THE MONTEREY BAY BROADBAND

OCEAN BOTTOM SEISMIC OBSERVATORY

Barbara Romanowicz*, Debra Stakes**, D. Dolenc*
D. Neuhauser*, P. McGill**, R. Uhrhammer*, T. Ramirez**

**Seismological Laboratory, University of California, Berkeley*

*** Monterey Bay Aquarium Research Institute*

November 24, 2003

1 Abstract

We report on the installation of a long-term buried ocean-floor broadband seismic station (MOBB) in Monterey Bay, California (USA), 40km off-shore, at a water depth of 1000 m. The station was installed in April 2002 using a ship and ROV, in a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and the Berkeley Seismological Laboratory (BSL). The station is located on the western side of the San Gregorio Fault, a major fault in the San Andreas plate boundary fault system. In addition to a 3-component CMG-1T seismometer package, the station comprises a current meter and Differential Pressure Gauge, both sampled at high-enough frequency (1 Hz) to allow the study of relations between background noise on the seismometers and ocean waves and currents. The proximity of several land-based broadband seismic stations of the Berkeley Digital Seismic Network allows insightful comparisons of land/ocean background seismic noise at periods relevant to regional and teleseismic studies. The station is currently autonomous. Recording and battery packages are exchanged every 3 months during scheduled one day dives. Ultimately, this station will be linked to shore using continuous telemetry (cable and/or buoy) and will contribute to the earthquake notification system in Northern California. We present examples of earthquake and noise data recorded during the first 6 months of operation of MOBB. Lessons learned from these and continued recordings will help understand the nature and character of background noise in regional off-shore environments and provide a reference for the installation of future off-shore temporary and permanent broadband seismic stations.

2 Introduction

Two-thirds of the earth's surface is covered by oceans, and this represents a significant challenge for the investigation of global scale dynamic processes in the earth's interior, as well as tectonic processes at ocean-continent boundaries. In particular, the need for long term ocean floor seismic observatories has now been widely recognized, and several national and international efforts are underway to resolve the technological and logistical issues associated with such deployments (e.g. COSOD II, 1987; Purdy and Dziewonski 1988; Purdy, 1995; Forsyth et al., 1995; Montagner and Lancelot, 1995)

Following pioneering efforts in the 1960's (Sutton et al., 1965), a number of pilot projects have been conducted in the last ten years, coordinated internationally by ION (International Ocean Network, Suyehiro et al., 1995), to test technological solutions and demonstrate the feasibility of seafloor seismic observatories either in boreholes or on the ocean floor (e.g. Suyehiro et al., 1992; Beranzoli et al., 1998). In particular, in 1992, a French experiment involving the manned underwater vessel *"Nautile"* installed two sets of 3-component broadband seismometers in the north-equatorial mid-Atlantic, one directly on the sea-floor, and the other, using the Ifremer re-entry vessel NADIA, at 300 m depth inside ODP hole 396B (Montagner et al., 1994a,b). The data comparison between the two systems seemed to indicate that the ocean-floor installation was quieter at long periods (Beauduin et al., 1996), however, this remained controversial, as only 10 days of data were acquired in this experiment, and water circulation may have increased the noise in the borehole. Since then, several other buried seafloor installations have been deployed in the deep oceans, some of them making use of abandoned submarine telecommunications cable (e.g. Butler et al., 1998; Kasahara et al., 1998)

During the OSN1 experiment in 1998 (e.g. Collins et al., 2001) 3 broadband systems were installed 225 km southwest of Oahu (Hawaii), at a water depth of 4407 m, one on the seafloor, one buried, and the third one at 248 m below the seafloor, in a borehole drilled by the ODP in 1992 for this purpose (Dziewonski and Wilkens, 1992). Data were collected for 4 months and demonstrated the importance of burying the seismometer package below the seafloor to obtain good coupling with the ground and ensure good quality of data at long periods. The OSN1 experiment also demonstrated that a borehole installation can be quieter at teleseismic body wave periods than a buried or sea-floor deployment, because it avoids signal-generated noise due to reverberations in the near surface sediment layers. This was confirmed by the long-term Japanese NEREID observatory deployment, which also documented that a properly cemented ocean-floor borehole in basement rock can be very quiet at long periods as well (Araki et al., 2002).

Long-term ocean floor observations are also necessary to better constrain regional tectonics, such as on the western margin of North America, where tectonics and seismic activity do not stop at the continental edge. For example, in California, the zone with most abundant seismicity is associated with the Mendocino Triple Junction, and is mostly off-shore. Much effort has been expended to deploy networks of seismic stations in the western U.S., most recently broadband stations, with multiple goals of monitoring the background seismicity, understanding modes of strain release, documenting seismic hazards and providing constraints on crustal and upper-mantle structure. However, because there are very few off-shore islands in central and Northern California, practically all stations are located on the continent. As a consequence, the study of plate-boundary processes, as afforded by regional seismological investigations, is heavily squewed on the continental side of the San Andreas Fault (SAF) system. Offshore seismicity is poorly constrained, both in location and in mechanisms, as is crustal structure at the continental edge.

While consensus seems to have been reached that permanent, borehole installations are best for seafloor deployments of broadband seismometers, they are very expensive: the spatial resolution required for regional studies, either off-shore or in the middle of the oceanic plates, may not be achieved for many years to come. It is therefore important to conduct pilot studies to determine how to optimally deploy ocean floor broadband systems, and in particular how to minimize the strong perturbing environmental effects, both through improved installation procedures, and through a posteriori deconvolution of ocean current, tide, pressure, temperature and other such signals that can be recorded simultaneously.

In the summer of 1997, the international MOISE experiment (Monterey Ocean bottom International Seismic Experiment) allowed us to collect 3 months of broadband seismic data from a sea-floor system installed 40 km off-shore in Monterey Bay, in a cooperative experiment between MBARI, IPG (Paris France) and UC Berkeley (e.g. Stakes et al., 1998; Romanowicz et al., 1998). During this experiment, the feasibility of performing underwater electrical and data cable connections between instruments, using an ROV operated from a ship, were successfully illustrated for the first time. The MOISE experiment also demonstrated the sensitivity of ocean floor systems to sea currents at long periods and the importance of simultaneous recording of current velocity and direction, at a sampling rate sufficient for quantitative comparisons with seismic data: the conventional current meter sampling rate used by oceanographers (4 sample points once every 4 minutes), was too low to correct the MOISE seismic data for noise generated by currents, although this is theoretically possible (e.g. Stutzmann et al., 2001).

The Monterey bay Ocean Broad Band Observatory (MOBB, McGill et al., 2002; Uhrhammer et al., 2002; Romanowicz et al., 2003) was installed in April 2002. It is a direct follow-up of MOISE, and capitalizes on the lessons learned during that pilot experiment. The ultimate goal of this collaborative project between MBARI and the Berkeley Seismological Laboratory (BSL) is to link the MOBB station by continuous telemetry to the shore, so that MOBB becomes part of the Berkeley Digital Seismic Network (BDSN, Romanowicz et al., 1994). The data can then be contributed to the real-time earthquake monitoring system in northern California (Gee et al., 2002). The opportunity to do so awaits the installation of the MARS cable (Monterey Accelerated Research System; http://www.mbari.org/mars). In the meantime, data are recorded on-site and retrieved every 3 months using MBARI's ship and ROV, and data analysis is focused on understanding sources of background noise at long periods in this relatively near-shore environment. We view MOBB as the 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. In what follows we describe this observatory and discuss some of the data recorded during the last 18 months.

3 Location, Instrument packages and deployment

The MOBB station is located at a water depth of 1000 m, 40 km off-shore in Monterey Bay, in an area called "Smooth Ridge" on the western side of the San Gregorio fault, and closer to it than was MOISE (Figure 1). The planned MARS cable route is down the center of Smooth Ridge and with a termination near the MOBB site.

The San Gregorio fault (SGF) splays from the SAF at the Golden Gate and extends south past the San Francisco peninsula and Santa Cruz mountains, mostly off-shore. It is the principal active fault west of the SAF in central coastal California, yet it remains the largest known fault whose seismogenic potential is not well characterized in this region. However, Begnaud and Stakes (2000) and Begnaud et al. (2000) used a temporary offshore seismic network to demonstrate the unusually high seismicity levels of the northern SGF, dominated by compressional mechanisms as well as an east-dipping focal plane (Simila et al. 1998). The SGF is thought to be capable of $M > 6$ earthquakes, making the MOBB site particularly interesting from the tectonic and seismic hazards point of view. Using refined crustal velocities based on the results of Begnaud et al (2000), Simila et al. (1998) relocated the 1926 $M > 6$ doublet to show that the first event occurred on the northern SGF followed by the second on the adjacent Monterey Bay Fault Zone.

The coseismic geodetic slip on the SAF during the 1906 earthquake and the late Holocene geologic slip rate on the San Francisco peninsula and southward are about 50-70% of their values north of San Francisco (Thatcher et al., 1997; Schwartz et al., 1998). Review by the Working Group on Northern California Earthquake Potential (1996) suggests that the slip rate on the SAF in the Santa Cruz mountains is about 14 mm/yr, which is 58% of the slip rate north of San Francisco, so the rest of the slip must be accommodated by other faults, both on-land and off-shore. This slip gradient reflects partitioning of the plate boundary slip onto the San Gregorio, Sargent and other faults south of the Golden Gate. Because of the limited onshore extent, few detailed geologic studies have been conducted to evaluate the style and rate of late Quaternary deformation along this complex fault zone.

The ocean-bottom MOBB station currently comprises a three-component seismometer package, a current meter, a differential pressure gauge (DPG) and a recording and battery package. The data logger, battery, and DPG are contained in a modular frame which is removed and replaced when the ROV services the system. This configuration permits hardware and software upgrades to take place as required. For instance, the DPG (Cox et al., 1984) was not present in the initial deployments, but was added later during a data retrieval dive in September, 2002.

The seismic package contains a low-power (2.2 W), three-component CMG-1T broadband seismometer system, built by Guralp, Inc., with a 24-bit digitizer, a leveling system, and a precision clock (Figure 2a). The seismometer package is mounted in a cylindrical titanium pressure vessel 54 cm in height and 41 cm in diameter (Figure 2b), custom built by the MBARI team and outfitted for underwater connection. The component design of the instruments permit the sensor, datalogger, and current meter to be carried to the seafloor separately, then tested and connected in situ. This component design permits us to update software, change batteries and replace instruments without disturbing the sensor package. The system has been designed to permit a GPS time mark, applied during an ROV visit, to establish the offset and drift rate of the Guralp clock. These errors are recorded and the timing of the seismic data is corrected in post-processing. The clock is not adjusted in situ to prevent abrupt jumps in the time marking of the data. Establishing these corrections on the seafloor and after the system has reached thermal equilibrium is a critically important feature for long-term autonomous deployments.

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, 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 (Figure 2b). This resulted in significant noise reduction on the 3 components, in the 10-100 sec period range (Figure 3).

Near-bottom water currents are measured by a Falmouth Scientific 2D-ACM acoustic current meter. It is held by a small standalone fixture and measures the current speed and direction about one meter above the seafloor. The recording system is a GEOSense LP1 data logger with custom software designed to acquire and record digital data from the Guralp sensor and from the current meter over RS-232 serial interfaces, as well as analog data from the DPG. The seismic data are sampled at 20 Hz and the current meter and DPG are sampled at 1 Hz. Data are stored on a 6-GB, 2.5-inch disk drive. All the electronics, including the seismometer, current meter, and DPG, are powered by a single 10 kWh 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, 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 11 m away from the caisson to allow the future exchange of the recording and battery package without disturbing the seismometer. The seismometer package was tested extensively at BSL, then brought to MBARI where its internal clock drift was calibrated against GPS time in an environmental test chamber at seafloor temperature.

The actual deployment occurred over 3 days (04/09-11/2002). On the first dive, the seismometer package was lowered into the PVC caisson (Figure 4a), and its connection cable brought to the site of the recording unit. On the second dive, the recording package was emplaced in its trawl-resistant mount (Figure 4b), and connected to the seismometer package (Figure 4c). Tiny (0.8 mm diameter) glass beads were poured into the caisson until the seismometer was completely covered, to further isolate it from water circulation, as dictated by lessons learned from previous experiments (e.g. Sutton and Duennebier, 1988; Duennebier and Sutton, 1995). The seismometer package is now buried at least 10 cm beneath the seafloor. On the third dive, the ROV immobilized the cable between the seismometer and recording package with steel "wickets" inserted into the sediment. It then connected the seismometer to the recording system, leveled and recentered the seismometer, and verified that everything was operational. Finally, the current meter was installed and connected to the recording system.

