSD for T1055 is excessively noisy at periods longer than ∼10 seconds.

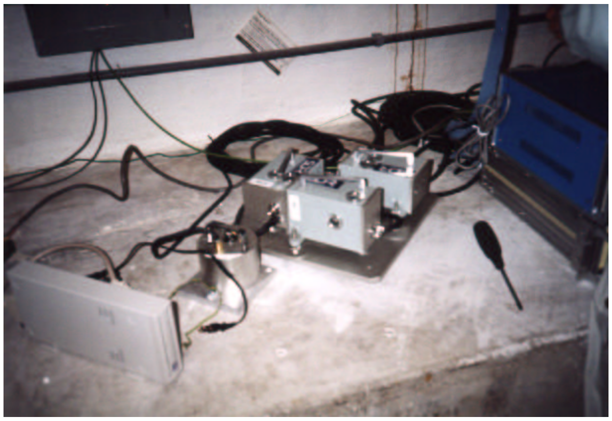

Figure 9.8: UrEDAS sensors installed at BKS site. The dedicated PC-based processing system (not shown here) is located in an adjacent room.

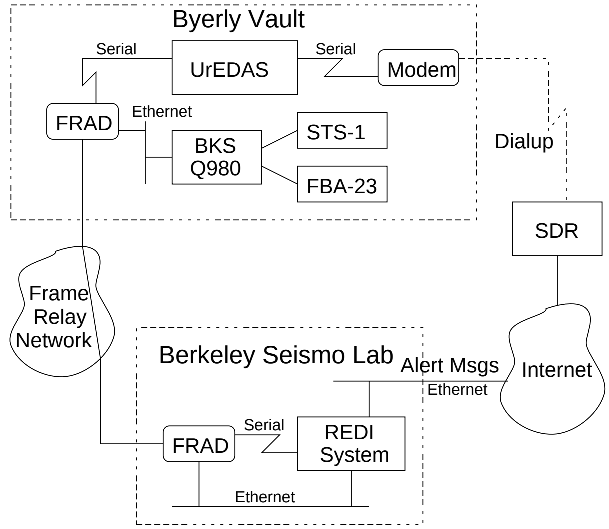

Figure 9.9: Schematical illustration of the UrEDAS collocation experiment with a Streckeisen STS-1 broadband instrument and a Kinematrics FBA-23 strong motion accelerometer with a Quanterra Q980 data logger at BKS.

7. UrEDAS Project

The established joint notification system in Northern California provides accurate and reliable determination of earthquake parameters, but there is a time delay between the occurrence of an event and the determination of its size. In an emergency, this time delay prevents actions which could mitigate damage from strong ground shaking. In an effort to develop such capability with the BDSN, we started an experiment collocating a set of UrEDAS (Urgent Earthquake Detection and Alarm System; see *Nakamura,* 1996), an integrated real-time earthquake warning system, with the BDSN site BKS in 2001. Previous annual reports have described the UrEDAS system and its installation in Byerly Vault. Here we provide an update.

7.1 Collocating Experiment

The initial system installation at BKS was completed with the event detection and notification in February 2001 and was upgraded to transmit waveform data to the BSL in July 2001. The SDR crew visited the site in July 2002 to check on the equipment and to revise the values of the parameters used by the UrEDAS algorithms. They again visited the site in July 2003 to upgrade the software and revise the values of the processing parameters that determine the seismic wave apparent azimuth and dip. Figure 9.8 shows the UrEDAS sensors and Figure 9.9 shows an illustration of the UrEDAS network configuration.

7.2 Rapid Event Detection

In the UrEDAS system the event detection velocity threshold is pre-set; the epicentral azimuth is estimated from the direction of the initial motion projected on the horizontal plane; and the preliminary estimate of the distance and magnitude is based on the frequency content and amplitudes of P-wave first motions (~3 sec). An alarm can be issued if a hazardous earthquake is detected by P-waves (Version 1 E-mail). If an S-wave arrival is detected, the preliminary estimate is revised (Version 2 E-mail)

The epicentral distance (R) is estimated using the relation $logR = a{\cdot}logA{+}b{\cdot}logT{+}c$ where A is the amplitude of the initial P-wave motion (in mkine), T its prominent period, and a, b, and c are constant. The magnitude is estimated from the prominent period (T) of the initial P-wave motion using the relation $M = 3.2 \cdot logT + 5.26$. We do not suppose that these relations apply universally but are testing them empirically. A UrEDAS waveform example is shown in Figure 9.10 and an expanded view of the P-wave is shown in Figure 9.11. The azimuth determination shows systematic biases, most likely due to the nearby Hayward fault where the impedance can change by ~40% across the fault zone. The erroneous location estimates can be also attributed to the propagation path effects through the faults, the near-site structural heterogeneity and/or noise level. If the azimuth estimate becomes reliable, the combined information from two stations could also make a reasonable estimate of an epicentral distance.

The estimated magnitudes of small local events in the epicentral distance between 20 and 200 km were within the range expected from other experiments. Magnitudes of the smaller events (M < 2.5) tend to be overestimated, and those of events at farther distances (R>200 km)

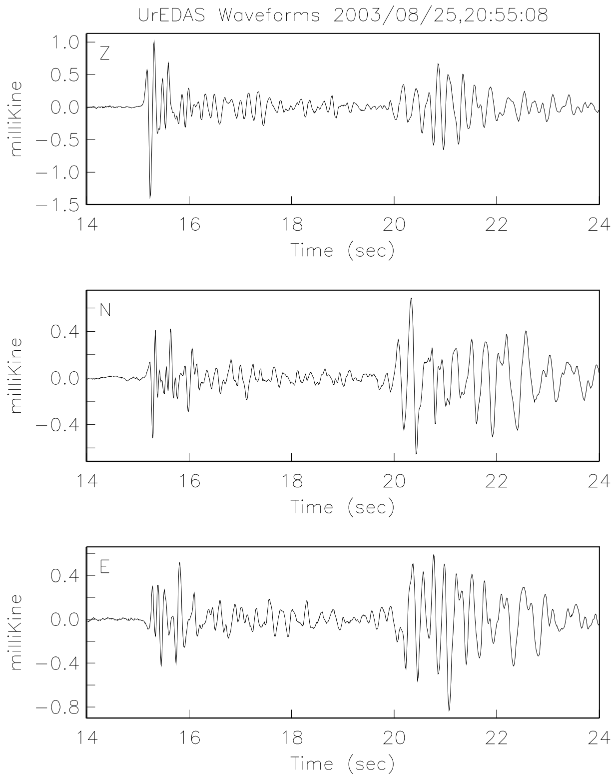

Figure 9.10: UrEDAS waveforms from a M 2.3 earthquake which occurred 32.2 km SE (123deg azimuth) from Berkeley and 8 km NNW of Pleasanton, CA. The vertical scales are in milliKine (1 Kine is 1 cm/sec).

are underestimated. See the previous Annual Report for more detail.

Since the installation of the UrEDAS system in February 2001, there have been 575 UrEDAS paged events (1.3≤M≤8.1) and 387 of these had corresponding NCSN events (within a 500 km radius and with a theoretical P-wave onset time at BKS within 20 seconds of the UrEDAS detection time). The 188 uncorrelated UrEDAS events are a mix of teleseisms (which UrEDAS has a tendency to mislocate as local events), some small local events near Berkeley, and a few random noise triggers. The UrEDAS performance was evaluated by comparing the event parameters with those recorded in the ANSS composite catalog. The event detection performance was satisfactory, although UrEDAS is designed to detect primarily local events (R≤200 km) and it does not have the ability to distinguish between teleseismic and local events at present.

We have done some preliminary comparison of the waveform data recorded by the BKS broadband instrument with those recorded by the UrEDAS. Because of the complexities of seismic structure, nonlinearities involved in the propagation of the complex faults areas,

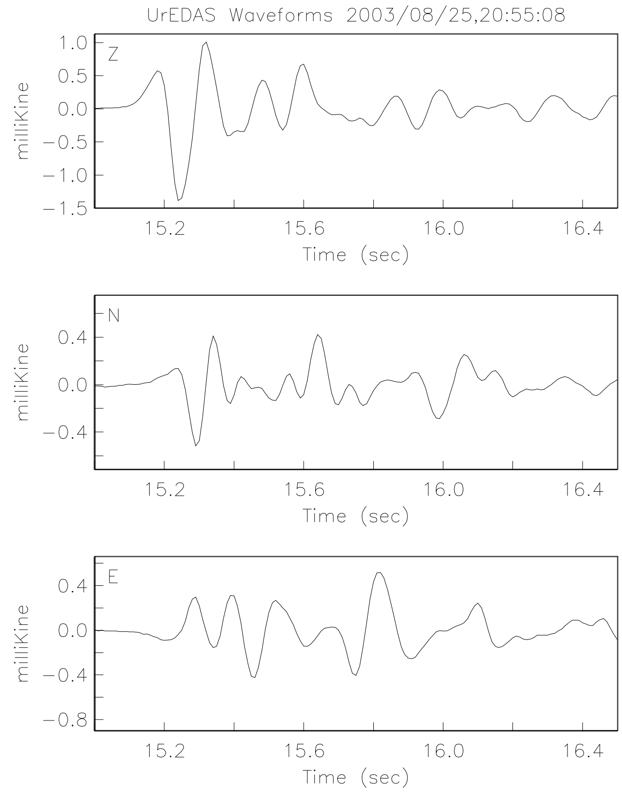

Figure 9.11: Expanded view of Figure 9.10 showing the first few seconds of the P-wave. Note that the P-wave particle motion is linear for the approximately the first cycle and then it predominantly elliptical owing to the near-receiver structural complexity of the crust and the proximity to the Hayward fault zone.

this problem does not lend itself to easy analysis without systematic and more advanced analyses and calibrations. We focus on improving the algorithm to rapidly evaluate preliminary earthquake source parameters, i.e., magnitude and location.

7.3 Discussion

To date UrEDAS readily detects the occurrence of local/regional events from the P-wave signal. It also does a fair job of determining the source distance out to 160 km or so but the azimuth determination is basically unusable. UrEDAS also has biased magnitude estimates. The UrEDAS algorithm assumes a one-dimensional velocity model with straight line propagation paths and a three-dimensional model of the crustal structure will likely be required to significantly improve the azimuthal estimates. Also, the magnitude estimation algorithm needs further tuning. During their July, 2003 visit, the UrEDAS engineers updated some of the UrEDAS algorithms parameter values. In particular, they shortened the time interval that is used to estimate the azimuth from the P-wave waveform.