On April 22nd, 2002, the ROV returned to the MOBB site to check the functioning of the seismometer and recording system. Some slight settling of the seismometer pressure vessel had occurred, and so the seismometer was recentered electronically. Over 3 MB of data were then downloaded from the recording system over a period of about two and a half hours, using a 9600 bps serial data connection through the ROV. These data included the recordings of two regional earthquakes in California and two teleseismic events that occurred in Guerrero, Mexico and in Northern Chile.

The site was revisited two months later, on June 27th, to check the functioning of the system and replace the data recording and battery module, in the first of a series of such dives planned for the next 3 years. The following functions were performed:

1. Disconnected the current meter and seismometer from old datalogger.
2. Removed old datalogger frame with datalogger and batteries from the trawl-resistant mount.
3. Installed new datalogger frame in the trawl-resistant mount.
4. Connected the current meter to the new datalogger.
5. Connected the ROV to the new datalogger and verified that the datalogger was operational.
6. Connected the seismometer to the new datalogger, and monitored its reboot.
7. Centered the seismometer.
8. Re-centered the seismometer.

9. Verified that the Guralp was receiving the GPS clock signals from the ROV (NMEA time messages and pulse per second), and recorded the clock offset. During this dive, the Guralp clock was not resynchronized to GPS time.

10. Brought the old datalogger frame with datalogger and batteries back to the ship.

Figure 5 shows the evolution of the tilt signal obtained from the seismometer mass position channels (MMZ, MME, MMN), for the first 7 months of deployment. These data indicate that the seismometer package has been experiencing an exponentially decaying tilt in a south-southwesterly direction, which is also the down slope direction (e.g. Figure 1). The large step on day 112 (04/22/2002) was caused by re-centering, when the instrument was checked 12 days after installation. The small step on day 134 (05/14/02) is coincident with the occurrence of a Mw4.96 earthquake which occurred 55 km N59W of MOBB on the San Andreas fault near the town of Gilroy. The instrument was recentered again on day 178 (06/27/2002). The slow drift rate of the horizontal component mass positions in the latter half of the plot (day 263 onward) indicates that the OBS pressure vessel stabilized in the ocean floor sediments after about two and a half months after deployment. On the MMZ component, the semidiurnal gravitational tide is visible, riding on the tilt signal. As with the horizontal components, the largest signals are associated with rapid changes in the second derivative of the tilt, caused by recentering or by significant ground shaking (day 134).

During the first two months of recording, many regional and teleseismic events were recorded, as described later. The site has been revisited regularly every three months since. During each visit, the datalogger and battery packages are changed, the seismometers are recentered, and the clock re-synchronized to GPS time. Due to multiple datalogger problems (hardware and software) encountered in the first half of 2003, the best data available so far span the time period April-December 2002, as illustrated below.

4 Examples of Data and preliminary analysis

Figure 6 shows the location of MOBB with respect to the nearby BDSN stations. Notably, we will be discussing comparisons between recordings on the ocean floor (MOBB), in the noisy Farallon Island environment (FARB) and on the continent (SAO, JRSC).

Figure 7 shows power density spectra for two different time periods, comparing background noise at MOBB and three land stations of the BDSN network. Day 143 (05/23/2002) is a "quiet" day, as assessed from the ocean wave data recorded on the NOAA buoy in Monterey Bay, whereas day 350 (12/16/2002) is a "stormy" day (spectral ocean wave density is an order of magnitude higher at around 30 sec). Increased noise level for periods between 20 and 500 sec, due to ocean currents and infragravity waves, is observed at MOBB on all 3 components on the stormy day, but only on the vertical component on the quiet day. The spectral width of the noisy long-period band is larger on the stormy day, and, interestingly, it also corresponds to a band of increased noise at the Island site FARB, where it is largest on the East component. This most likely indicates loading of shallow water around the small Farallon Island by gravity waves, similarly to what is observed in Hawaii (Stephen et al., 2003). We are currently investigating the source of this noise in more detail. In particular, it should be correlated with the DPG data, if it is indeed due to gravity waves generated by breaking waves at the coastline (Webb et al., 1991). The bell shape of this noise peak is in agreement with theoretical calculations by Araki et al. (2003). On the other hand, the noise level at MOBB between 30 and 100 sec on a quiet day is comparable to the noise level at the island station FARB on a stormy day. The "low noise notch" (Webb, 1998) is very narrow at MOBB (10-30 sec), and contains the single-frequency micro-seismic peak (12 sec), but the level of noise is comparable to the land station YBH, one of the quietest BDSN stations. The corresponding "double-frequency" micro-seismic peak around 6 sec is visible at all stations most of the time, but on day 350, it is hidden by higher amplitudes between 2 and 4 sec at MOBB. On day 143, two additional narrow-band micro-seismic peaks are clearly resolved at MOBB (around 2.5 and 4 sec). These could be related to a combination of local sea-state and distant storms (e.g. Bromirski and Duennebier, 2002). They are clearly distinct in frequency from those observed in the open sea (i.e. Stephen et al., 2003).

Noise levels at frequencies higher than 2 Hz and lower than 200 sec are comparable to those observed at some of the land stations. FARB (island site) is sometimes noisier at long periods, but the seismometer there is a Guralp CMG-3 with a higher frequency high-pass corner than MOBB. Some of the longer period background noise is clearly correlated with currents that are associated with tidal flows, as was documented from MOISE (Romanowicz et al., 1998; Stutzmann et al., 2001). Figure 8 shows a spectrum of the ocean current speed at MOBB computed using a 78 day time series, illustrating the dominant effects of tides on the bottom currents. This is also illustrated in Figure 9, which shows the corresponding distribution of current direction and velocity as a function of azimuth. With the current meter and DPG data sampled at 1 sec, it will now be possible to deconvolve the tide and current related noise from the MOBB data. Unfortunately, the DPG dataset is still too small (recording system problems since 01/01/03) to assess the effectiveness of such a deconvolution.

Figures 10-12 illustrate observations that have been recorded at MOBB during the two months period 04/10/2002-06/28/2002, and which were retrieved during the first datalogger exchange, on 06/29/2002.

Figure 10 shows a component-by-component comparison of the recording of the 04/26/2002 Mw 7.1 teleseism in the Mariana Islands at MOBB and 3 nearby BDSN stations (see location on Figure 6). The comparison shows consistency between the recordings of MOBB and nearby stations. On the horizontal components, there appears to be some signal-generated noise following the S waves and the Love wave, which is associated with ringing in the shallow mud layers as we will show below. In Figure 11, such ringing is clearly demonstrated for a deep earthquake (11/17/2002, depth = 459 km, Mw = 7.3). Only the vertical component P-wave portion of the seismograms is displayed, filtered in two pass-bands. Signal-generated noise is very apparent in the P waves in the 0.03-0.3 Hz pass-band, where the P wave at MOBB displays a 3 min long coda. The ringing is narrow-band and disappears at frequencies lower than 0.1 Hz. Such observations should be helpful in understanding the triggering of submarine landslides in strong motion events, and may be relevant for ocean floor structures such as oil platforms and pipelines. On the other hand, this type of noise may be unavoidable in a shallow buried installation. We are currently evaluating ways to eliminate this signal-generated noise by post-processing. One possibility is to design an "observational" transfer-function, using data from near-by land stations that do not show the ringing. This is illustrated in Figure 12, where we show a comparison of original P-wave train at MOBB (blue) and JRSC (green) and "cleaned" MOBB data (red) after removal of the corresponding transfer function. We are working on combining this type of processing with direct modelling of the ringing effect, by computing theoretical transfer functions based on simple sediment layer models (Uhrhammer et al., 2003; Dolenc et al., in preparation) that can be obtained from local studies (e.g. Begnaud et al., 2000).

Figure 13 shows the records, deconvolved to ground velocity, for a Mw 3.63 regional event which occurred on 04/23/2002 on the SAF at a distance of 53.4 km from MOBB. The very large S wave pulse on the horizontal components as well as the subsequent ringing are likely due to site response, as observed for the teleseismic events and could be similarly removed. On the vertical component, the water reflection of the P wave is clearly seen 1.3 sec after the P wave. In spite of these strong site effects, these data can be used in moment tensor studies, as illustrated in Figure 14, which shows the results of a moment tensor inversion using a time domain whole waveform methodology (Dreger and Romanowicz, 1994). A robust solution is obtained using data from 5 stations, including data from MOBB. The waveform fit at MOBB is outstanding with a 92.8% variance reduction. The addition of MOBB to the existing BDSN stations in this particular case provides an additional SH lobe but, since 3 SH lobes are already sampled by other BDSN stations, this particular strike-slip mechanism is well constrained in any case. However, this example serves to show that the MOBB data are well calibrated and have potential for providing valuable constraints in moment tensor studies of events of other types, such as reverse fault events in the Coast Ranges or strike slip events on faults closer to the shore or off-shore.

To further demonstrate the consistency of the MOBB data, we also show the results of a single station moment tensor inversion using only MOBB, and the comparison of the corresponding synthetic predictions with the actual data at the four other BDSN stations. The single station solution results in a nearly identical focal mechanism, but a slightly larger CLVD component and scalar moment, which is not unlike other single station inversions.

5 Discussion and Future Work

Data collected at the MOBB site can be used for several purposes. They provide complementary constraints for regional crustal and upper mantle structure to land-based broad band stations, as well as for the study of earthquakes along the San Andreas fault system. Currently, they are noisier than records from land-based stations, so that only relatively large events can be successfully analyzed. As we have seen, there are two sources of increased noise: signal-generated noise due to reverberation in the sediment pile, and background noise generated by currents as well as local and distant waves in the ocean. The first type of noise can be dealt with by designing appropriate deconvolution filters. In particular, the vicinity of high quality broadband land stations of the BDSN provides a helpful reference. The second type of noise is complex and time variable, however, the combination of MOBB and BDSN seismic data, current meter and DPG data, sampled at sufficiently high rates, as well as local and regional buoy data, provides a promising dataset to try to reduce the MOBB background noise - at least in the infragravity wave band. Ultimately, the level of success that we may reach in this endeavor will provide a reference for what can be expected of data from shallow-buried broadband ocean bottom systems.

Finally, the collection of these different types of data and their geographical distribution also provides an opportunity to further study the generation of such infragravity waves, at least in the particular setting of a relatively shallow ocean bay, as was pioneered by Bromirski and Duennebier (2003).

6 Acknowledgements

The MOBB station instrumentation and deployment was supported by funds to MBARI from the Lucile and David Packard Foundation, the NSF (grant OCE-9911392) and UC Berkeley funds to BSL. We thank Doug Dreger for performing the test moment tensor inversion and providing Figure 14.

References

Araki, E., M. Shinohara, S. Sacks, A. Linde, T. Kanazawa and K. Suyehiro (2002) Improvement of seismic observation in the ocean by use of ocean boreholes, Bull. Seism. Soc. Am. COMPLETE REFERENCE

Beauduin, R., J.-P. Montagner, J.-F. Karczewski (1996) Time evolution of broadband seismic noise during the French Pilot experiment OFM/SISMOBS, Geophys. Res. Lett., 23, 2995-2998.

Begnaud, M.L. and D.S. Stakes, Constraining continental margin seismicity by extending onshore seismograph stations to critical off-shore sites, Bull. Seism. Soc. Am., 90, 414-424, 2000.

Beranzoli L., De Santis A., Etiope G., Favali P., Frugoni F., Smriglio G., Gasparoni F., Marigo A., (1998) - GEOSTAR A GEophysical and Oceanographic STation for Abyssal Research, Physics Of The Earth And Planetary Interiors, 108(2), 175-183.

Bromirski, P. and F. Duennebier (2002) The near-coastal microseism spectrum: spatial and temporal climate relationships, J. Geoph. Res., 107, 10.1029/2001JB000265.

Butler, R., A. D. Chave, F. K. Duennebier, D. R. Yoerger, R. Petitt, D. Harris, F. B. Wooding, A. D. Bowen, J. Bailey, J. Jolly, E. Hobart, J. A. Hildebrand, and A. H. Dodeman (2000) Hawaii-2 Observatory pioneers opportunities for remote instrumentation in ocean studies, EOS Trans. AGU, vol. 81, 157, 162-163.

Collins, J.A., Vernon, F.L., Orcutt, J.A., Stephen, R.A., Peal, K.R., Wooding, F.B., Spiess, F.N. and Hildebrand, J.A., 2001. Broadband seismology in the oceans: Lessons from the

Ocean Seismic Network Pilot Experiment, Geophys. Res. Lett., 28, 49-52.

Cox, C., T. Deaton and S. Webb, A deep-sea differential pressure gauge, *J. Atm. Ocean. Tech., 1*, 237-245, 1984.