Assuming that the primary goal is to determine the event location and size as rapidly as possible, the fastest approach will prove to be a hybrid approach where the remote stations determine the azimuth and ramp growth rate and associated uncertainties and the central site uses a fuzzy logic algorithm to determine the location and size of the event. The primary advantage of this hybrid method is that the ramp growth rate can be reliably determined before the S-wave arrives. In the limiting case, and with a sufficiently high station density, one could even go so far as to determine and report from the remote sites using only the broadband P-wave impulse, the associated azimuth and apparent angle of incidence (along with estimates of their resolution). The central site could then coalesce the data into a viable and rapid event report.

The critical issue for a successful installation of a UrEDAS type system in the BDSN is the calibration of specific site effects at individual stations. A joint use of the single station detection system with the current northern California earthquake notification system would significantly increase the capability of real-time earthquake warning system.

8. Acknowledgements

Doug Neuhauser, Bob Uhrhammer, Lind Gee, 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 and/or incentive to set up and operate the facility and we thank them for their support.

Bob Uhrhammer led the testing and problem solving effort of the KECK sensors, with help from John Friday, Doug Neuhauser, and Bill Karavas.

Bob Uhrhammer and Bob Nadeau evaluated the impact of the FIR filters on the BDSN data.

Fumiko Tajima initiated the collaboration with SDR on testing the UrEDAS system, which is now coordinated by Bob Uhrhammer. Doug Neuhauser, Bill Karavas, John Friday, and Dave Rapkin helped with installation and maintenance. We thank Yutaka Nakamura and his colleagues at SDR for providing us with the installation of UrEDAS system and information on the accumulated data by this system.

Bob Uhrhammer, Lind Gee, and Doug Neuhauser contributed to the preparation of this chapter.

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Chapter 10

Northern California Earthquake Monitoring

1. Introduction

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 10 years, the BSL has invested in the development of the hardware and software necessary for an automated earthquake notification system (*Gee et al.*, 2003; *Gee et al.*, 1996). 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. A long-term goal of the project is the development 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.

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 BSL and USGS system forms the Northern California Management Center (NCMC) of the California Integrated Seismic Network (Chapter 2).

2. Northern California Management Center

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

Figure 10.1 illustrates the NCMC as part of the the CISN communications ring. The NCMC is a distributed center, with elements in Berkeley and 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 2, 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 communication link to provide bandwidth for shipping waveform data and other information between their processing systems.

Figure 10.2 provides more detail on the current system at the NCMC. 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 the standard detection, location, estimation of M_d, M_L, and M_w, as well as processing of 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 smaller quakes. The high dynamic range data loggers, digital telemetry, and broadband and strong-motion sensors of the BDSN and REDI analysis software provide reliable magnitude determination, moment tensor estima-

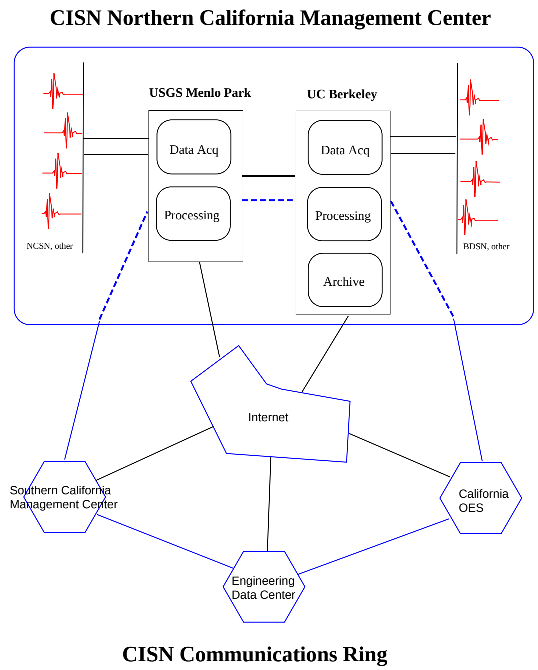

Figure 10.1: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley, forming the northern California Management Center, and with other elements of the CISN.

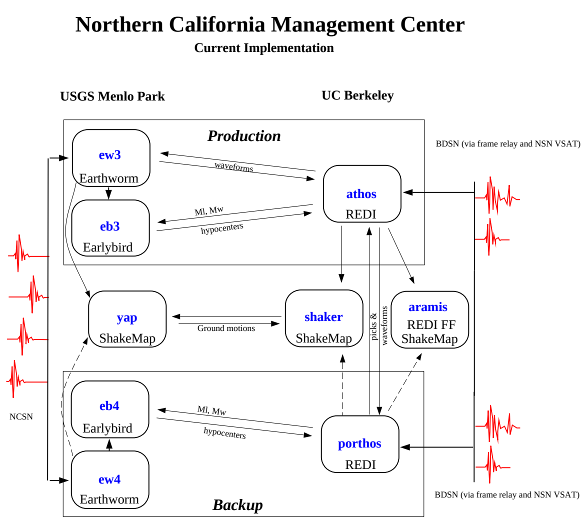

Figure 10.2: Detailed view of the current Northern California processing system, showing the two Earthworm-Earlybird-REDI systems, the two ShakeMap systems, and the finite-fault system.

tion, 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 10.3).

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. 2002-2003 Activities

3.1 ShakeMap

The BSL and USGS/Menlo Park staff met in August 2002 to discuss how to improve the robustness of ShakeMap operation in northern California. At that time, ShakeMaps in northern California depended on the operation of a single computer, located in Menlo Park. This was in contrast to other earthquake monitoring operations, where 2 parallel systems provide back-up capability should a computer fail. The BSL and USGS Menlo Park agreed to bring up a second ShakeMap system at UC Berkeley, which will be twin or clone of the Menlo Park system.

The implementation of the second ShakeMap system was completed in early 2003, using one of the new CISN processing computers. Both ShakeMap systems are be driven off the "production" monitoring system and both are configured to allow distribution of ShakeMaps to the Web and to recipients such as OES. At any one time, however, only one system distributes information.

In parallel, Pete Lombard at the BSL was trained to review ShakeMaps following an earthquake. Since early in 2003, the BSL has been trading the responsibility of ShakeMap production. The key to making a ShakeMap machine take over the production duty is to copy the earthquake database file from the former production machine to the new production machine. In that way, both machines can produce consistent ShakeMap archive lists.

The BSL has started work on a system to help with review of ShakeMaps. By modifying the program `grind`, we now write logs of the PGA and PGV values from station data, the regression curve, and the limits used by

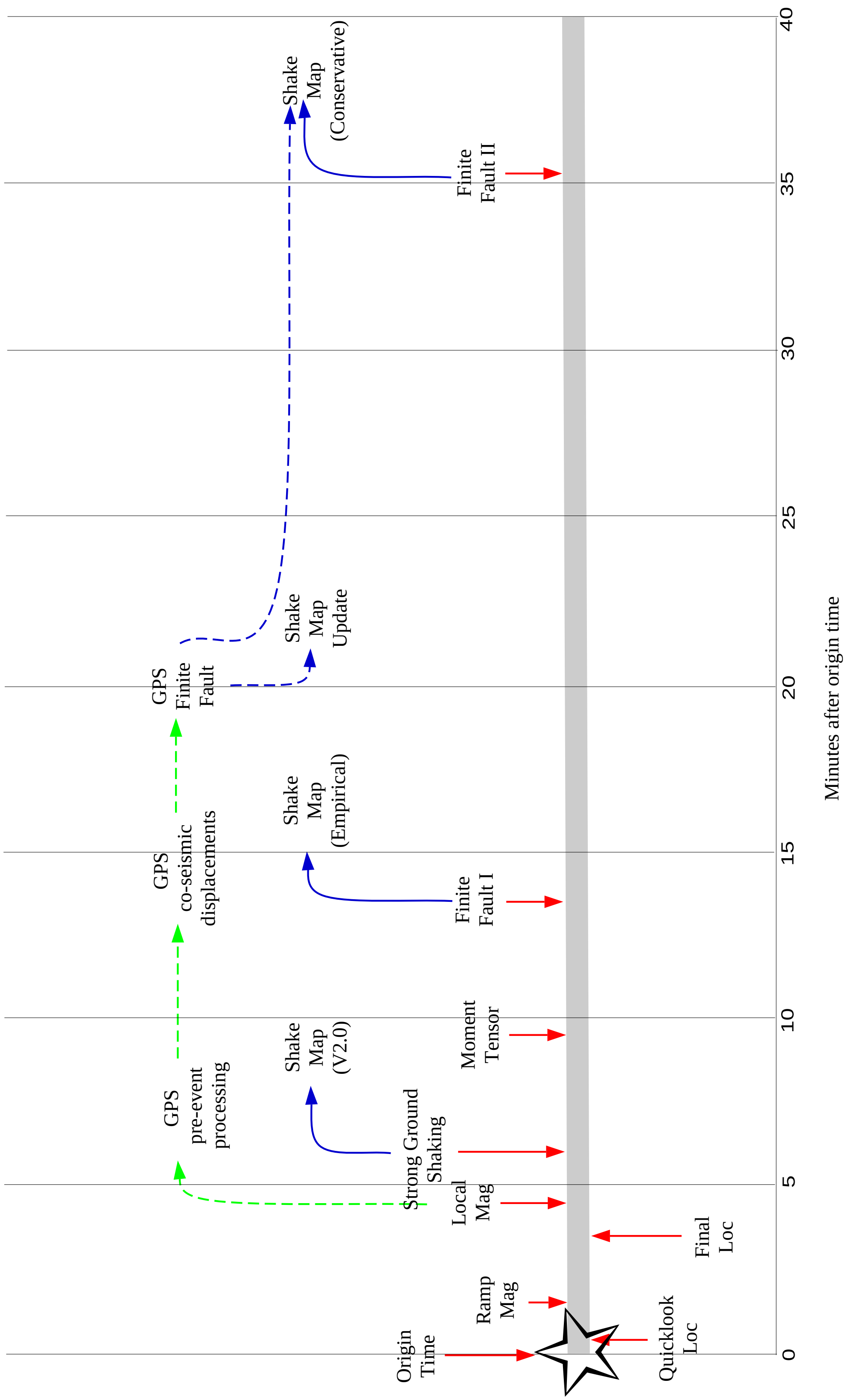

Figure 10.3: Illustration of the current (solid lines) and planned/proposed (dotted lines) development of real-time processing in northern California. The Finite Fault I and II are fully implemented within the REDI system at UC Berkeley and are integrated with ShakeMap. The resulting maps are still being evaluated and are not currently available to the public.

grind to flag outlier stations. This data is then plotted on amplitude vs. distance log-log plots. While this simple plot loses the spatial information available from a map view, it accurately reflects the process that grind uses for flagging stations. And the outlying data are more apparent on the x-y plots. For now, our plotting is done by a crude script running gnuplot. We intend at least to change this to use GMT for plotting. And we imagine that some day a pair of "clickable" plots could be presented on an internal Web server for use by ShakeMap reviewers.