Dreger, D. and B. Romanowicz (1994) Source characteristics of events in the San Francisco Bay region, in USGS Open-file report no 94-176, 301-309, 1994.

Duennebier, J. K., and G. H. Sutton (1995) Fidelity of ocean bottom seismic observations, Mar. Geophys. Res., 17, 535-555, 1995.

Dziewonski, A., R. F. J.Wilkens, et al. (1992) Proceedings of the Ocean Drilling Program, Initial Reports, vol. 136.

Forsyth, D., A. Dziewonski and B. Romanowicz (1995) Scientific objectives and required instrumentation, in proceedings of Ocean Seismic Network workshop :" Broadband Seismology in the Oceans: towards a five year plan", 8-18.

Gee, L., D. Neuhauser, D. Dreger, R. Uhrhammer and B. Romanowicz (2003) The Rapid Earthquake Data Integration Project, in International Handbook of Earthquake and Engineering Seismology, 81B, 1261-1273.

Kasahara, J., T. Sato, H. Momma, and Y. Shirasaki (1998) A new approach to geophysical real-time measurements on a deep-seafloor using decommisioned submarine cables, Earth Planets Space, vol. 50, 913-925.

McGill, P., D. Neuhauser, D. Stakes, B. Romanowicz, T. Ramirez, and R. Uhrhammer (2002). Deployment of a long-term broadband seafloor observatory in Monterey Bay, EOS Trans. Amer. Geophys. Un., 83, F1008.

Montagner, J.P. and Y. Lancelot (1995), Editors, "Multidisciplinary observatories on the deep seafloor", report of International Ocean Network workshop held at Marseille, France, 01/11-01/13, 1995 published by INSU/CNRS, IFREMER, ODP-France.

Montagner, J.P., B. Romanowicz and J.F. Karczewski (1994a) "A first step toward an oceanic geophysical observatory", Trans AGU, 75, 150-151.

Montagner, J.P., J. F. Karczewski, B. Romanowicz, S. Bouaricha, P. Lognonne, G. Roult, E. Stutzmann, J.L. Thirot, J Brion, B. Dole, D. Fouassier, J-C Koenig, J.C. Savary, L. Floury, J. Dupond, A. Echardour and H. Floc'h, (1994b) " The french pilot experiment OFM-SISMOBS: first scientific results on noise level and event detection", Phys. Earth and Planet Inter., 84, 321-336.

OMD Workshop Committee (2003) Ocean Mantle Dynamics Implementation Plan, Report of a Community Workshop, SNowbird, Utah, 18-20 September 2002.

OSN1 reference

Purdy, M. (1995) editor: " Broadband Seismology in the Oceans: towards a five year plan", report of Ocean Seismic Network workshop published by Joint Oceanographic Institutions.

Purdy, G.M., and A.M. Dziewonski (1988) Proc. Workshop on Broad-Band Downhole Seismometers in the Deep Ocean, Woods Hole, MA, Apr. 26-28, 1988, Joint Oceanogr. Inst. and U.S. Sci. Advisory Comm..

Romanowicz, B., D. Neuhauser, B. Bogaert and D. Oppenheimer (1994) Accessing Northern California Earthquake Data Via Internet, EOS Trans A.G.U., 75, 258-261.

Romanowicz, B., D. Stakes, J. P. Montagner, P. Tarits, R. Uhrhammer. M. Begnaud, E. Stutzmann, M. Pasyanos, J.F. Karczewski, S. Etchemendy (1998) MOISE: a pilot experiment towards long term Sea-floor geophysical observatories, Earth Planets Space, 50,927-937.

Romanowicz, B., D. Stakes, R. Uhrhammer, P. MvGill, D. Neuhauser, T. Ramirez. D. Dolenc (2003) The MOBB experiment: a prototype permanent off-shore ocean bottom broadband station, EOS Trans., AGU, 84, 325-332.

Schwartz, D. P. , D. Pantosti, K. Okumura, T. J. Powers and J.C. Hamilton (1998) Paleoseismic investigations in the Santa Cruz moutnains, California: implications for recurrence of large-magnitude earthquakes on the San Andreas fault, *J. Geophys. Res.*, 103, 17,985-18,001.

Simila, G. W., V. A. Gallardo, K. C. McNally, M. L. Begnaud, and D. S. Stakes, New investigation of significant Monterey Bay area earthquakes (M¿4.0, 1926-79) utilizing data from a 1998 deployment of PASSCAL Ref-Teks and master-event methods, EOS Trans. AGU, 79 (45), F589, 1998. Begnaud, M. L., K. C. McNally, D. S. Stakes and V. A. Gallardo, A crustal velocity model for locating earthquakes in Monterey Bay, California, Bull. Seism. Soc. Am., 90, 1391-1408, 2000.

Stakes, D., B. Romanowicz, J.P. Montagner, P. Tarits, J.F. Karczewski, S. Etchemendy, D. Neuhauser, P. McGill, J-C. Koenig, J.Savary, M. Begnaud and M. Pasyanos, MOISE: Monterey Bay Ocean Bottom International Seismic Experiment, EOS Trans., A.G.U., 79, 301-309, 1998.

Stephen, R.A., Spiess, F.N., Collins, J.A., Hildebrand, J.A., Orcutt, J.A., Peal, K.R., Vernon, F.L. and Wooding, F.B. (2003) The ocean seismic network pilot experiment, Geochemistry, Geophysics Geosystems, in press.

Stutzmann, E., J.P. Montagner et al., MOISE: a prototype multiparameter ocean-bottom station, *Bull. Seism. Soc. Am., 81*, 885-902, 2001.

Sutton, G. H., W. G. McDonald, D. D. Prentiss, and S. N. Thomson (1965) Ocean-bottom seismic observatories, Proc. IEEE, 53, 1909=1921.

Sutton, G. H., F. K. Duennebier, and B. Iwataki (1992) Coupling of ocean bottom seismometers to soft bottom, Mar. Geophys. Res., 5, 35-51, 1981.

Suyehiro, K., T. Kanazawa, N. Hirata, M. Shinohara and H. Kinoshita (1992) Broadband downhole digital seismometer experiment at site 794", Proc. O.D.P. 127/128, 1061-1073.

Suyehiro, K., J.P. Montagner, A. M. Dziewonski and B. Romanowicz, The International Ocean Network Structure, Proceedings ION/ODP International Workshop, " Multidisciplinary observatories on the deep seafloor", Marseille, 61-72, 1995.

Suyehiro, K., E. Araki, S. Amasao, T. Kanazawa, Deep sea borehole observatories ready and capturing seismic waves in the western Pacific, EOS, Trans, AGU, 83, 624-625., 2002.

Thatcher, W., G. Marshall and M. Lisowski (1997) Resolution of fault slip along the 470-km-long rupture of the great 1906 San Francisco earthquake and its implications, *J. Geophys. res.*, 102, 535-5367.

Uhrhammer, R., B. Romanowicz, D. Neuhauser, D. Stakes, P. McGill, and T. Ramirez (2002). Instrument testing and first results from the MOBB Observatory, EOS Trans. Amer. Geophys. Un., 83, F1008.

Uhrhammer, R., (2003), Fall'03 AGU abstract

Webb, S. C., Broadband seismology and noise under the ocean (1998) Rev. Geophys. Space Phys., 36, 105-142.

Webb, S. C., X. Zhang and W. Crawford (1991) Infragravity waves in the deep ocean, J.

Geophys. Res., 96, 2723-2736.

Working Group on Northern California Earthquake Potential (1996) Database of potential sources for earthquakes larger than magnitude 6 in northern California, *U. S. Geol. Surv. Open File Rep.*, 96-705, 40 pp.

7 Figure Captions

Figure 1. Location of the MOBB and MOISE stations in Monterey Bay, California, against seafloor and land topography. Fault lines are from the California Division of Mines and Geology database. MOBB is located at a water depth of 1000 m.

Figure 2. (a); Photo of a Guralp CMG-1TD seismometer 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 front and the system clock is on the circuit board on the right. The seismometers are in the mu metal shielded container mounted on leveling gimbals in the center. (b) Photo of the titanium pressure vessel containing the CMG-1TD and resting on a ~1 cm thick bed of kiln dried fine sand on the concrete pier at BKS, for the purpose of noise comparisons (Uhrhammer et al., in preparation).

Figure 3. Comparison of typical background noise PSD levels observed by the CMG-1TD and the co-sited STS-1's in the BKS vault, (a) before and (b) after it had been installed in the titanium pressure vessel, appropriately insulated and purged with argon gas. The large dashed line and the solid lines are the Z component and horizontal component PSD's, respectively, and the small dashed lines are the STS-1 PSD's. Note that the CMG-1TD PSD levels are within ~5 dB of the STS-1 PSD levels at long periods after insulation (Uhrhammer et al., in preparation).

Figure 4. MOBB installation snapshots. (a) The seismometer package is being lowered into the hole bounded by the PVC pipe, held by the arm of the ROV *Ventana*. (b) The recording and battery package is being installed inside the trawl-resistant mount. (c) The ROV arm (at

front) is connecting the current meter cable to the recording system. The connector of the seismometer package on the right is already in place.

Figure 5. Mass position data for portions of the time period 04/11/2002-01/07/2003, showing the progressive settling of the seismometers. The large steps on the horizontal components (MMN, MME) are associated with: 1) installation (day 100); 2) re-centering (day 112, day 263). There is a smaller step on day 134, associated with a local Mw4.95 earthquake. The vertical component data (MMZ) have been detrended by subtracting a running 36 hour average (+/-18 hours) from each 1/2 hour duration smoothed data sample, to bring out the cleraly visible tide signal. Note the different scale on MMZ.

Figure 6. Location of MOBB (and MOIS) with respect to nearby broadband stations of the Berkeley Digital Seismic Network (BDSN). FARB is located on the Farallon Islands. MOBB is located just west of the San Gregorio fault.

Figure 7. Comparison of noise recorded at MOBB and 2 other stations of the BDSN network, on two days in 2002 when no significant earthquake signals were recorded: a "quiet day" (143), and a "stormy" day (350), as assessed by the mean wave height recordings at a nearby NOAA buoy, located in Monterey Bay. The USGS high- and low-noise models for land stations are shown in black. Increased noise level for periods between 20 and 500 sec, due to ocean currents and infragravity waves, is observed at MOBB, as well as at the island station FARB. The noise level at MOBB between 10 and 20 sec is comparable to the land station YBH, one of the quietest stations of the BDSN. See Figure 6 for FARB and SAO locations. Station YBH is 560 km north of MOBB. (a) Vertical component; (b) North Component; (c) East Component.

Figure 8. Spectrum of current speed (units are (mm/s)/Hz) based on a 78-day period of current meter data. The four dominant group of peaks coincide precisely with the frequencies of the diurnal, semi-diurnal, 8 hour and 6 hour components of the gravitational tides.

Figure 9. Distribution of current velocity data as a function of azimuth for the 78-day period shown in Figure 8. The contour label units are fractions of the average density distribution of the current velocity. The two dominant maxima (centered at 60^o and 240^o, i.e. orthogonal to the continental shelf) are associated with the semi-diurnal tidal currents. The third directional peak is roughly parallel to the coastline and appears to be related to the dominant ocean circulation.

Figure 10. Comparison of vertical, N and E component records of the 04/26/2002 Mw 7.1 Mariana earthquake (depth = 85.7 km, distance = 85.2^o, azimuth = 283^o from MOBB), at MOBB and 3 stations of the BDSN. The records have been band-pass filtered between 10-100 sec.