3.2 M_w

The REDI system has routinely produced automatic estimates of moment magnitude (M_w) for many years. However, these estimates have not routinely used as the "official" magnitude, due in part to questions about the reliability of the automatic solutions. However, in response to the 05/14/2002 Gilroy earthquake (M_w 4.9, M_L 5.1) and the complications created by the publication of multiple magnitudes, the BSL and USGS Menlo Park have agreed to use automatically determined moment magnitudes, when available, to supplement estimates of local magnitude (M_L). This work was completed in the last year and M_w is now routinely reported when the solution is "good enough".

When is a solution "good enough"? This question has been under review in the last year - both to ensure reliable reporting of M_w in northern California and as part of the CISN-effort to establish rules for a magnitude hierarchy. Figures 10.4 & 10.5 illustrate a dataset compiled since the most recent modification of the moment tensor software. The dataset indicates that the estimate M_w from the complete waveform inversion is quite robust for when a variance reduction of 40% or higher is obtained. In general, earthquakes of M4.5 and higher almost always achieve that level of variance reduction. Under the current rules, the Northern California Management Center always reports M_w if the variance reduction is 40% or better.

We have also looked at comparisons between our regional estimate of M_w and the moment magnitudes determined by Harvard as part of the Centroid Moment Tensor project. Figure 10.6 illustrates the regional M_w compared with the CMT M_w, along with comparisons between the NEIC estimates of M_w, m_b, M_s and the CMT M_w. This dataset spans approximately 60 events in the western US and good agreement between the regional and global methods is observed, although there appears to be a systematic difference in the estimates of approximately 0.08 - 0.09 magnitude units, with the CMT estimate being higher.

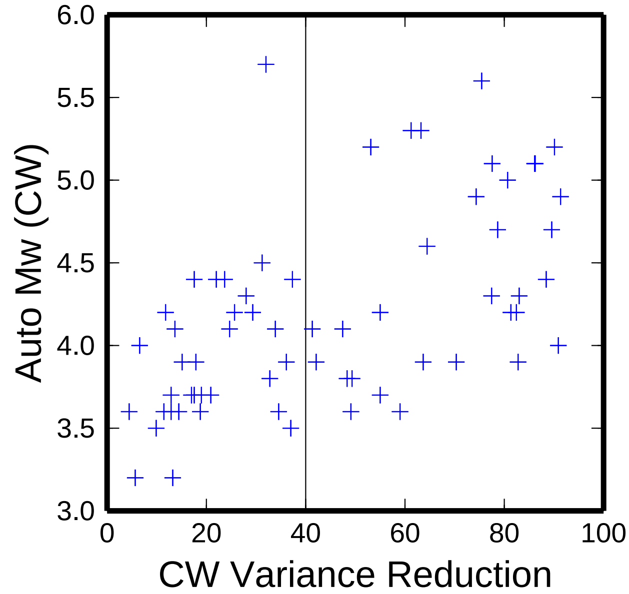

Figure 10.5: Results from the last year of complete waveform moment tensor inversions in the REDI system, with a few older events. With one exception, all events of M4.5 and higher achieved a variance reduction of 40%; approximately one third of the smaller events achieved the same level.

3.3 Version Numbers/Quake Data Delivery System

In the last year, the BSL and the USGS Menlo Park completed the software modifications necessary to track version numbers in the processing system. Version numbers are important for identifying the latest (and therefore hopefully the best) hypocenter and magnitude for an earthquake. Because both Menlo Park and Berkeley can be a source of earthquake information, it was critical to design a common versioning system. The modifications enabled the BSL to begin contributing solutions to QDDS, increasing the robustness of data distribution in northern California. At the present time, the USGS Menlo Park distributes solutions to 2 of the 3 QDDS hubs and the BSL distributes solutions to 2 of the 3 hubs (that is, 2 hubs receive notices from either the USGS or the BSL and 1 hub receives notices from both). This implementation should allow information to be distributed in the case of Internet shutdown of the Department of Interior (as occurred in December 2001 - see http://www.cisn.org/news/doi.html).

3.4 Database Implementation

During the past year, the BSL completed modifications to implement a database within real-time system. At this point, the database is used as a storage system,

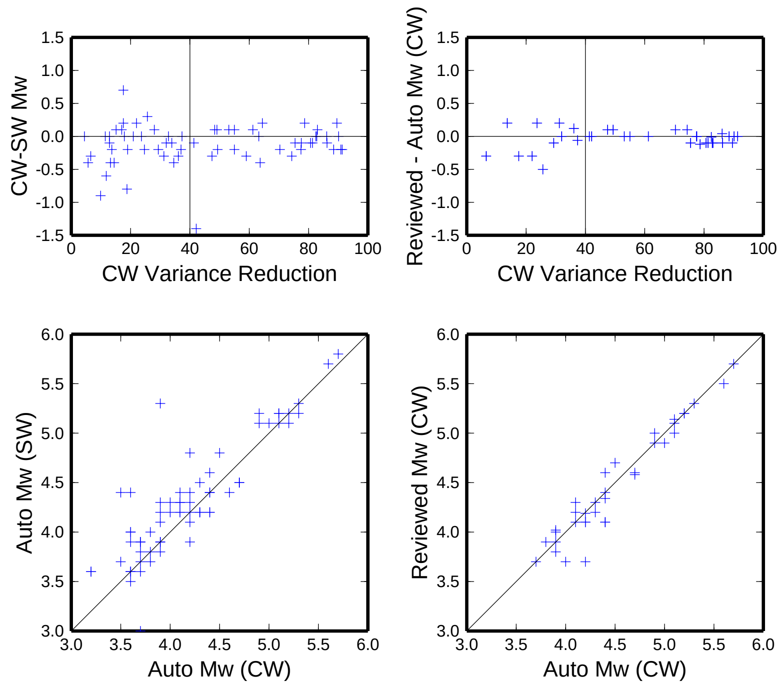

Figure 10.4: Left: Left: Comparison of the two regional estimates of moment magnitude – the complete waveform (CW) and the surface wave (SW) methods – from the last year of REDI results and a few older events rerun through the system. As observed in *Pasyanos et al., 1996*, the estimates of moment from the surface wave inversion are larger than the complete waveform inversion. Right: Comparison of the estimates of M_w from automatic and reviewed complete waveform solutions.

supplementing the flat files that have been the basis of the REDI system. The modified software has now been installed on both REDI platforms.

3.5 System Development

As part of ongoing efforts to improve the monitoring systems in northern California, the BSL and the USGS Menlo Park have begun to plan for the next generation of the northern California joint notification system.

Figure 10.2 illustrates the current organization of the two systems. As described above, an 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 7 years, there are a number of potential problems associated with the separation of critical system elements by 30 miles of San Francisco Bay.

Recognizing this, we intend to redesign the Northern California operations so that a single independent system operates at the USGS and at UC Berkeley. Figure 10.7 illustrates the planned configuration. In FY01/02, our discussions proceeded to the stage of establishing specifications and determining the details required for design. However, in the last year, most of the development effort focused on CISN activities and specific plans for the "next generation" Northern California system were put on hold. This enforced wait provided the opportunity for some ideas to mature and the current plans for the NCMC are somewhat different from those envisioned in 2001.

The current design draws strongly on the experience in Southern California for the development of TriNet. In the last year, BSL staff, particularly Pete Lombard, have become extremely familiar with portions of the TriNet software. We have begun to adapt the software for Northern California, making adjustments and modifications along the way.

We anticipate that the next generation of Northern California Management Center system will include many elements from the TriNet software. Certain components, such as the dependence on third part software for communication among processing modules, will be modified and an alternative distribution system utilized.

4. Routine Earthquake Analysis

On a daily basis, the BSL continues to locate and determine the magnitude of earthquakes in northern California and adjacent regions. As a general rule, events are analyzed if their magnitude is greater than 2.8 in the Central Coast ranges, greater than 3.0 in all of northern Califor-

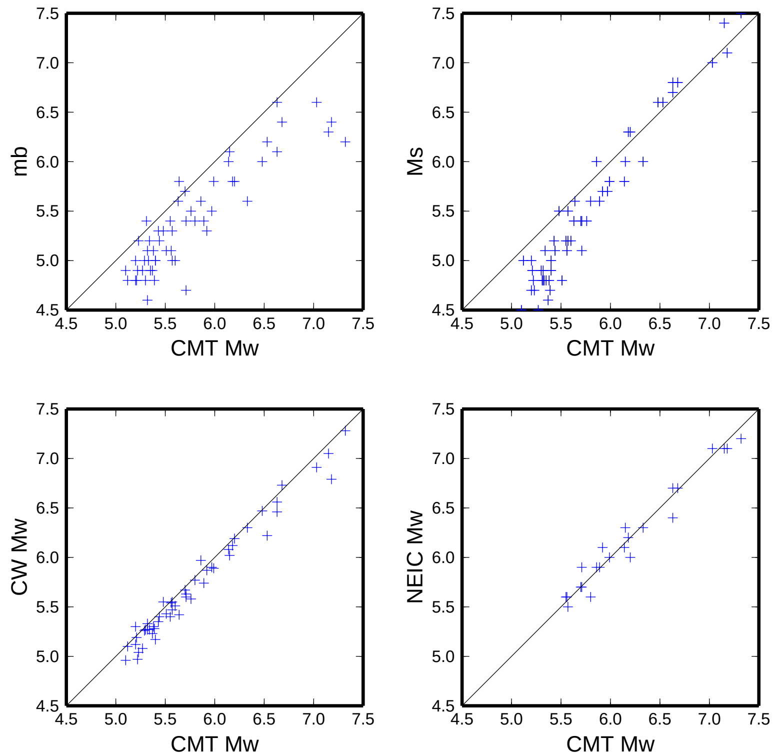

Figure 10.6: Comparison of several magnitudes with the M_w estimates determined from the Harvard Centroid Moment Tensor project. Lower left: Regional M_w from the reviewed solutions of the BSL; lower right: Global M_w from NEIC; upper left: m_b from NEIC; upper right: M_s from NEIC.

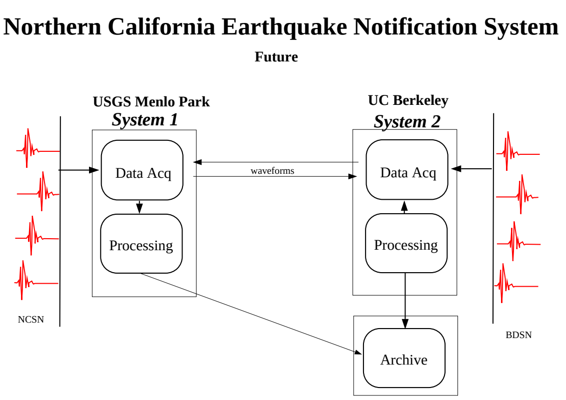

Figure 10.7: Future design of the Northern California Earthquake Notification System. In contrast with the current situation (Figure 10.2), the system is being redesigned to integrate the Earthworm/Earlybird/REDI software into a single package. Parallel systems will be run at the Berkeley and Menlo Park facilities of the Northern California Operations Center.

nia, or greater than 3.8 in the bordering regions. Traditionally, these events were located using hand-picked arrival times from the BDSN stations in conjunction with P-arrival times from the NCSN using the program strelp. Over the past several years, the BSL has made a transition in the daily analysis to take advantage of the automatic processing system. As part of this transition, events which have been processed by the automatic system are not generally relocated, although phase arrivals are still hand-picked and the synthetic Wood-Anderson readings are checked. Instead, analysts are focusing on the determination of additional parameters, such as the seismic moment tensor, phase azimuth, and measures of strong ground shaking.

From July 2002 through June 2003, BSL analysts reviewed nearly 150 earthquakes in northern California and adjoining areas, ranging from M2.2 to 6.2. Reviewed moment tensor solutions were obtained for 24 events (through 6/30/2002). Figure 10.8 and Table 10.1 displays the earthquakes located in the BSL catalog and the moment tensor solutions.

4.1 Special Events

In late November, a small swarm of earthquakes occurred near the Calaveras fault in San Ramon. The

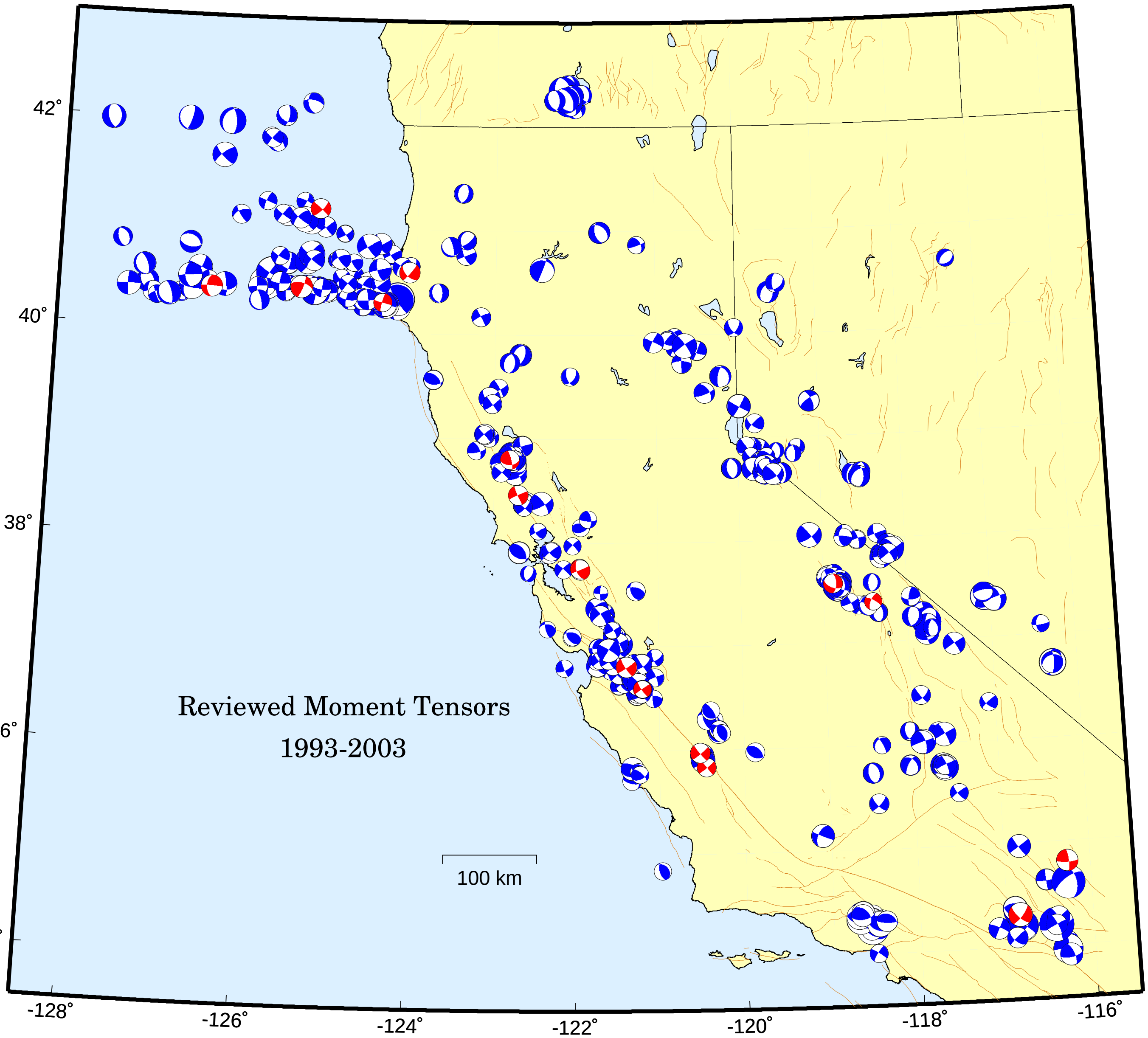

Figure 10.8: Map comparing the reviewed moment tensor solutions determined by the BSL in the last 10 years (blue) and those from the last fiscal year (red).

largest event was a M_w 3.9 and with 4 events over M3.5. The pre-Thanksgiving events were felt over a large area - the Community Internet Intensity Map reports approximately 2400 responses for the M3.9. The Northern California Management Center put together an Internet report on the sequence and posted it on the CISN Web page: `http://www.cisn.org/special/evt.02.11.24/` In early February, a small swarm of earthquakes occurred near the Calaveras fault in Dublin. The largest event in this sequence was an M_L4.2, with 3 events of M3.5. In contrast to the events in November, these events occurred sub parallel to the Calaveras fault (Figure 10.9). As in November, these events were felt over a broad area, although no damage was reported.

4.2 Teleseisms

In addition to the routine analysis of local and regional earthquakes, the BSL also processes teleseismic earthquakes. Taking advantage of the ANSS catalog, analysts review teleseisms of magnitude 5.8 and higher. All events of magnitude 6 and higher are read on the quietest BDSN station, while events of magnitude 6.5 and higher are read on the quietest station and BKS. Earthquakes of magnitude 7 and higher are read on all BDSN stations.

The locations and magnitude determined by the BSL are cataloged on the NCEDC. The phase and amplitude

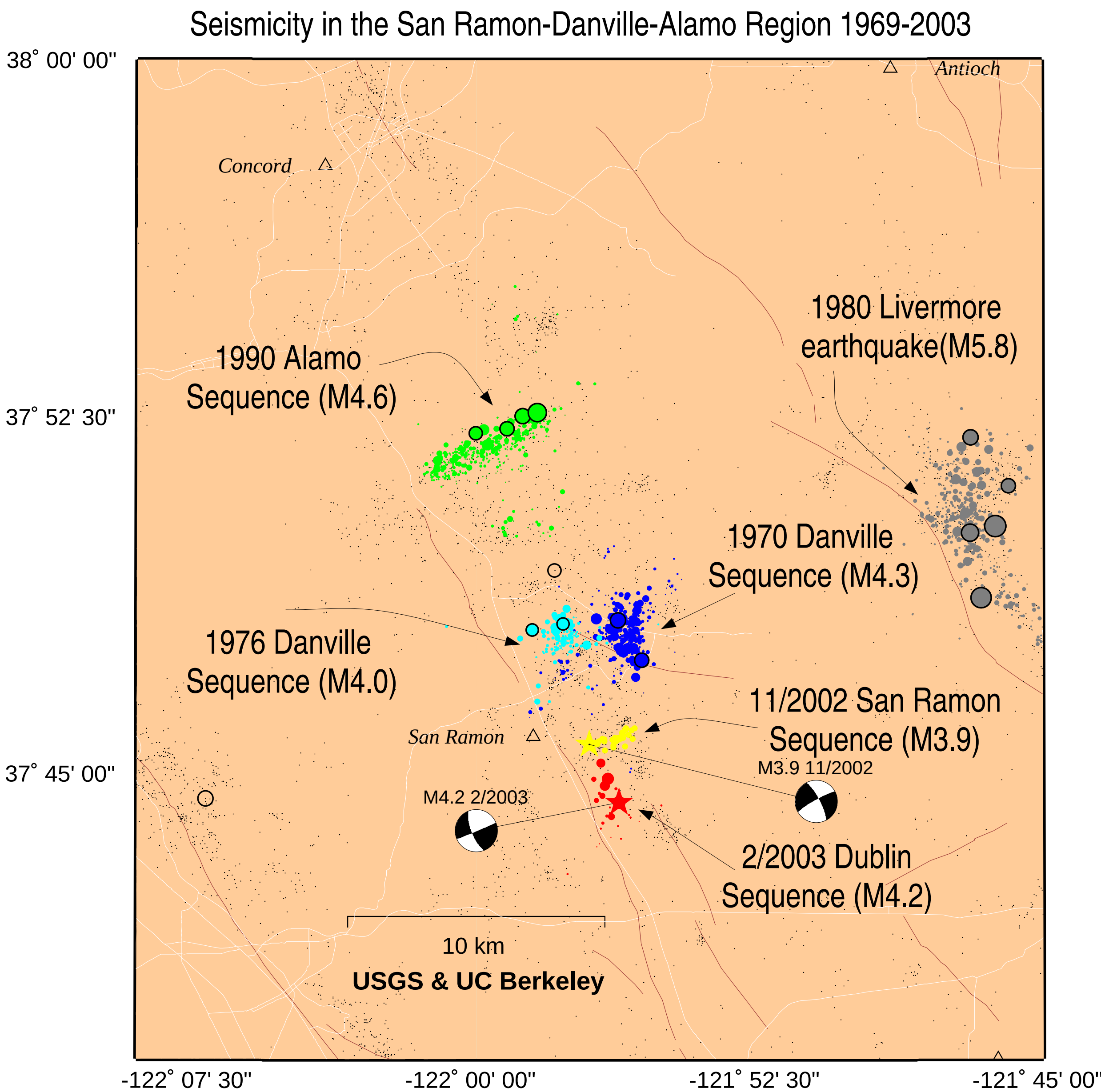

Figure 10.9: This map illustrates the Feb 2003 Dublin and Nov 2002 San Ramon swarms in the context of historical seismicity. Earthquakes from the USGS catalog 1970-2003 are plotted, with events of M_L ¿= 4.0 plotted with large circles. Events associated with various sequences are plotted in color: 1970 Danville (blue), 1976 Danville (turquoise), 1980 Livermore (grey), and 1990 Alamo (green). Events from the 2002 swarm are plotted in yellow and the events from 2003 are plotted in red.

data are provided to the NEIC, along with the locations and magnitudes, as contributions to the global catalogs, such as that of the ISC.