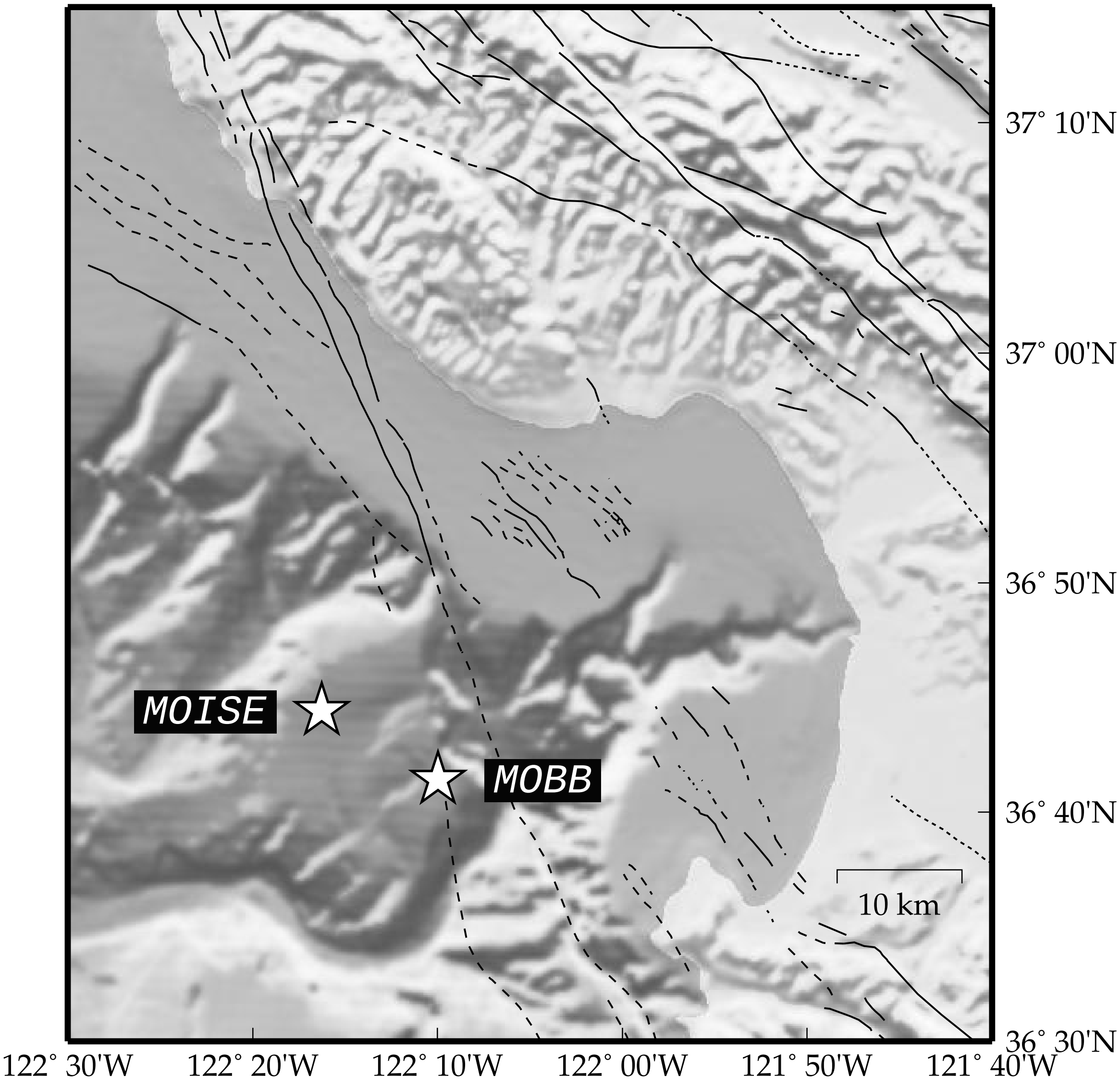
Figure 11. Comparison of vertical component records at stations FARB, JRSC, MOBB and SAO for the deep Kurile Island earthquake of 11/17/2002 (Mw = 7.3; depth = 459 km; distance to MOBB = 65^o). The data are shown in two pass-bands : 0.03-0.1 Hz and 0.03-0.3 Hz to emphasize the narrow-band character of the ringing in the MOBB P wave data. Clearly visible in the lower frequency band are the P, pP and sP arrivals.

Figure 12. Raw vertical component data (P wave and depth phases) observed on the vertical component at stations MOBB (blue) and JRSC (green) for the 11/17/2002 deep Kurile Island earthquake. Clearly seen is the ringing due to the soft sediment layer in Monterey Bay. The

red trace shows the MOBB data after removal of the transfer function constructed using JRSC data.

Figure 13. Deconvolved ground velocity records at MOBB of the 04/23/2002 M 3.63 San Andreas fault event (lat = 36.866, lon = -121.61, depth = 9 km).

Figure 14. Results of moment tensor inversions for the M 3.63 regional event shown in Figure 13. Top: inversion using 4 stations of the BDSN and MOBB (BDM,BKS,CMB are bandpass filtered between 0.02 and 0.05 Hz; MHC and MOBB, between 0.05 and 0.10 Hz). Bottom: results of inversion using only MOBB, showing the good fits of the single station solution to the other BDSN waveform data.


MOISE
MOBB
10 km
37° 10'N
37° 00'N
36° 50'N
36° 40'N
36° 30'N
122° 30'W
122° 20'W
122° 10'W
122° 00'W
121° 50'W
121° 40'W

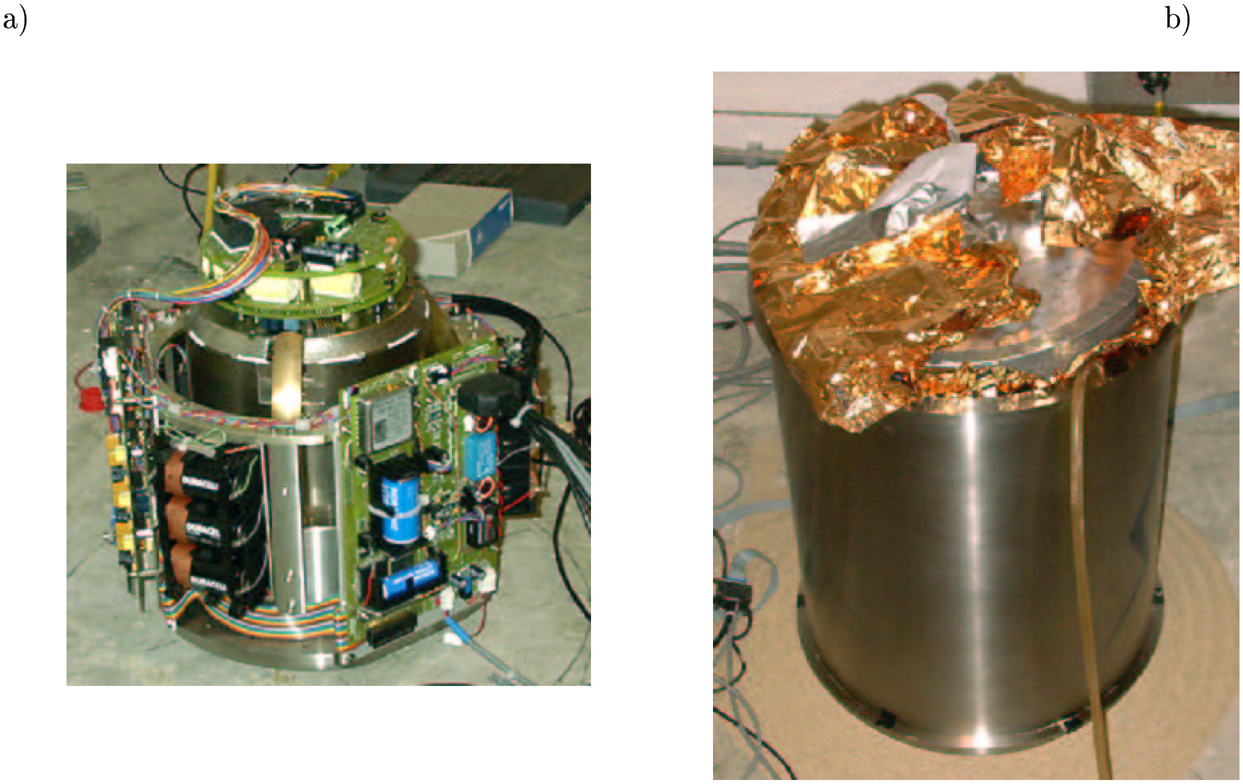
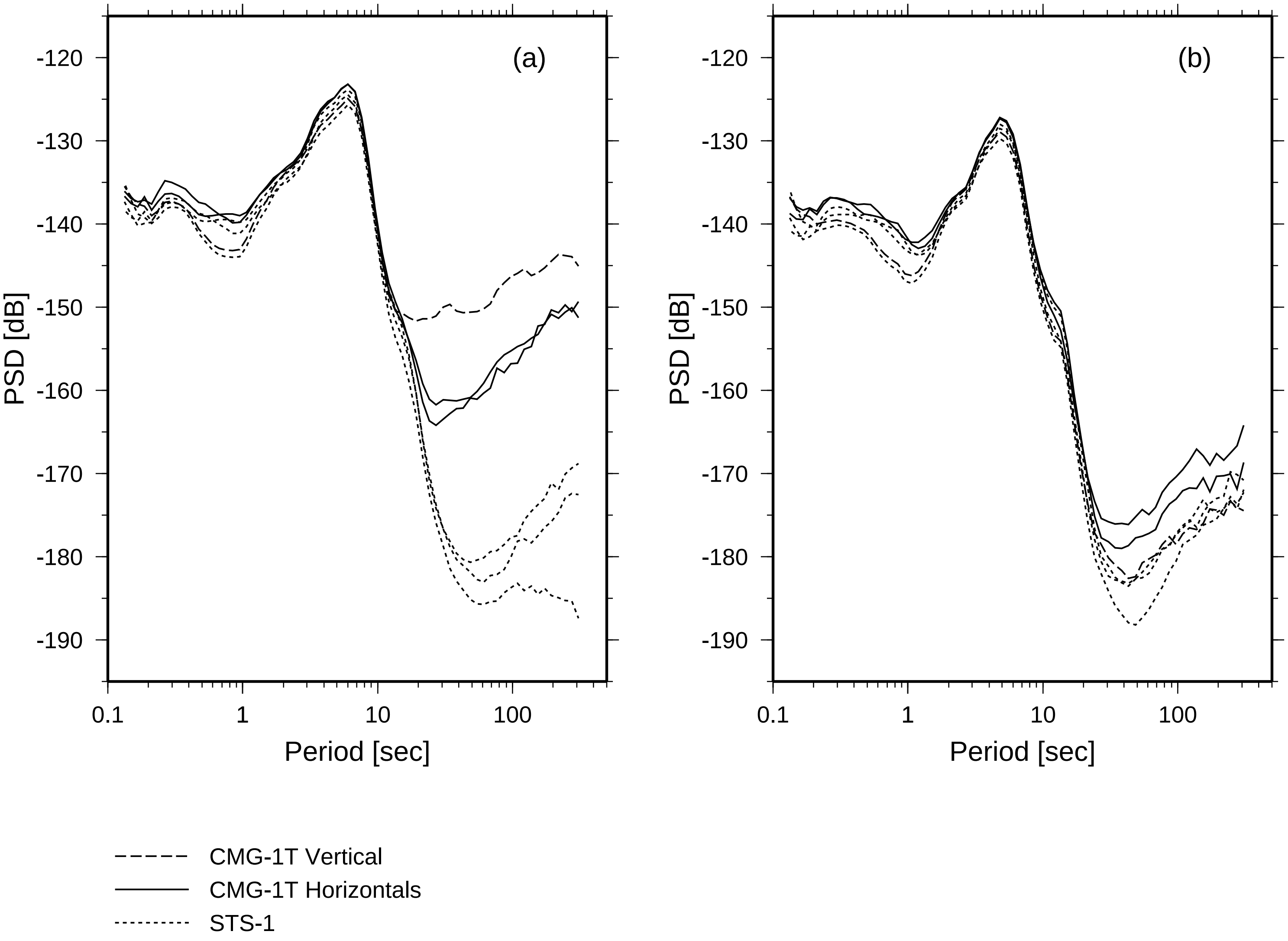


Figure 2:


(a)
(b)
PSD [dB]
-120
-130
-140
-150
-160
-170
-180
-190
Period [sec]
0.1
1
10
100
CMG-1T Vertical
CMG-1T Horizontals
STS-1

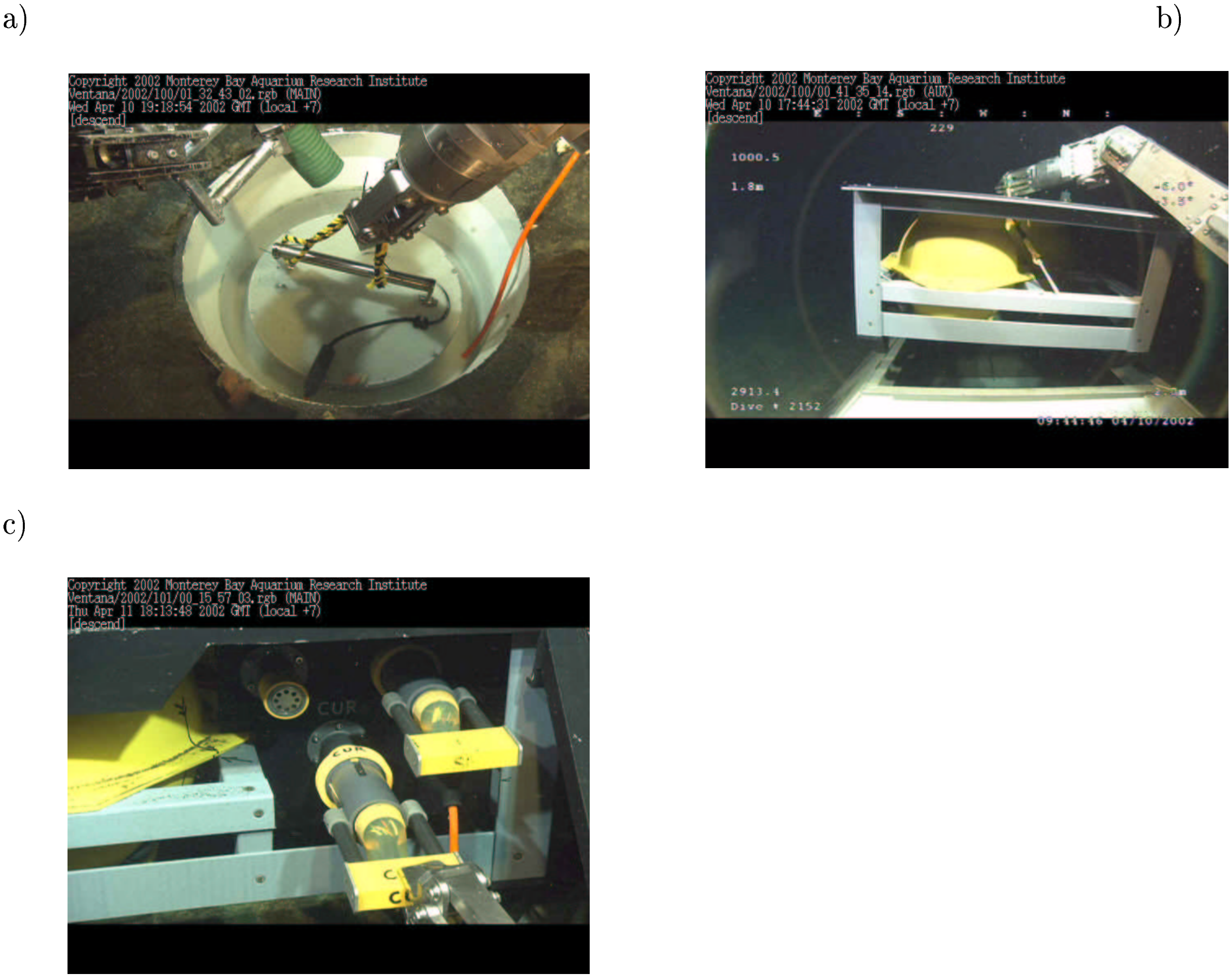
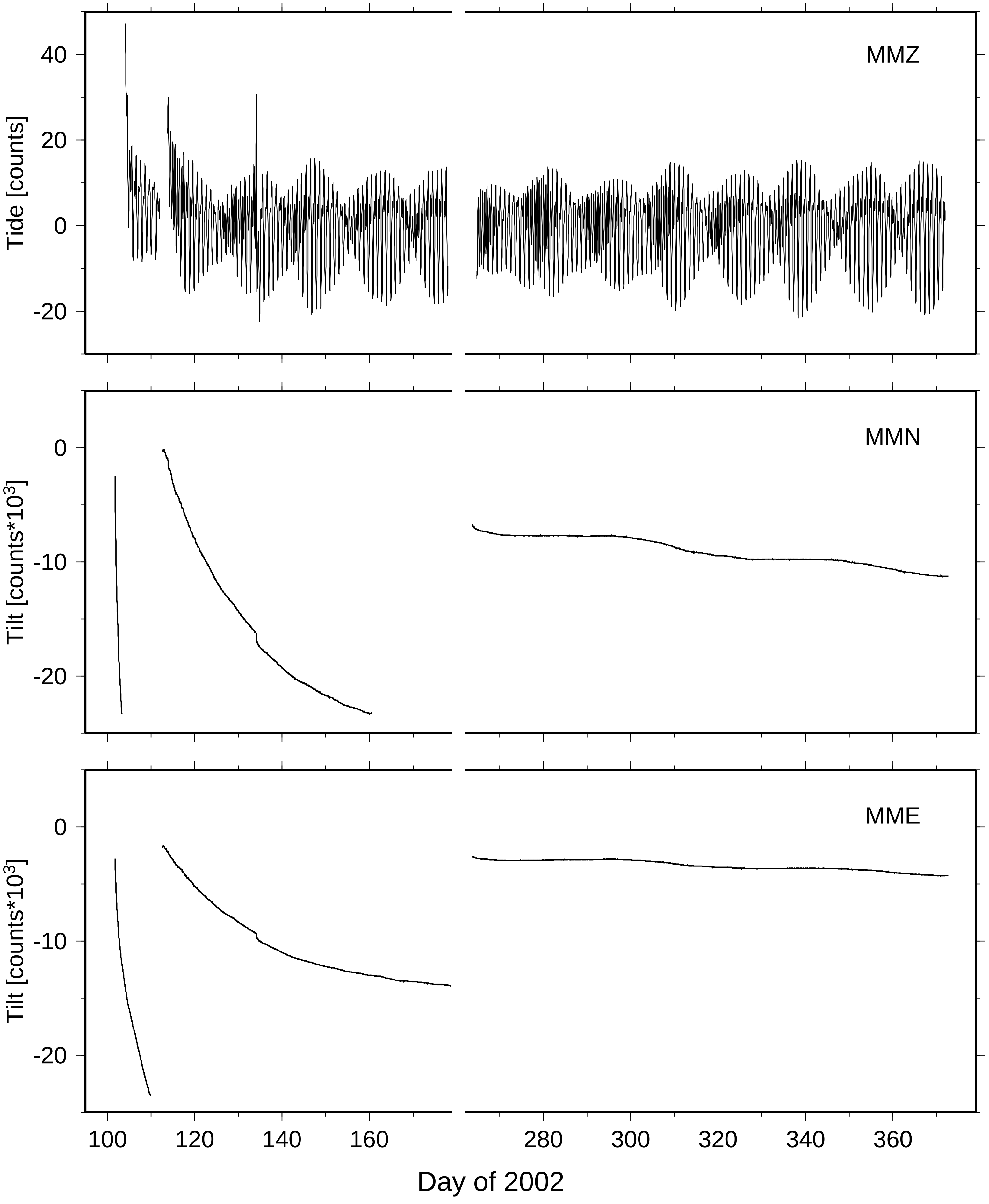
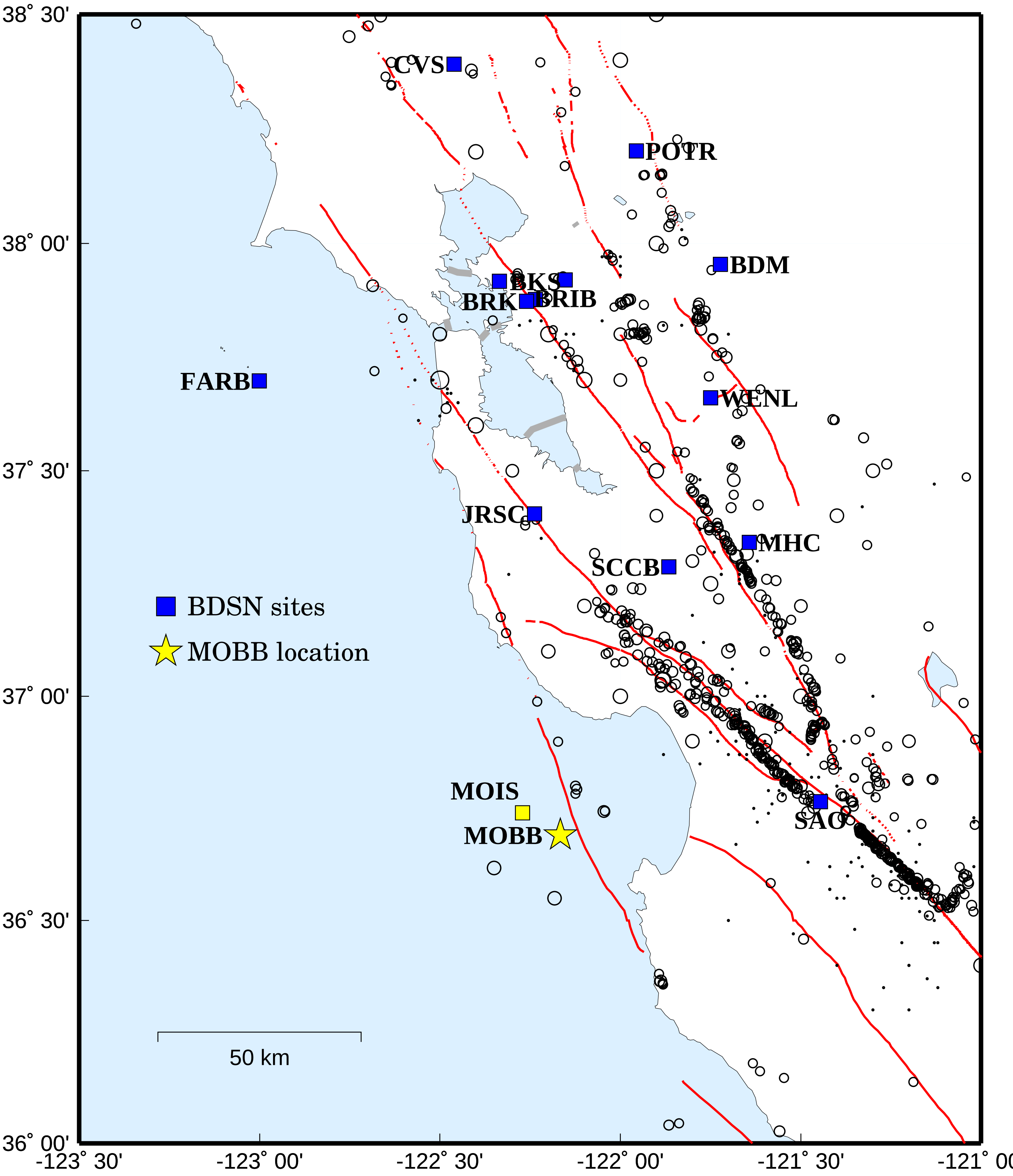
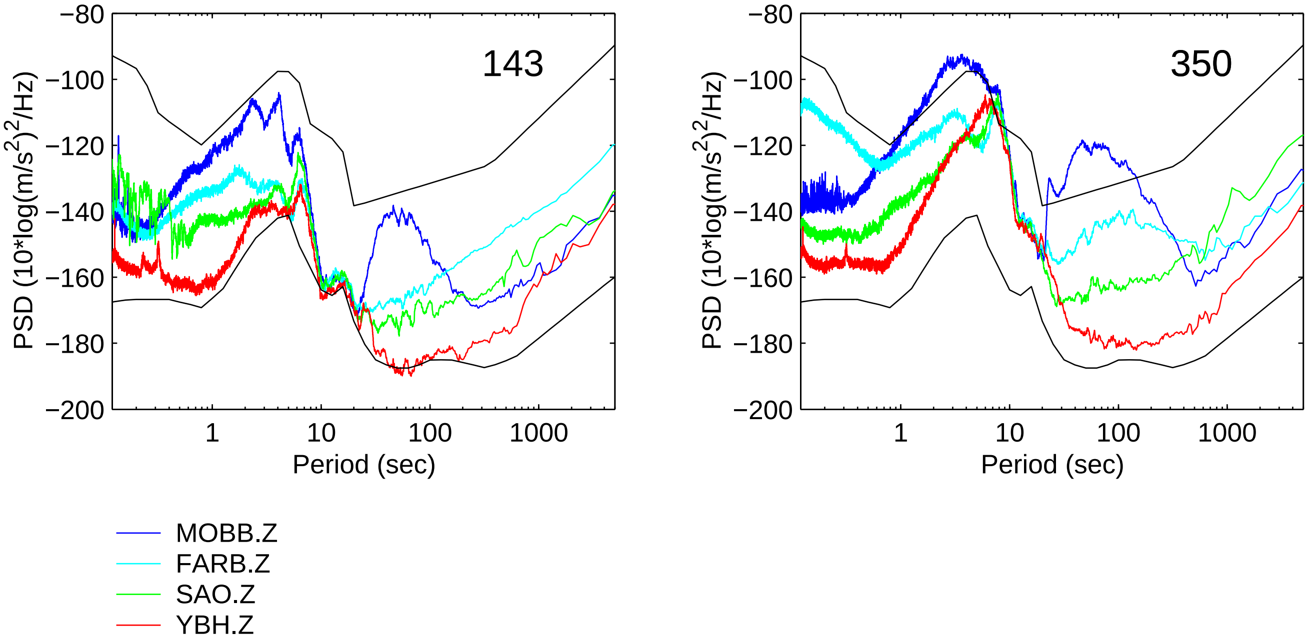

a)
Copyright 2002 Monterey Bay Aquarium Research Institute
Ventana/2002/100/01_32_43_02.rgb (MAIN)
Wed Apr 10 19:18:54 2002 GMT (local +7)
[descend]
b)
Copyright 2002 Monterey Bay Aquarium Research Institute
Ventana/2002/100/00_41_35_14.rgb (AUX)
Wed Apr 10 17:44:31 2002 GMT (local +7)
[descend]
229
1000.5
1.8m
2913.4
Dive # 2152
09:44:46 04/10/2002
c)
Copyright 2002 Monterey Bay Aquarium Research Institute
Ventana/2002/101/00_15_57_03.rgb (MAIN)
Thu Apr 11 18:13:48 2002 GMT (local +7)
[descend]
CUR
CUR