5. Acknowledgements

Lind Gee leads the development of the REDI system and directs the routine analysis. Peter Lombard and Doug Neuhauser contribute to the development of software. Rick McKenzie, Doug Dreger, and Dennise Templeton contribute to the routine analysis. Lind Gee, Doug

Location	Date	Time	Lat.	Lon.	MT Dep.	M_L	M_w	M_o	Str.	Dip	Rake
Bishop	07/15/2002	20:18:17.0	37.385	-118.407	14.0	4.1	3.7	3.50e21	300	76	-154
Parkfield	09/06/2002	07:28:22.0	35.834	-120.450	14.0	4.0	4.0	9.79e21	321	88	175
San Benito	09/25/2002	07:08:46.0	36.592	-121.199	11.0	3.9	3.8	6.70e21	134	87	176
Pinnacles	09/28/2002	16:07:47.0	36.595	-121.200	14.0	3.7	3.7	4.49e21	146	81	177
Ludlow	10/29/2002	14:16:53.0	34.807	-116.267	8.0	4.9	4.6	7.84e22	356	79	167
Parkfield	11/12/2002	16:48:25.0	35.972	-120.522	11.0	4.2	4.1	1.80e22	141	87	-173
Punta Gorda	11/21/2002	13:17:39.0	40.295	-124.420	11.0	3.5	3.9	8.65e21	104	88	173
San Ramon	11/24/2002	14:54:23.0	37.760	-121.950	8.0	3.9	3.9	7.75e21	242	84	-13
Hollister	01/07/2003	22:29:27.0	36.806	-121.389	11.0	4.7	4.3	3.71e22	147	80	-174
Petrolia	01/08/2003	05:41:43.0	40.422	-125.445	8.0	4.2	4.7	1.12e23	20	79	31
Dublin	02/02/2003	16:22:52.0	37.746	-121.943	14.0	3.6	3.7	4.46e21	259	81	14
Dublin	02/02/2003	18:22:58.0	37.740	-121.937	14.0	4.2	4.1	1.36e22	67	88	-19
Dublin	02/02/2003	18:47:39.0	37.748	-121.942	11.0	4.0	4.1	1.36e22	67	87	-34
Arcata	02/18/2003	14:44:24.0	41.179	-125.237	11.0	3.7	4.2	2.39e22	44	75	3
Big Bear City	02/22/2003	12:19:10.0	34.310	-116.848	5.0	5.4	5.0	3.20e23	40	75	-20
Mammoth Lakes	03/08/2003	15:35:02.0	37.572	-118.885	5.0	4.3	4.1	1.36e22	2	62	-39
Hydesville	04/22/2003	10:46:09.0	40.588	-124.086	27.0	3.9	4.4	3.76e22	40	84	-33
Geysers	05/20/2003	16:50:42.0	38.800	-122.804	5.0	3.6	4.0	1.31e22	346	79	136
Santa Rosa	05/25/2003	00:09:33.0	38.460	-122.700	8.0	4.3	4.2	1.96e22	245	86	4
Petrolia	06/26/2003	03:39:35.4	40.395	-126.574	14.0	4.1	4.6	8.22e22	272	87	-142

Table 10.1: Moment tensor solutions for significant events from July 1, 2001 to June 30, 2002 using the complete waveform fitting method. Epicentral information from the UC Berkeley/USGS Northern California Earthquake Data Center. Moment is in dyne-cm and depth is in km.

Neuhauser, and Dennise Templeton contributed to the writing of this chapter.

Partial support for the develop of the REDI system is provided by the USGS.

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Chapter 11

Northern California Earthquake Data Center

1. Introduction

The Northern California Earthquake Data Center, a joint project of the Berkeley Seismological Laboratory and the U.S. Geological Survey at Menlo Park, serves as an "on-line" 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 northern and central California such as seismic waveforms, electromagnetic data, GPS data, and earthquake parametric data. The principal networks contributing seismic data to the data center are the Berkeley Digital Seismic Network (BDSN) operated by the Seismological Laboratory, the Northern California Seismic Network (NCSN) operated by the USGS, and the Bay Area Regional Deformation (BARD) GPS network. The collection of NCSN digital waveforms date 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 NCEDC continues to use the World Wide Web as a principal interface for users to request, search, and receive data from the NCEDC. The NCEDC has implemented a number of useful and original mechanisms of data search and retrieval using the World Wide Web, which are available to anyone on the Internet. All of the documentation about the NCEDC, including the research users' guide, is available via the Web. Users can perform catalog searches and retrieve hypocentral information and phase readings from the various earthquake catalogs at the NCEDC via easy-to-use forms on the Web. In addition, users can peruse the index of available broadband data at the NCEDC, and can request and retrieve broadband data in standard SEED format via the Web. Access to all datasets is available via research accounts at the NCEDC. The NCEDC's Web address is `http://quake.geo.berkeley.edu/`

2. NCEDC Overview

The NCEDC is located within the computing facilities at the Berkeley Seismological Laboratory in McCone Hall. The BSL facility provides the NCEDC with air conditioning, 100 bit switched network, and reliable power from a UPS with generator backup.

The current NCEDC facilities consist of a Sun Ultra 450 computer, a 2.5 TByte capacity DISC 517 slot jukebox with four 5.2 GByte MO drives and 5.2 GB MO media, a 15-slot AIT tape jukebox which holds 25 GBytes per tape, and the SAM-FS hierarchical storage management (HSM) software, and 4.6 TB of online disk storage. A dual processor Sun Ultra 60 provides Web services and research account access to the NCEDC.

The hardware and software system can be configured to automatically create multiple copies of each data file. The NCEDC uses this feature to create an online copy of each data file on MO media, and another copy on AIT tape which is stored offline. As of 2003, all data is stored on magnetic disk, with backup copies on MO and tape media.

3. 2002-2003 Activities

By its nature, data archiving is an ongoing activity. In 2002-2003, the NCEDC continued to expand its data holdings and enhance access to the data. Projects and activities of particular note include:

- Establishment of a continuous archive for NCSN broadband data

- Significant progress on populating NCSN hardware information, instrument response, and waveform inventory in the NCEDC database

- Development and implementation of *IRIS FISSURES* services as a data distribution method for data from the NCEDC

- Improvement and implementation of *STP* at the NCEDC

- Conversion of the remaining 16-bit BDSN data to MiniSEED

- Development of new Web pages

- Migration of all waveform data from near-online storage to online storage

These activities and projects are described in detail below.

4. Data Collections

The bulk of the data at the NCEDC consist of waveform and GPS data from northern California. Figure 11.1 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 11.1. Figure 11.2 shows the geographic distribution of data archived by the NCEDC.

4.1 BDSN/NHFN/MPBO Seismic Data

The archival of current BDSN (Chapter 3), NHFN (Chapter 4), and Mini-PBO (Chapter 8) (all stations using the network code BK) seismic data is an ongoing task. These data are telemetered from more than 30 seismic data loggers in real-time to the BSL, where they are written to disk files. Each day, an extraction process creates a daily archive by retrieving all continuous and event-triggered data for the previous day. The daily archive is run through quality control procedures to correct any timing errors, triggered data is reselected based on the REDI, NCSN, and BSL earthquake catalogs, and the resulting daily collection of data is archived at the NCEDC.

All of the data acquired from the BDSN/NHFN/MPBO Quanterra data loggers are archived at the NCEDC. The NCEDC has made an effort to archive older digital data, and the 16-bit BDSN digital broadband data from 1987-1991 have been converted to MiniSEED and are now online. In late June 2002, the NCEDC initiated a project to convert the remaining 16-bit BDSN data (MHC, SAO, and PKD1) from late 1991 through mid-1992 to MiniSEED. An undergraduate student was hired to read the old tapes and to work on the conversion. All remaining 20 Hz 16 bit BDSN data has been converted to MiniSEED, and we are working on the decimation procedures to create the 1 Hz data channels. Data acquired by portable 24-bit RefTek recorders before the installation of Quanterra data loggers at NHFN sites has not yet been converted to MiniSEED and archived.

4.2 NCSN/SHFN Seismic Data

NCSN and SHFN waveform data are sent to the NCEDC via the Internet. The NCSN event waveform files are automatically transferred from the Menlo Park to the NCEDC as part of the routine analysis procedure by the USGS, and are automatically verified and archived by the NCEDC.

A few corrupt NCSN event files were discovered at the NCEDC several years ago, and were eventually traced down to suspected flaws in the 12-inch WORM media and/or firmware problems on the Sony WDA-600 series jukeboxes used by the NCEDC. When we transcribed the data from the 12-inch WORM media to the current 5.25 inch magneto-optical media, we verified that all files were transcribed accurately. In 2000-2001, using software developed at the NCEDC to detect possibly corrupt NCSN files, we identified 4704 possibly corrupted NCSN waveform event files. We re-read the original NCSN tapes for all of these events, discovered that only 71 of the files were actually corrupt, and replaced the corrupted event waveform files.

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.

The NCSN installed 9 continuously telemetered digital broadband stations in northwest California and southwest Oregon in support of the USGS/NOAA Consolidated Reporting of EarthquakeS and Tsunamis (CREST) system, and 2 continuously telemetered digital broadband stations in the Mammoth region. The NCEDC established procedures to create an archive of continuous data from these stations, in addition to the event waveform files. These data initially included channels at 50 and 100 Hz, but now are all 100 Hz sampling. The NCEDC hoped to generate an archive of 20 Hz data (for consistency with the BDSN data) from these 100 Hz waveforms, but incomplete continuous data due to telemetry problems between the stations and the USGS Menlo Park data collection center has made this difficult. At this point, the NCEDC is archiving the 100 Hz data without decimation.