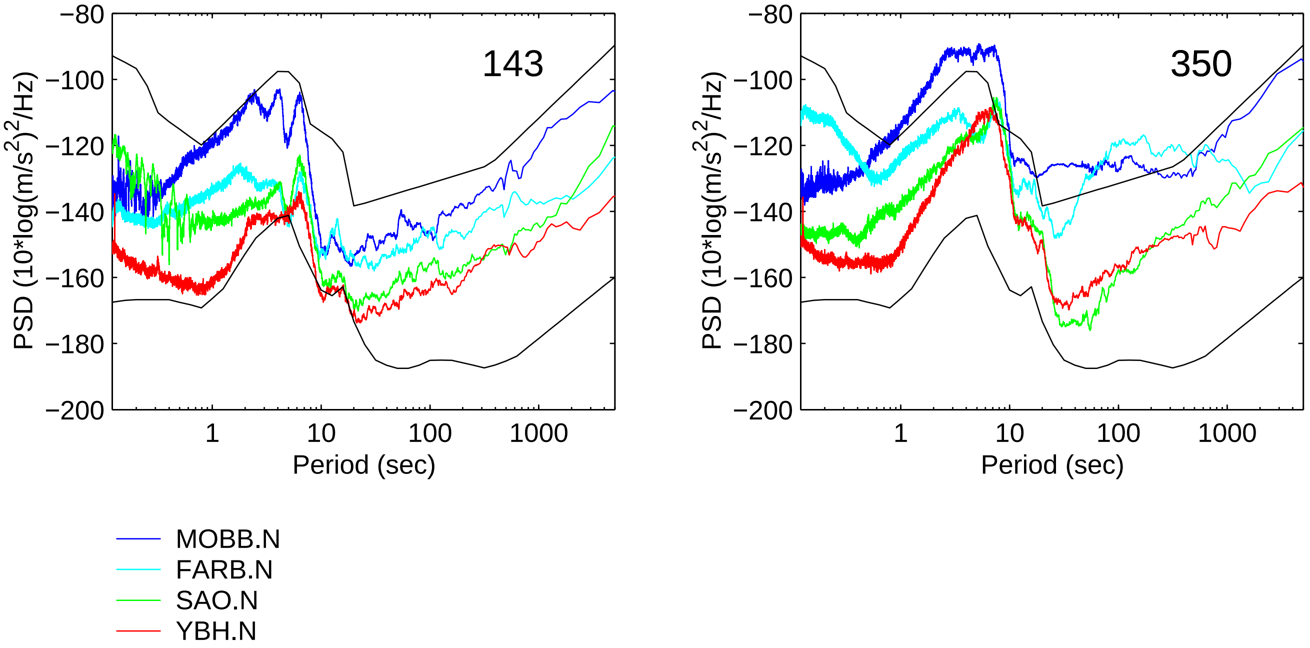
Figure 4:

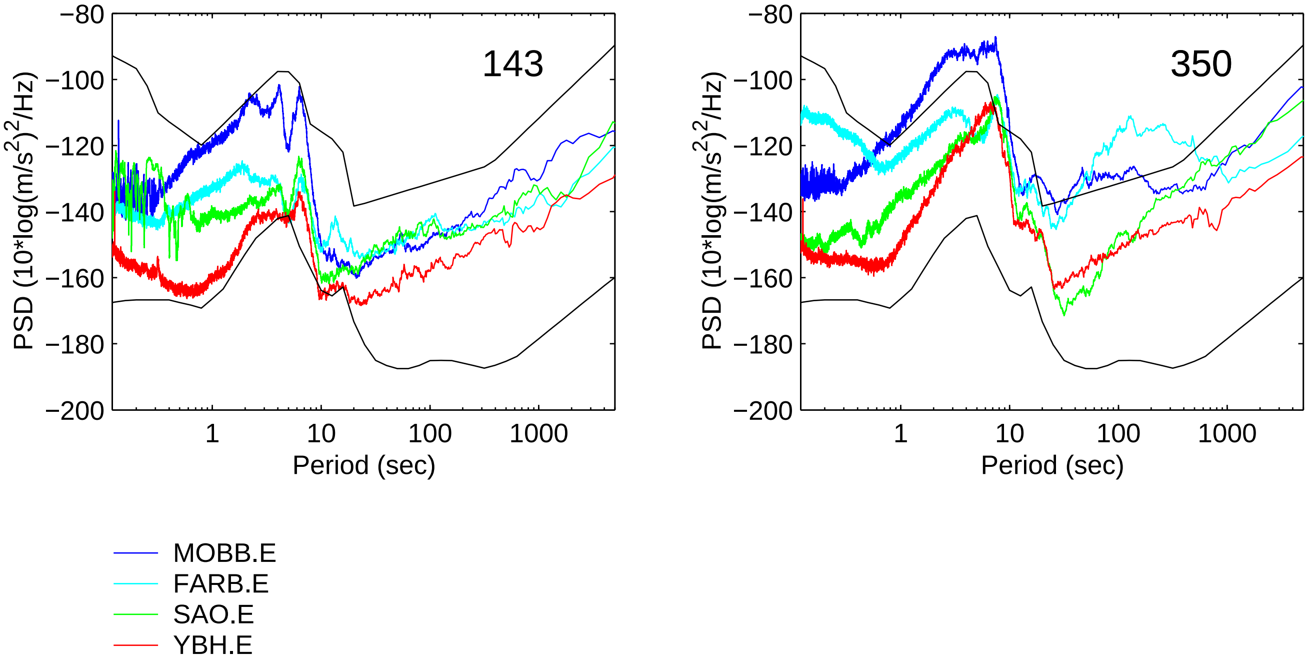


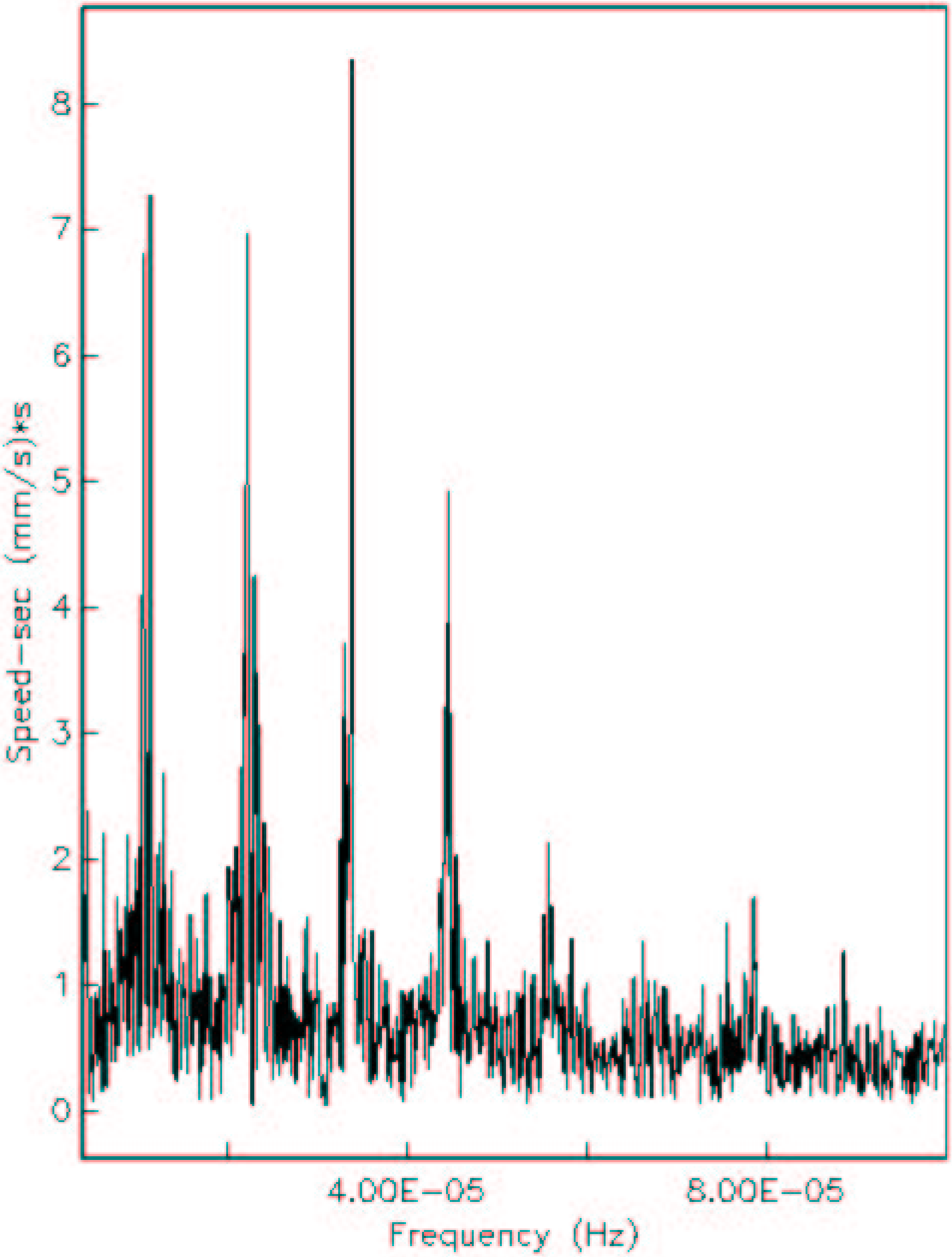
MMZ
Tide [counts]
40
20
0
-20
MMN
Tilt [counts*10^3]
0
-10
-20
MME
Tilt [counts*10^3]
0
-10
-20
100
120
140
160
280
300
320
340
360
Day of 2002


38° 30'
38° 00'
37° 30'
37° 00'
36° 30'
36° 00'
-123° 30'
-123° 00'
-122° 30'
-122° 00'
-121° 30'
-121° 00'
CVS
POTR
BDM
BKS
BRK
BRIB
FARB
WENL
JRSC
MHC
SCCB
SAO
MOIS
MOBB
BDSN sites
MOBB location
50 km