4.3 Parkfield HRSN 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 time source for the network. Due to funding limitations, there is currently no ongoing work to correct the timing problems

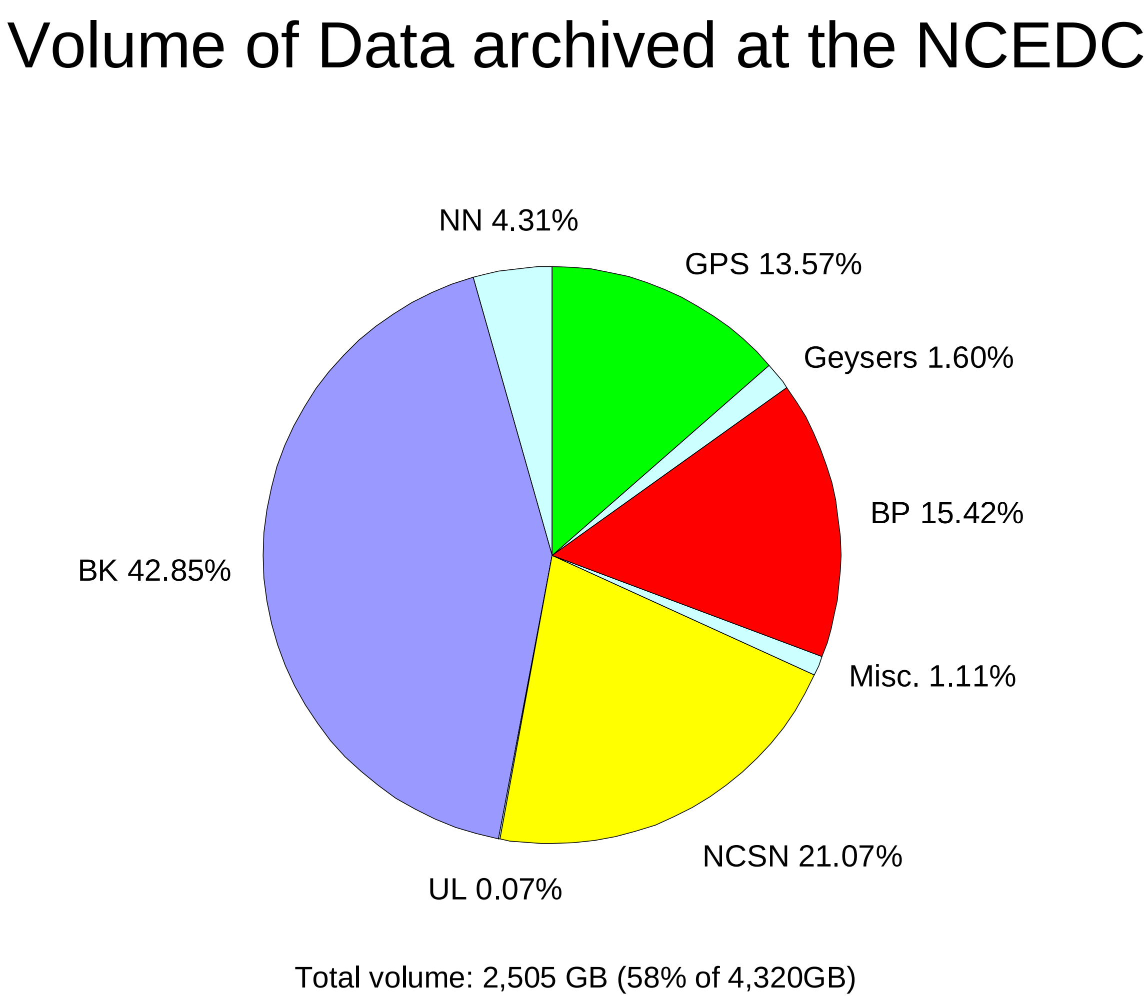

Figure 11.1: Chart showing the relative proportion of each data set at the NCEDC.

Data Type	MBytes
BDSN/NHFN/MPBO (broadband, electric field, magnetic field, strain) waveforms	1,073,842
NCSN seismograms	527,935
Parkfield HRSN seismograms	386,471
BARD GPS (RINEX and raw data)	339,970
UNR Nevada seismograms	107,887
Calpine/Unocal Geysers region seismograms	39,999
USGS Low frequency geophysical waveforms	18,585
Misc data	27,846
Total size of archived data	2,505,810

Table 11.1: Volume of Data Archived at the NCEDC by network

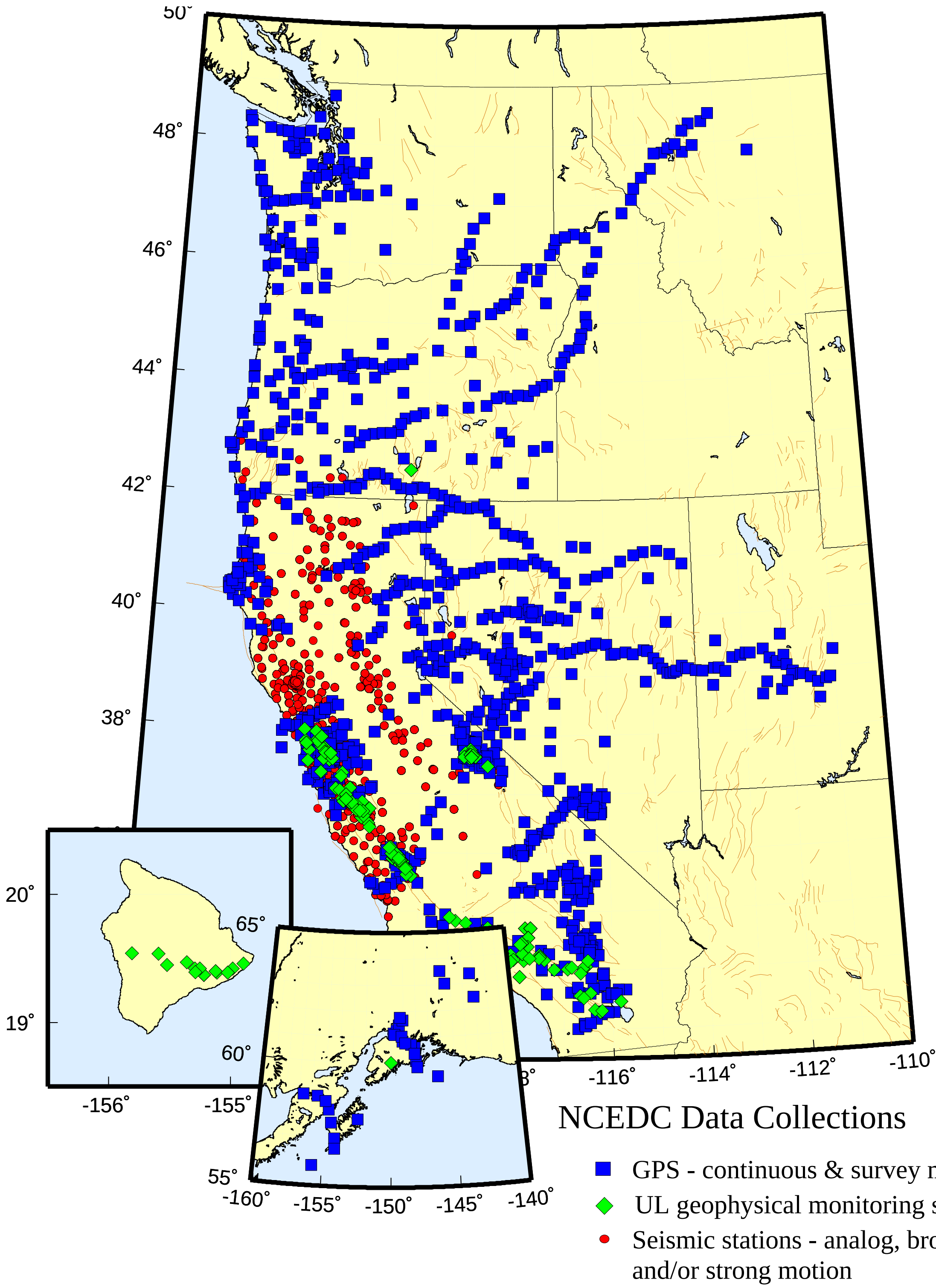

Figure 11.2: Map showing the location of stations whose data are archived at the NCEDC. Circles are seismic sites; squares are GPS sites, and diamonds are the locations of USGS Low-frequency experiments.

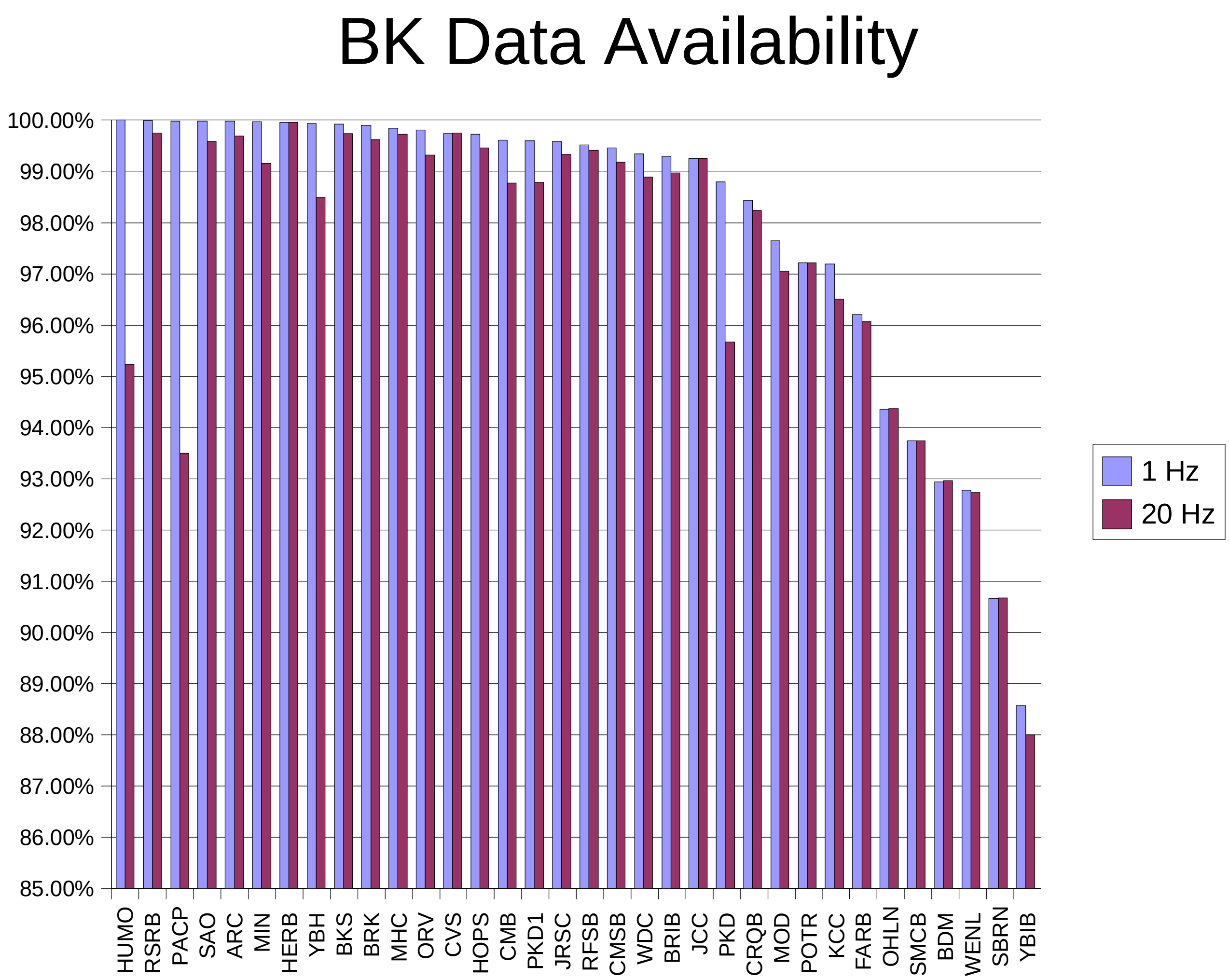

Figure 11.3: Chart showing the availability of BDSN/NHFN/MPBO data at the NCEDC for the 1 Hz and 20 Hz channels from 01/01/1996 - 06/30/2002. The "uptime" of these networks is better than 95% at nearly all stations. Exceptions are BDM (damaged by a lightning strike in May 2000), FARB (power problems when the USFWS generator failed in 1998), MOD (which suffered some delays during installation), WENL (flooded during the winter of 1997), YBIB (damaged during a lightning strike in 1997 and without AC power for the past 4 years), and SBRN and OHLN (which experienced software problems related to data acquisition from a digital pore pressure sensor). In general, a difference between the 1 and 20 Hz data is indicative of significant telemetry problems. Following a major telemetry outage, BSL staff will recover 1 Hz continuous data but only event data for the 20 Hz channels.

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 5, 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.

In 2000 and 2001, 3 new borehole sites were installed, and the network was upgraded to operate with Quanterra Q730 data loggers and digital telemetry. The upgraded acquisition system detects events using the HRSN stations and extracts waveforms from both the HRSN and the PASO stations. The event waveform files are automatically transferred to the NCEDC, where they are made available to the research community via anonymous FTP until they are reviewed and permanently archived. During the deployment of the temporary PASSCAL network (PASO) Parkfield during in 2000-2003 with the IRIS broadband array telemetry, 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 20 Hz (BP) and state-of-health channels are being archived continuously at the NCEDC. As an interim measure, the NCEDC also archived continuous data from the 250 Hz (DP) channels through mid 2002 in order to help researchers retrieve events that were not detected during the network upgrade.

4.4 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 it is made available for real-time earthquake processing and for archiving.

In a situation similar to that of the broadband waveforms from the NCSN, the NCEDC originally planned to create an archive of 20 Hz data from the 100 Hz data. However, frequent gaps in the data complicate the development of a robust decimation process. At this time, the UNR broadband waveforms are being archived at 100 Hz.

4.5 Electro-Magnetic Data

The NCEDC continues to archive and process electric and magnetic field data acquired from data loggers at two sites (SAO and PKD). At PKD and SAO, 3 components of magnetic field and 2 or 4 components of electric field are digitized and telemetered in real-time along with seismic data to the Seismological Laboratory, where they are processed and archived at the NCEDC in a similar fashion to the seismic data (Chapter 6). The system generates continuous data channels at 40 Hz, 1 Hz, and .1 Hz for each component of data. All of these data are archived and remain available online at the NCEDC. Using programs developed by Dr. Martin Fullerkrug at the Stanford University STAR Laboratory (now at the Institute for Meteorology and Geophysics at the University of Frankfurt), the NCEDC is computing and archiving 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.

In addition to the electromagnetic data from PKD and SAO, the NCEDC archives data from a low-frequency, long-baseline electric field project operated by Dr. Steve Park of UC Riverside at site PKD2. This experiment (which is separate from the equipment at PKD1 described in Chapter 6), uses an 8-channel Quanterra data logger to record the data, which are transmitted to the BSL using the same circuit as the BDSN seismic data. These data is acquired and archived in an identical manner to the other electric field data at the NCEDC.

4.6 GPS Data

The NCEDC archives GPS data from the BARD (Bay Area Regional Deformation) network of continuously monitored GPS receivers in northern California (Chapter 7). The NCEDC GPS archive now includes 77 continuous sites in northern California. There are approximately 70 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.

The NCEDC also archives non-continuous survey GPS data. The NCEDC is the principal archive for the survey GPS data collected by the USGS Menlo Park for northern California and other locations. Significant quality control efforts were implemented by the NCEDC to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS MP GPS data 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.

4.7 Calpine/Unocal Geysers Seismic Data

The Calpine Corporation currently operates a microseismic monitoring network in the Geysers regions of northern California. Prior to 1999 this network was operated by Unocal. Through various agreements with both

Unocal and Calpine, the companies have release triggered event waveform data from 1989 to through 2000 along with and 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.

4.8 USGS Low Frequency Data

Over the last 26 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.

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 for the channels, and will work with the USGS to clearly define the attributes of the "processed" data channels.

4.9 Earthquake Catalogs

Northern California

Currently both the USGS and BSL construct and maintain earthquake catalogs for northern and central California. The "official" UC Berkeley earthquake catalog begins in 1910, and the USGS "official" 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. 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 world-wide 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 ANSS, the NCEDC was asked to update the Web pages to present the composite catalog as a product of the ANSS. This conversion was completed in the fall of 2002.

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 BK, NC broadband, NN, and BP data sets.

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

- data extraction of a full day of data,
- quick check program to summarize the quality and stability of the stations' clock,
- checks for missing data along with procedures to retrieve data from the stations and incorporate it into the day of 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 BK network, and all continuous data from the NN, NC, and BP networks that is archived by the NCEDC.

6. Database Development

Most of the parametric data archived at the NCEDC, such as earthquake catalogs, phase and amplitude readings, waveform inventory, and instrument responses have been stored in flat text files. Flat file are easily stored and viewed, but are not efficiently searched. Over the last year, the NCEDC, in collaboration with the Southern California Earthquake Data Center (SCEDC) and the California Integrated Seismic Network (CISN), has continued development of database schemas to store the parametric data from the joint earthquake catalog, station history, complete instrument response for all data channels, and waveform inventory.

The parametric schema supports tables and associations for the joint earthquake catalog. It allows for multiple hypocenters per event, multiple magnitudes per hypocenter, and association of phases and amplitudes with multiple versions of hypocenters and magnitudes respectively. The instrument response schema represents full multi-stage instrument responses (including filter coefficients) for the broadband data loggers. The hardware tracking schema will represent the interconnection of instruments, amplifiers, filters, and data loggers over time. This schema will be used to store the joint northern California earthquake catalog and the ANSS composite catalog.

The entire description for the BDSN/NHFN/MPBO, HRSN, and USGS Low Frequency Geophysical networks and data archive has been entered into the hardware tracking, SEED instrument response, and waveform tables. Using programs developed to perform queries of waveform inventory and instrument responses, the NCEDC can now generate full SEED volumes for these network based on information from the database and the waveforms on the mass storage system.

During 2002-2003, the NCEDC and NCSN jointly developed a system consisting of an extensive spreadsheet that contains 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. As of June 2003, the NCEDC has the preliminary response for approximately 75 percent of the NCSN network. However, significant work must still be done to complete and verify the NCSN instrument responses.

The second part of this project is the conversion of the NCSN waveforms from their native CUSP format into MiniSEED, the standard NCEDC waveform format. This process must deal with multiple problems such as ambiguous or erroneously labeled CUSP data channel, sensor that were recorded on multiple data channels, and ensuring that each distinct data channel is mapped to a distinct SEED channel name. The NCEDC developed programs to use the time-dependent NCSN instrument response spreadsheet and NSCN-supplied name channel name transformation rules to determine the the SEED channel naming, and to provide feedback to the NCSN on channel naming problems. When the channel transformation rules have stabilized, the NCEDC will perform a bulk conversion of all historic NCSN waveforms to MiniSEED format.

The second stage of development will include the NCSN waveform inventory and later the NCSN instrument response data as they are made available. We distributed all of our programs and procedures to populate the hardware tracking and instrument response tables to the SCEDC in order to help them populate their database.

During 2002-2003, the BSL has been processing events detected by the HRSN (BP) network. The waveform data and event parameters (picks and hypocenters) are stored in separate HRSN database tables, and will be merged with events from the NCSN when the NCSN catalog is migrated to the database.

Additional details on the joint catalog effort and database schema development may be found at `http://quake.geo.berkeley.edu/db`

7. Data Access & Distribution

The various earthquake catalogs, phase, and earthquake mechanism can be searched using NCEDC Web interfaces that allow users to select the catalog, attributes such as geographical region, time and magnitude. The GPS data is available to all users via anonymous FTP. Research accounts are available to any qualified researcher who needs access to the other datasets that currently are not available via the Web.

7.1 SeismiQuery

During 2000 and 2001, the NCEDC has developed a generalized database query system to support the development of portable database query applications among data centers with different internal database schemas. The initial goal was to modify the IRIS SeismiQuery Web interface program to make installation easier at the NCEDC and other data centers, as well as to introduce a new query language that would be schema independent.

In order to support SeismiQuery and other future database query applications, we defined a set of Generic Data Views (GDV) for the database that encompassed the basic objects that we expect most data centers to support. We introduced a new language we call MSQL (Meta SeismiQuery Language), which is based on generic SQL, and uses the GDV's for its core schema. MSQL queries are converted to Data Center specific SQL queries by the parsing program MSQL2SQL. This parser stores the MSQL parsing tree in a data structure and API's were implemented to browse and modify elements in the parsing tree. These API's are the only data center or database specific source codes. We finally modified the SeismiQuery Web interface to uniformly generate MSQL requests and to process these requests in a consistent fashion.

We have installed SeismiQuery at the NCEDC, where it provides a common interface for querying attributes and available data for SEED format data, and have provided both IRIS and the SCEC Data Center with our modified version of SeismiQuery. We envision using this approach to support other database query programs in the future.