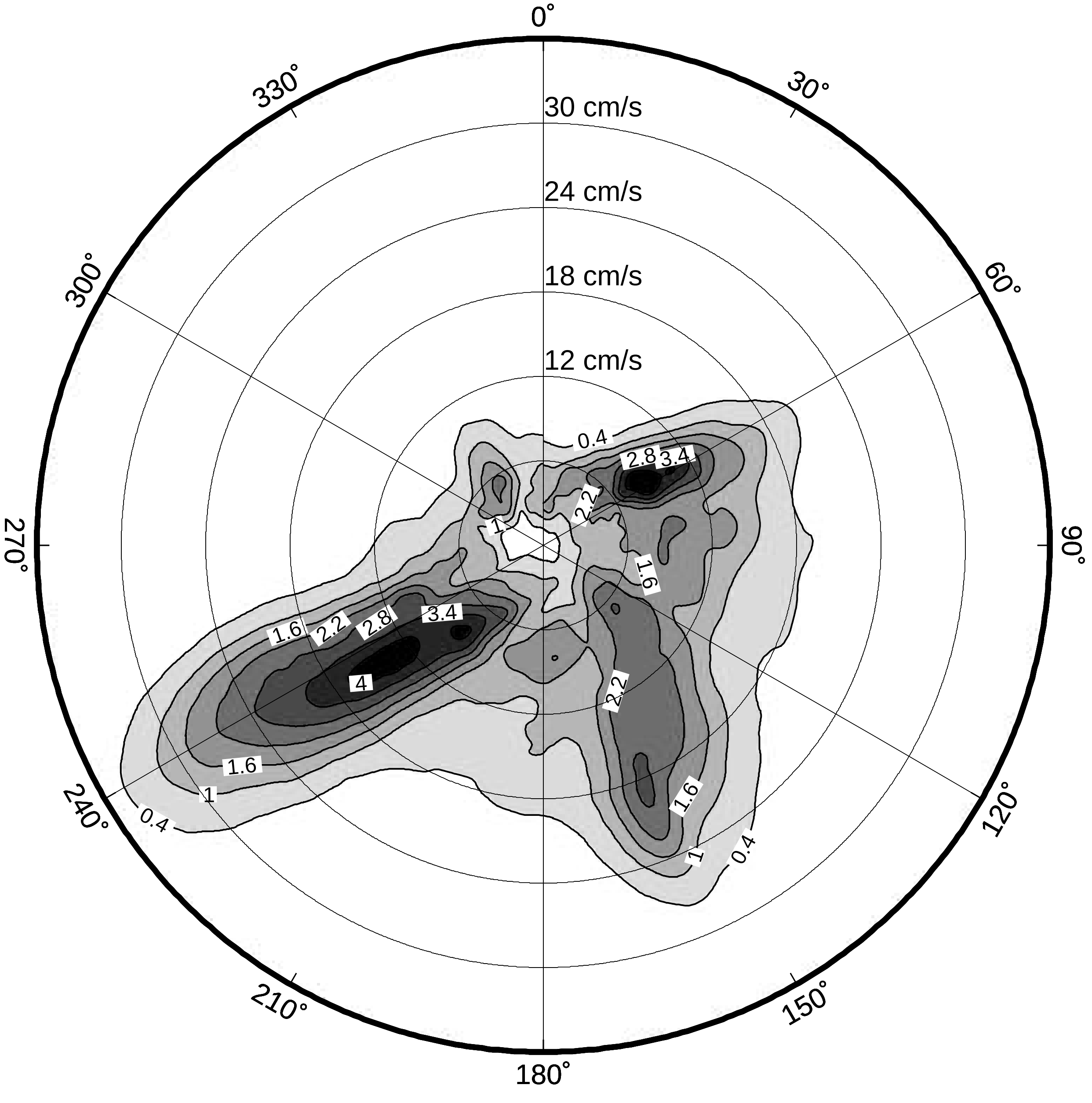

143
350
PSD (10*log(m/s^2)^2/Hz)
−80
−100
−120
−140
−160
−180
−200
1
10
100
1000
Period (sec)
MOBB.Z
FARB.Z
SAO.Z
YBH.Z

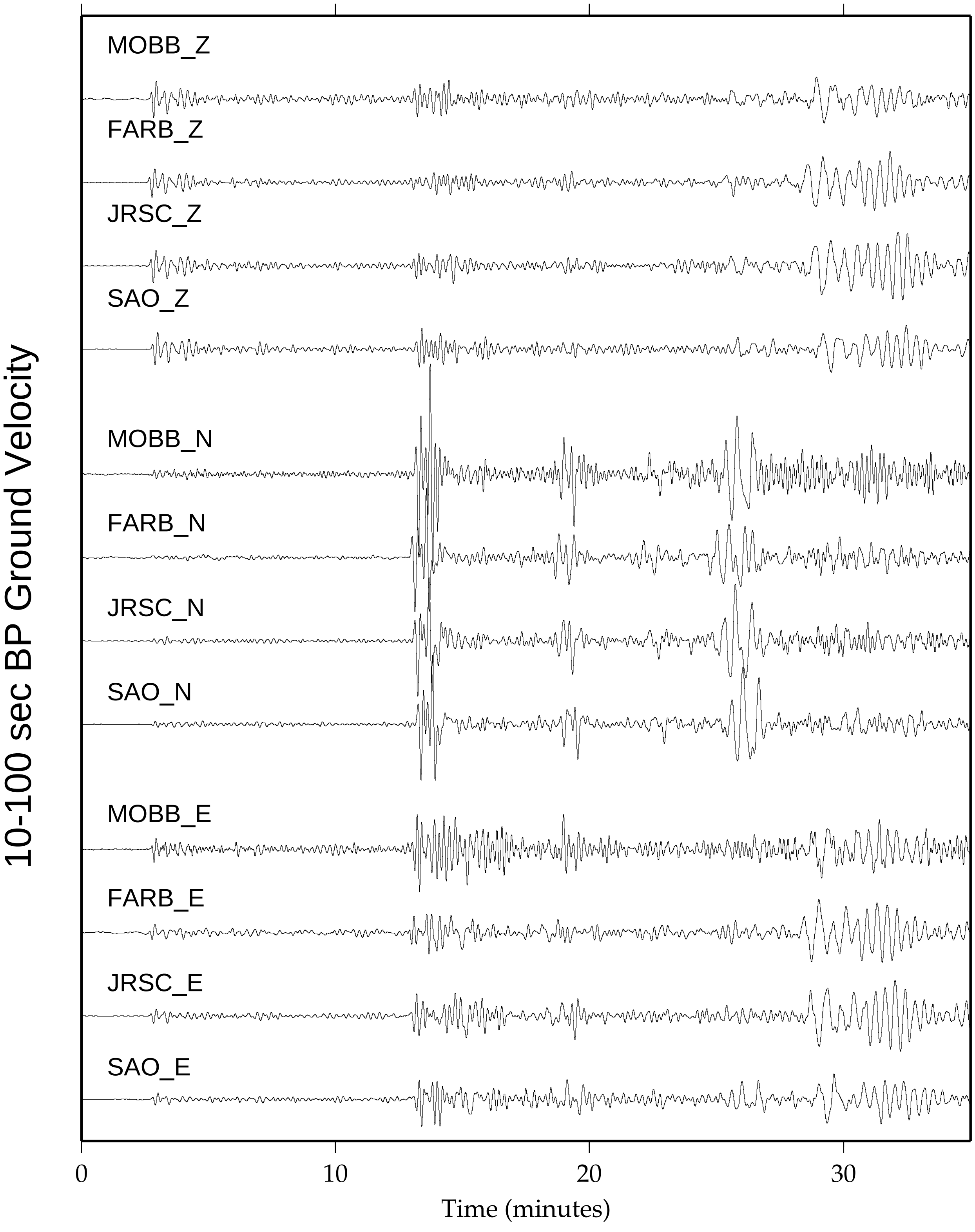

143
350
PSD (10*log(m/s^2)^2/Hz)
−80
−100
−120
−140
−160
−180
−200
Period (sec)
1
10
100
1000
MOBB.N
FARB.N
SAO.N
YBH.N

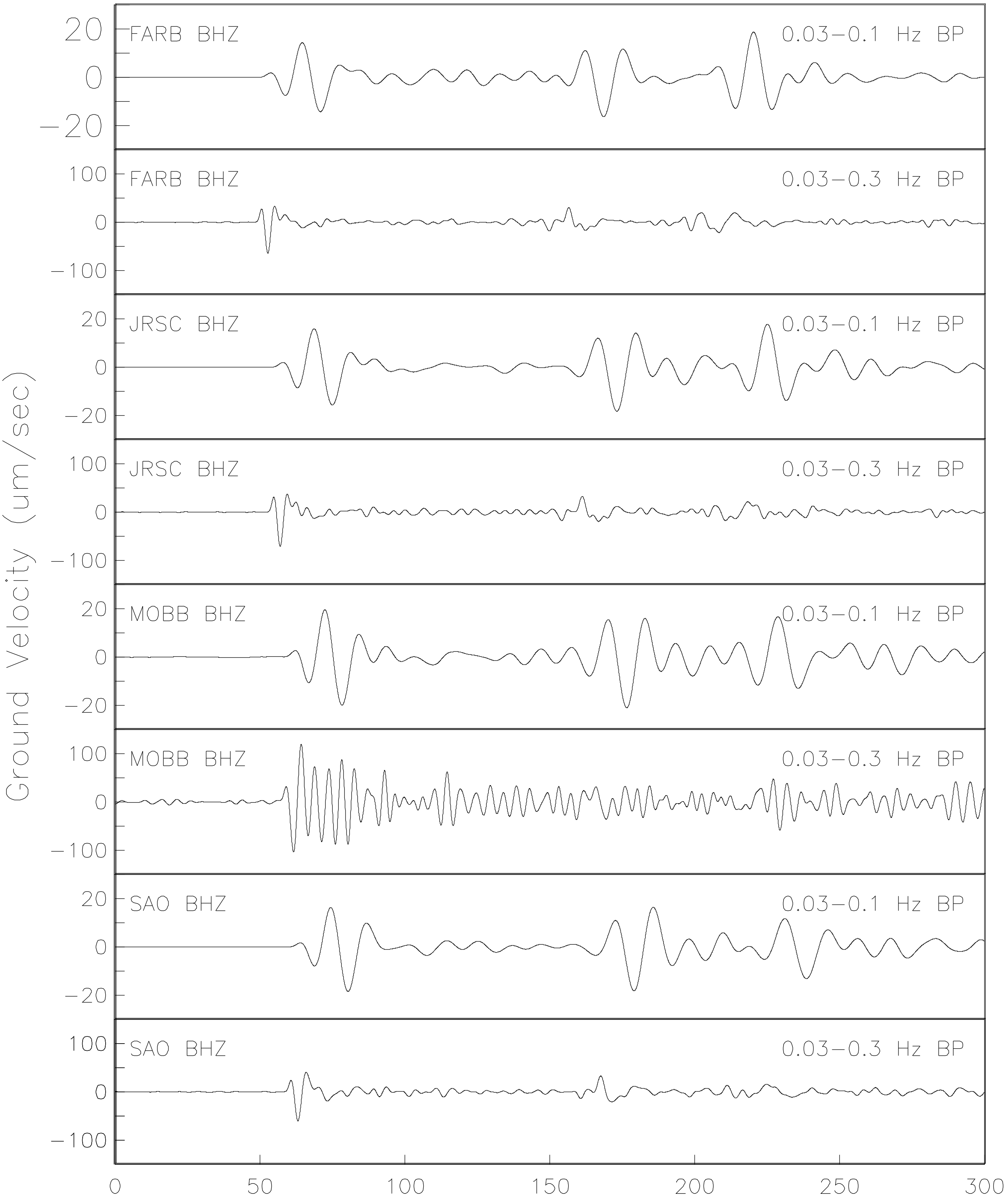

143
350
PSD (10*log(m/s^2)^2/Hz)
−80
−100
−120
−140
−160
−180
−200
1
10
100
1000
Period (sec)
MOBB.E
FARB.E
SAO.E
YBH.E