7.2 NetDC

In a collaborative project with the IRIS DMC and other worldwide data centers, the NCEDC helped develop and implement NetDC, a protocol which will provide a seamless user interface to multiple data centers 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 three data centers worldwide – the NCEDC, IRIS DMC, and Geoscope. The NetDC system receives user requests via email, automatically routes the appropriate portion of the requests to the appropriate data center, optionally aggregates the responses from the various data centers, and delivers the data (or FTP pointers to the data) to the users via email.

The NCEDC hosts a Web page that allows users to easily query the NCEDC waveform inventory, generate and submit NetDC requests to the NCEDC. The NCEDC currently supports both the BREQ_FAST and NetDC request formats. As part of our collaboration with SCEDC, the NCEDC provided its BREQ_FAST interface code to SCEDC, have worked closely with them to implement BREQ_FAST requests at the SCEDC.

7.3 STP

Last year, 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 GUI-based client-server program, developed at at the SCEDC. Access to STP is either through a simple direct interface that is available for Sun or Linux platforms or through a Web interface. With the direct interface, the data are placed directly on a users' 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 started implementing STP, working with the SCEDC on extensions and needed additions. We are adding support for the full SEED channel identifiers (Station, Network, Channel, and Location), and improving the waveform retrieval formats

7.4 EVT_FAST

In order to provide Web access to the NCSN waveforms before the SEED conversion and instrument response for the NCSN has been completed, the NCEDC implemented EVT_FAST, and interim email-based waveform request system similar to the BREQ_FAST email request systems. Users can email EVT_FAST requests to the NCEDC and request NCSN waveform data based on the NCSN event id. The NCSN waveform data is converted to either SAC ASCII, SAC binary, or AH format, and placed in the anonymous FTP directory so that users can retrieve the data. The EVT_FAST waveforms are currently named with the USGS's native NCSN channel names, since the SEED channel names conversion is not yet complete.

7.5 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 started to implement the FISSURES Data Handling Interface (DHI) services at the NCEDC, which involves interfacing the DHI servers with the NCEDC database schema. We started with the source code for the IRIS DMC's DHI servers, which reduced significantly the implementation's time. We now have the waveform and event FISSURES services running in demonstration mode at the NCEDC. These services interact with the NCEDC database and data storage system, and can deliver NCEDC event and channel metadata as well as waveforms using the FISSURES interfaces. We are currently still performing tests on FISSURES and are waiting to import our catalog data into the database before we start running the software in production mode.

7.6 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, as a wholesale collection point for other data collected in northern California, and, in the next year, as a retail provider for the global distribution of all data archived within the GSAC system. We have helped to define database schema and file formats for the GSAC project, and for several years have produced complete and incremental monumentation and data holdings files describing the data sets that are produced by the BARD project or archived at the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings. Currently, the NCEDC is the primary provider for over 89,000 data files from over 1500 continuous and survey-mode monuments. The data holdings records for these data have been incorporated into the retailer system, which became publicly available in late 2002.

7.7 Web Pages

The NCEDC developed its Web pages in the early days of the Web. Unfortunately, time constraints have kept the pages somewhat static and limited in their use. In June of 2002, the NCEDC began an project to update and expand their Web offerings. This project was completed in October 2002, and provides the NCEDC with a uniform look-and-feel for all Web pages.

8. Acknowledgements

The NCEDC is a joint project of the BSL and the USGS Menlo Park and is partially funded by the USGS.

Doug Neuhauser is the manager of the NCEDC. Stephane Zuzlewski, Rick McKenzie, Mark Murray, André Basset, and Lind Gee of the BSL and David Oppenheimer, Hal Macbeth, and Fred Klein of the USGS Menlo Park contribute to the operation of the NCEDC. Steve Chu developed the *CalQC* program. Doug Neuhauser, Lind Gee, and Stephane Zuzlewski contributed to the preparation of this chapter.

Chapter 12

Outreach and Educational Activities

1. Introduction

The BSL is involved in a variety of outreach activities, ranging from lectures and lab tours to educational displays and the development of classroom materials for K-12 teachers. We maintain an earthquake information tape (510-642-2160) and an extensive set of Web pages, providing basic earthquake and seismic hazard information for northern and central California.

2. Outreach Overview

The BSL has several on-going outreach programs, such as the educational displays, WWW development, and the Earthquake Research Affiliates Program.

2.1 Educational Displays

As part of the BSL's outreach activities, we have made REDI earthquake data available to a number of universities, colleges, and museums as educational displays. As noted above, this year marked the expansion of this program to the K-12 environment. 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 earthquake 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. In a pilot project initiated two years ago, the San Francisco Unified School District has been given two pager systems for use in middle school classrooms.

In addition to the seismicity displays, the BSL provides local waveform feeds for helicorders at several 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.

2.2 WWW

Over the last year, we have continued to expand our presence on the WWW. Our primary goal has been to provide a source of earthquake information for the public, although we also provide information about the networks, such as station profiles, which benefits the research community as well. We provide such information as seminar schedules, course advertisements, descriptions of operations and research, 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 for our own information distribution, with such details as the computing and operational resources, rosters, and schedules for various purposes. Last year, we began an effort to update and revamp our Web pages, as described below.

2.3 Earthquake Research Affiliates Program

The UC Berkeley Earthquake Research Affiliates (ERA) Program is an outreach project of the BSL, the Department of Geology and Geophysics, 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.

3. 2002-2003 Activities

3.1 Tours and Presentations

BSL staff spent considerable time with public relations activities during the past year. Several tours are given each month, with audiences ranging from middle-school students to scientists and engineers from China and Japan.

The BSL hosted several special groups during 2002-2003. Several of large groups visited, including a class from San Francisco State and 20 members of the Alameda County Sheriff's Emergency Communications Team A number of schools scheduled visits, many of them in April during Earthquake Awareness Month. April was so busy this year that we actually turned away tours.

In addition to the tours, Drs. Romanowicz, Dreger, Uhrhammer, and Gee presented talks on earthquakes and related phenomena to public groups. Dr. Gee gave a presentation for the City of Berkeley, directed at visitors from Japan visiting the Bay Area.

UC Regents

The BSL held a special tour this year for the UC Regents, who visited the Berkeley campus on June 11-12th. The Regents met in the BSL conference room and heard a presentation from Dr. Gee on the BSL history, operations, and research. Fortunately, an M3.3 earthquake occurred just a few minutes before the presentation, so the Regents could see the waveforms on the live data feed and see the automatic earthquake location shown on the REDI/CUBE display and on the new CISN Display software. BSL staff put together an Quanterra datalogger with an FBA-23 as an example of seismic instrumentation. When the FBA was placed on the earthquake machine, the Regents could "make" earthquakes by turning the crank that applies a force to pull a brick along the sandpaper surface. Chancellor Bergdahl was seen jumping up and down to create earthquakes on the helicorder.

3.2 Open Houses

The BSL participated in both *Cal Day* (April 12th) and *Take Your Child to Work Day* (April 24) this year. The attendance for both festivities was quite 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. As a special activity during *Cal Day*, Dr. Peggy Hellweg gave two walking tours of the Hayward fault. These were quite well attended - despite the damp weather.

3.3 Quake 2003

The campus held an earthquake drill on June 5, 2000. Dr. Gee worked with Sarah Nathe and Professor Mary Comerio to design a scenario earthquake. Taking advantage of the new USGS scenario ShakeMaps, an M6.5 on the Northern Hayward Fault was selected and the BSL put together a set of Web pages similar to those routinely put together following an event of interest. The Web pages included a press release, the aftershock probabilities, and maps. With help from Johanna Fenton of OES, the scenario ShakeMaps were turned into HAZUS runs predicting regional damage. An unusual aspect of this earthquake exercise was its focus on business resumption. The drill started 48 hours after the simulated earthquake. More information about the exercise is available at `http://www.seismo.berkeley.edu/seismo/eqw/q2003/`.

3.4 1906 Centennial

The centennial of the great 1906 San Francisco earthquake is rapidly approaching! A number of Bay Area organizations are participating in the '06 Earthquake Centennial Alliance and beginning to plan activities memorializing the event and celebrating the progress we've made in reducing earthquake losses.

Although UC Berkeley was spared major damage, the 1906 earthquake did have a significant impact on the campus community. These effects were documented in an issue of the Chronicle of the University of California in 1998 which describes the refugee camps established on the campus and the dispatch of University cadets to help maintain order in San Francisco. Professor Andrew Lawson chaired the State Earthquake Investigation Commission which produced the first comprehensive government-commissioned report on an earthquake.

Given the many ties between the 1906 earthquake and fire and the University, many UC Berkeley units are beginning to coordinate plans for centennial activities. Ideas for centennial activities include new classes, public lecture series, symposia, displays on the progress of the SAFER program, exhibits of 1906 artifacts and photographs, film series, walking tours, and many others. A small group of people are meeting quarterly at the BSL to plan activities. Information about their plans is available at `http://www.seismo.berkeley.edu/seismo/1906/`.

Lawson Lecture

As part of centennial activities, the BSL established an annual lecture this year. The public lecture will be held each April and focus on issues of earthquakes and society. This year, the lecture series had a fabulous kick-off with a presentation by Dr. David Schwartz of USGS, Menlo Park. Dr. Schwartz is the leader of Working Group '02, a wide cross-section of the Earth science community, dedicated to quantifying earthquake hazards in the San Francisco Bay Area (Figure 12.1). This lecture was part of the first public announcement of the new earthquake probabilities by Working Group '02. If you missed the lecture, don't despair! A Web cast of the talk is available at `http://www.seismo.berkeley.edu/seismo/news/seismo_lecture.html`.

SSA 2006

The BSL will co-host the annual meeting of the Seismological Society of America (SSA), scheduled for 4/18/2006 - 4/21/2006, with the USGS. Discussions are currently underway among SSA, the Earthquake Engineering Research Institute (EERI), and OES to create a "mega" spanning earth sciences, earthquake engineering, and disaster response and mitigation. The SSA meeting will also provide the opportunity to kick-off the centennial of the Society.

3.5 Web Pages

The BSL began a program to update and revamp their Web pages this year. Although still in progress, the new Web pages are designed to give greater focus to the research program.

3.6 Brochure

The BSL published a four-page brochure this year. This publication fills an important gap. Prior to the brochure, the best handout on BSL activities was this document - the Annual Report! The depth - and length - of the Annual Report limit its use as a general purpose publication. The brochure is also available through the BSL Web site.

4. Acknowledgements

Lind Gee 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. Lisa Krain helped with the upkeep and development of new web pages. Lind Gee contributed to the preparation of this chapter.

Figure 12.1: David Schwartz, Lind Gee, and Barbara Romanowicz at the inaugural Lawson lecture.