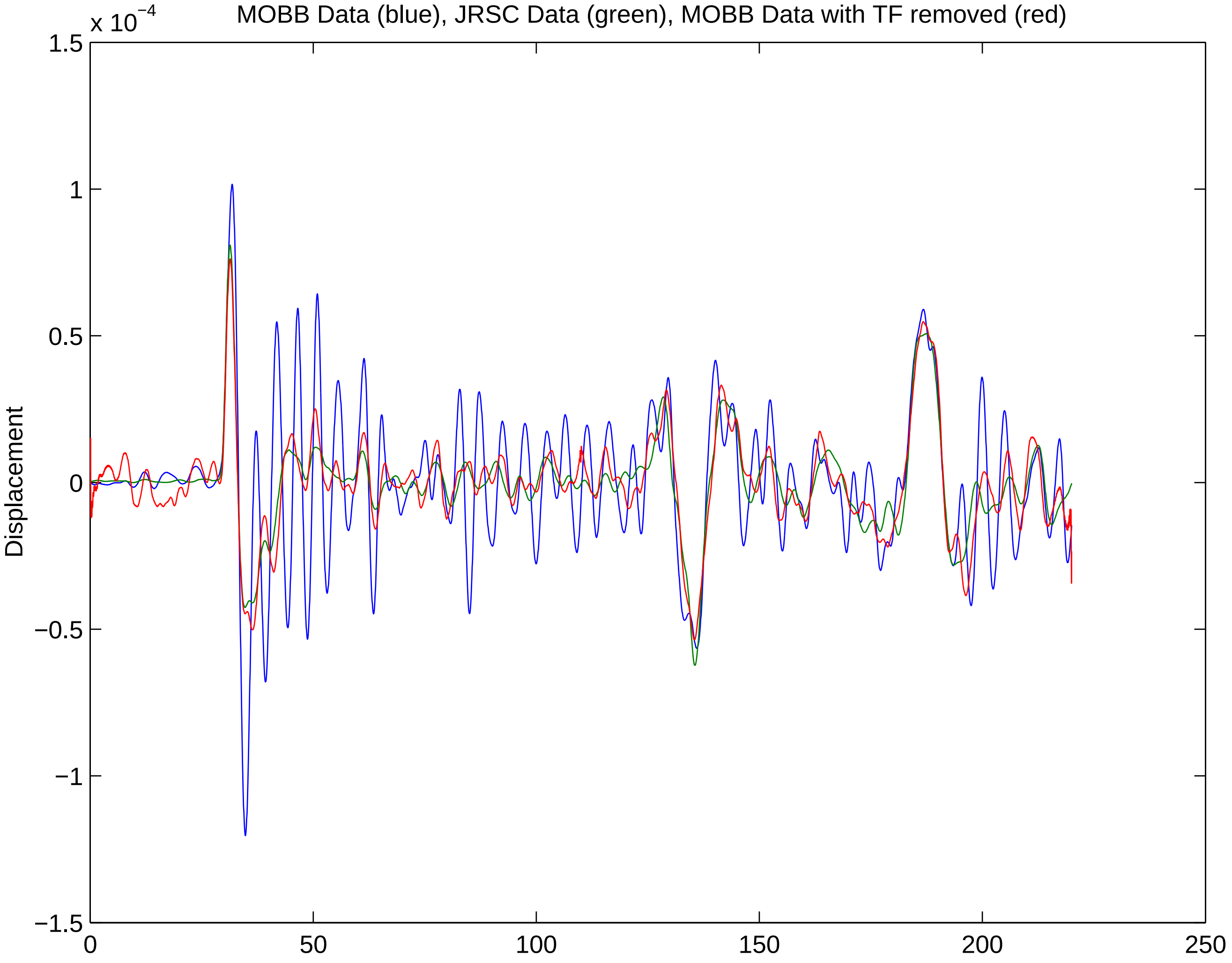


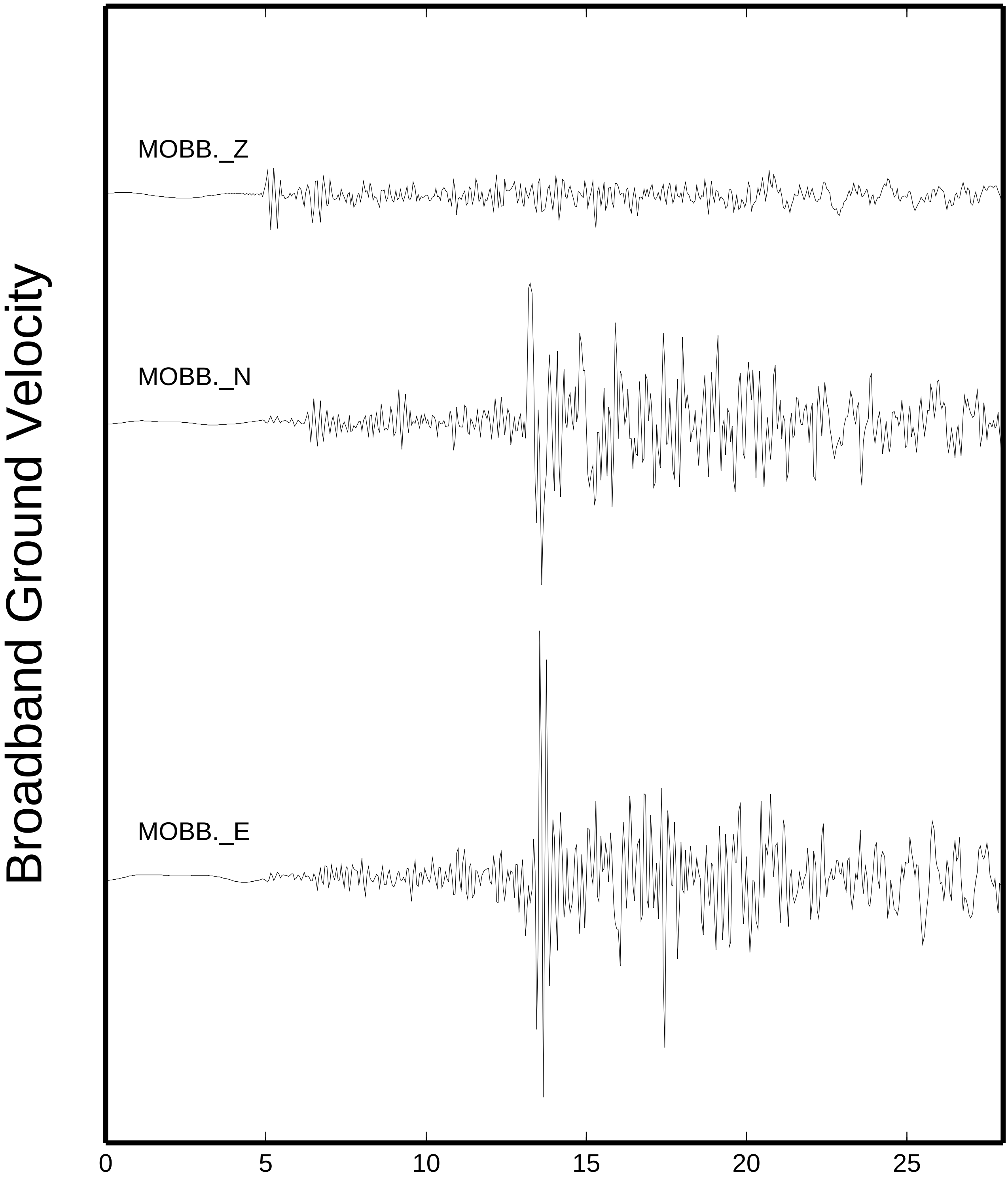
Speed-sec (mm/s)*s
0
1
2
3
4
5
6
7
8
4.00E-05
8.00E-05
Frequency (Hz)

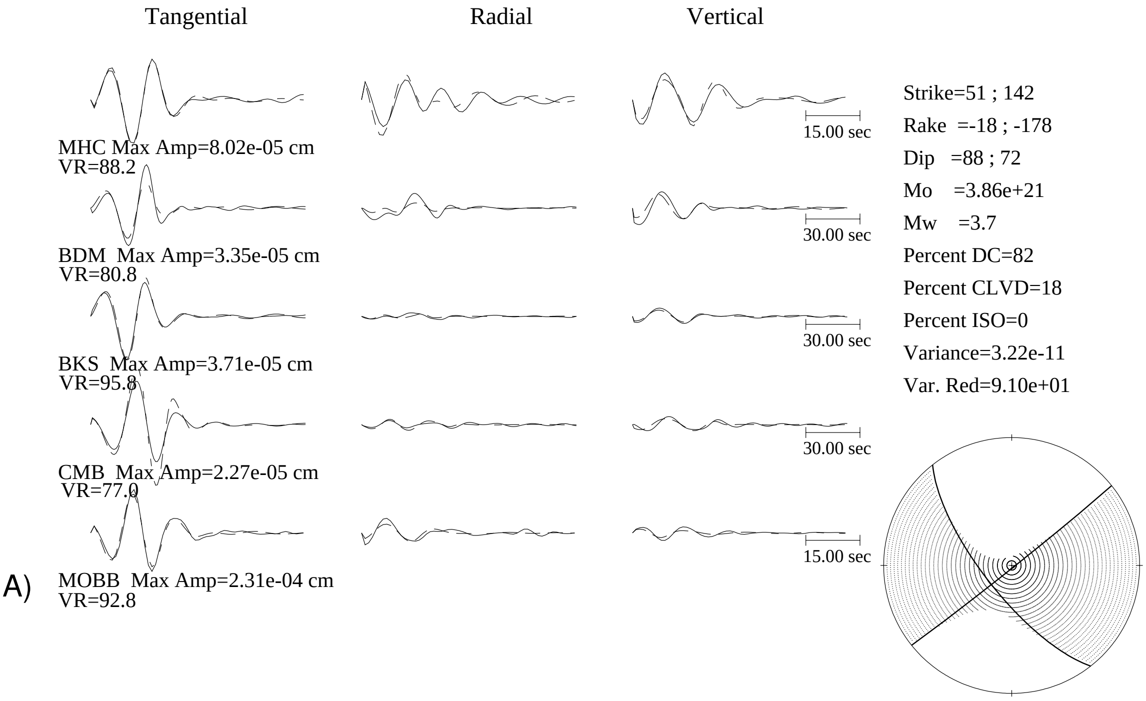

0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
30 cm/s
24 cm/s
18 cm/s
12 cm/s
0.4
1
1.6
2.2
2.8
3.4
4

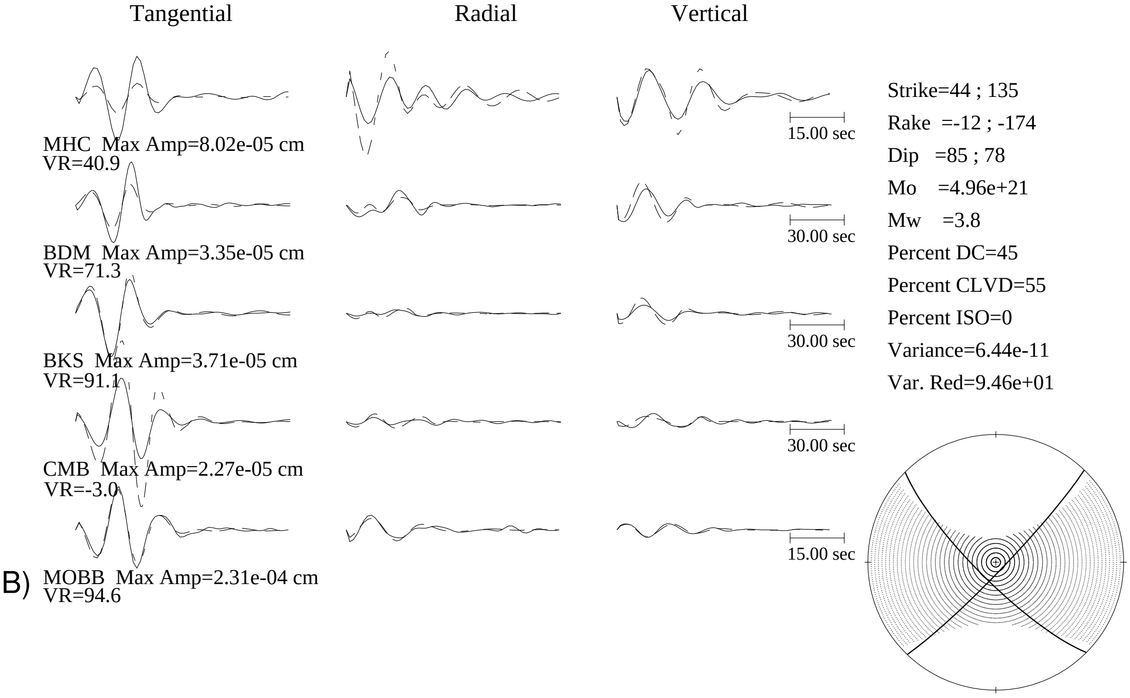

10-100 sec BP Ground Velocity
MOBB_Z
FARB_Z
JRSC_Z
SAO_Z
MOBB_N
FARB_N
JRSC_N
SAO_N
MOBB_E
FARB_E
JRSC_E
SAO_E
0
10
20
30
Time (minutes)


2003.321.0453 Mw 7.3 h = 459km Δ = 65


MOBB Data (blue), JRSC Data (green), MOBB Data with TF removed (red)
x 10^{-4}
1.5
1
0.5
0
−0.5
−1
−1.5
Displacement
0
50
100
150
200
250


Broadband Ground Velocity
MOBB._Z
MOBB._N
MOBB._E
0
5
10
15
20
25
Time (seconds)


Tangential
Radial
Vertical
MHC Max Amp=8.02e-05 cm
VR=88.2
15.00 sec
BDM Max Amp=3.35e-05 cm
VR=80.8
30.00 sec
BKS Max Amp=3.71e-05 cm
VR=95.8
30.00 sec
CMB Max Amp=2.27e-05 cm
VR=77.0
30.00 sec
MOBB Max Amp=2.31e-04 cm
VR=92.8
15.00 sec
A)
Strike=51 ; 142
Rake =-18 ; -178
Dip =88 ; 72
Mo =3.86e+21
Mw =3.7
Percent DC=82
Percent CLVD=18
Percent ISO=0
Variance=3.22e-11
Var. Red=9.10e+01


Tangential
Radial
Vertical
MHC Max Amp=8.02e-05 cm
VR=40.9
15.00 sec
BDM Max Amp=3.35e-05 cm
VR=71.3
30.00 sec
BKS Max Amp=3.71e-05 cm
VR=91.1
30.00 sec
CMB Max Amp=2.27e-05 cm
VR=-3.0
30.00 sec
MOBB Max Amp=2.31e-04 cm
VR=94.6
15.00 sec
B)
Strike=44 ; 135
Rake =-12 ; -174
Dip =85 ; 78
Mo =4.96e+21
Mw =3.8
Percent DC=45
Percent CLVD=55
Percent ISO=0
Variance=6.44e-11
Var. Red=9.46e+01