PMD Sensor Testing Results

by

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PMD Scientific, Inc. (http://pmdsci.home.att.net) loaned the Berkeley Seismological Laboratory (BSL) three PMD broadband three−component seismometers for testing. A series of tests were done in the Byerly Seismic Vault (BKS). The PMD sensor signals were recorded by an eight channel Quanterra Q4128 data logger (SN 981205) with 24−bit integer resolution. Our primary interest is to compare the waveforms from the PMD sensors and the co−sited STS−1's and to characterize the linearity and useful dynamic range of the PMD sensors. The testing was done from October 1999 through January 2000.

The PMD seismometers use an unique Molecular Electronic Transfer (MET) transducer (Abramovich et al., 1997) to detect the velocity of a highly conductive electrolytic fluid. It is noteworthy that, prior to the introduction of the PMD MET transducer, all seismic sensors with velocity transduction invariably used a coil and magnet. A detailed description of the MET sensor (Abramovich et al., 1997) is given in Appendix A. The MET transducer has a peaked response with its greatest output at ~1 Hz and thus the electronics are most likely to saturate at frequencies ~1 Hz (Abramovich, personal communication, 1999). The current generation of the PMD sensors do not employ any feedback mechanism but there are plans to use a magnetohydrodynamic feedback system to lower the self noise and to improve stability (see Appendix A).

The first part of the test was to install a pair of PMD sensors (SN #219 and #443) on the seismic pier in the Byerly Seismic Vault (BKS) 5 m SE of the BKS Streckeisen STS−1 broadband sensors and to record their output using a Quanterra Q4128 (SN 981205) 24−bit integer resolution datalogger (2.38 μV LSB). We operated these sensors for a few weeks to record background noise and some seismic events so that the PMD outputs could be compared with each other and the co−sited STS−1's. The second part of the experiment was to measure the linearity of the PMD sensors. The third PMD sensor (SN #218) was received in December 1999 from the Albuquerque Seismological Laboratory after they finished their testing.

The most significant result of the testing was that the PMD sensor signals exhibited non−linear behavior in the form of severe harmonic distortion when the ground velocity exceeded ~200 μm/s at frequencies above ~4 Hz.

Calibration Data.

The factory supplied transfer functions were used for the three PMD sensors. The transfer functions are given in Table 1 and the corresponding velocity sensitivities as a function of frequency are plotted in Figure 1. The BKS STS–1 vertical, for comparison, is also shown in Figure 1. Note the variation in frequency response between these sensors. The response of the seismometer, in units of V/(m/s) is given by:

$$W(if) = 1000 * (if)^4 / [k * \prod_{n=1}^{9} (if - s_n)]$$

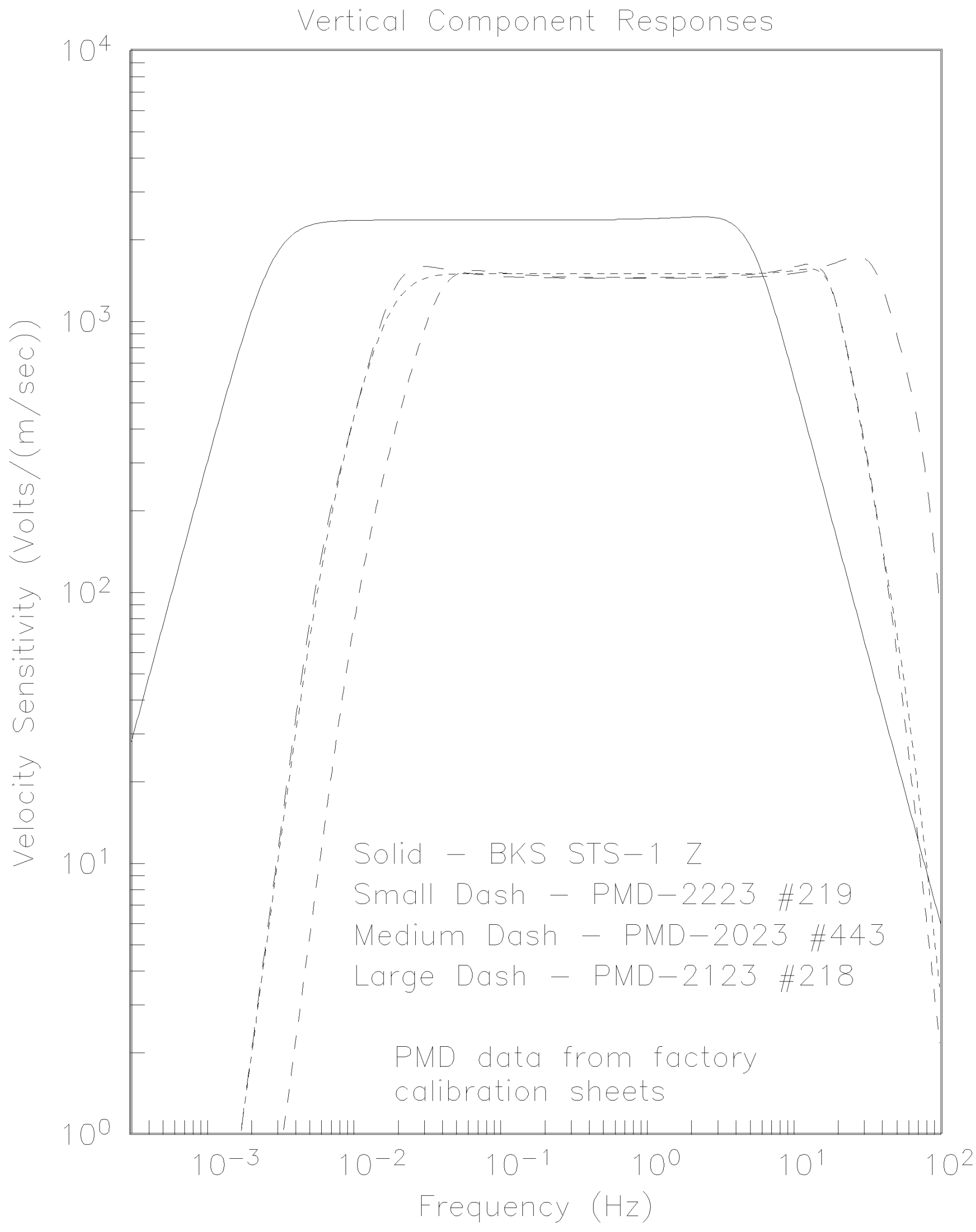
where, from the factory supplied calibration sheets:

Table 1.

	Model 2223	SN #219	Model 2023	SN #443	Model 2123	SN #218
k	3.73237e–8		5.64735e–8		1.85306e–9	
Pole	Real	Imaginary	Real	Imaginary	Real	Imaginary
1	–2.99674e+1	–5.22788e+1	–2.40641e+1	–3.94605e+1	–2.43337e+1	–7.28334e+1
2	–2.99674e+1	5.22788e+1	–2.40641e+1	3.94605e+1	–2.43337e+1	7.28334e+1
3	–1.48290e+1	0.00000e+0	–1.86500e+1	0.00000e+0	–5.05389e+1	0.00000e+0
4	–7.03287e+0	–1.68240e+1	–7.21188e+0	–1.59463e+1	–1.61600e+1	–3.15145e+1
5	–7.03287e+0	1.68240e+1	–7.21188e+0	1.59463e+1	–1.61600e+1	3.15145e+1
6	–1.22599e–2	–1.27948e–2	–2.22905e–2	–3.08886e–2	–1.06472e–2	–1.62447e–2
7	–1.22599e–2	1.27948e–2	–2.22905e–2	3.08886e–2	–1.06472e–2	1.62447e–2
8	–4.14386e–3	–4.62496e–3	–6.48522e–3	–8.73746e–3	–3.06760e–3	–4.68514e–3
9	–4.14386e–3	4.62496e–3	–6.48522e–3	8.73746e–3	–3.06760e–3	–4.68514e–3

The complex pole values vary by a factor of up to approximately three among the PMD sensors.

Figure 1. Transfer Functions



Noise PSD and Response to Seismic Events.

The first part of the test was to characterize the noise floor of two PMD sensors (SN #219 and #443) and their response to seismic events. The vertical−component background noise PSD is shown in Figure 2 for the two PMD sensors and the BKS STS−1 inferred background noise PSD (solid line) is provided for reference. At first the factory supplied scaling constants were used but we discovered that they produced results that differed by up to 1.5 dB from each other so we empirically determined appropriate scaling constants for the PMD sensors so that they matched the microseismic peak noise PSD levels inferred from the STS−1. Note that the PMD sensors only track the background noise in the vicinity of the microseismic peak from approximately 1 second to 10 seconds. At periods shorter than 1 second, the PMD sensor noise is a few dB higher than the background noise and at periods longer than ~15 seconds, the PMD inferred noise PSD levels are dominated by the self noise of the MET sensors. The ~156 dB minimum in the PMD sensor self noise is consistent with the specifications published by PMD (see Appendix B). Note the difference in the PMD noise PSD at a period of 30 seconds. As shown later, this may be an artifact of an inaccurate calibration at low frequencies for sensor #443.

Figure 3 shows the vertical−component absolute ground velocity records, for a M 2.88 earthquake which occurred 126 km SE of BKS at San Juan Bautista, as inferred from the STS−1 and the two PMD sensors. The three traces are highly correlated with only small differences apparent in the visual record. The linear correlation coefficients are:

Table 2. Linear Correlation Coefficients

	STS−1	PMD #443	PMD #219
STS−1	1.000	0.948	0.969
PMD #443		1.000	0.975
PMD #219			1.000

Note that the linear correlation between the two PMD sensors is higher than the linear correlation between either PMD and the STS−1. This is expected given the higher frequency passband of the PMD sensors (see Figure 1) and the high frequencies generated by the small earthquake. For reference, the peak ground velocities, inferred from the BKS STS−1 records, are 5.4 μm/s (Z), 5.1 μm/s (N), and 4.5 μm/s (E).

Figure 2. Background Noise PSD.

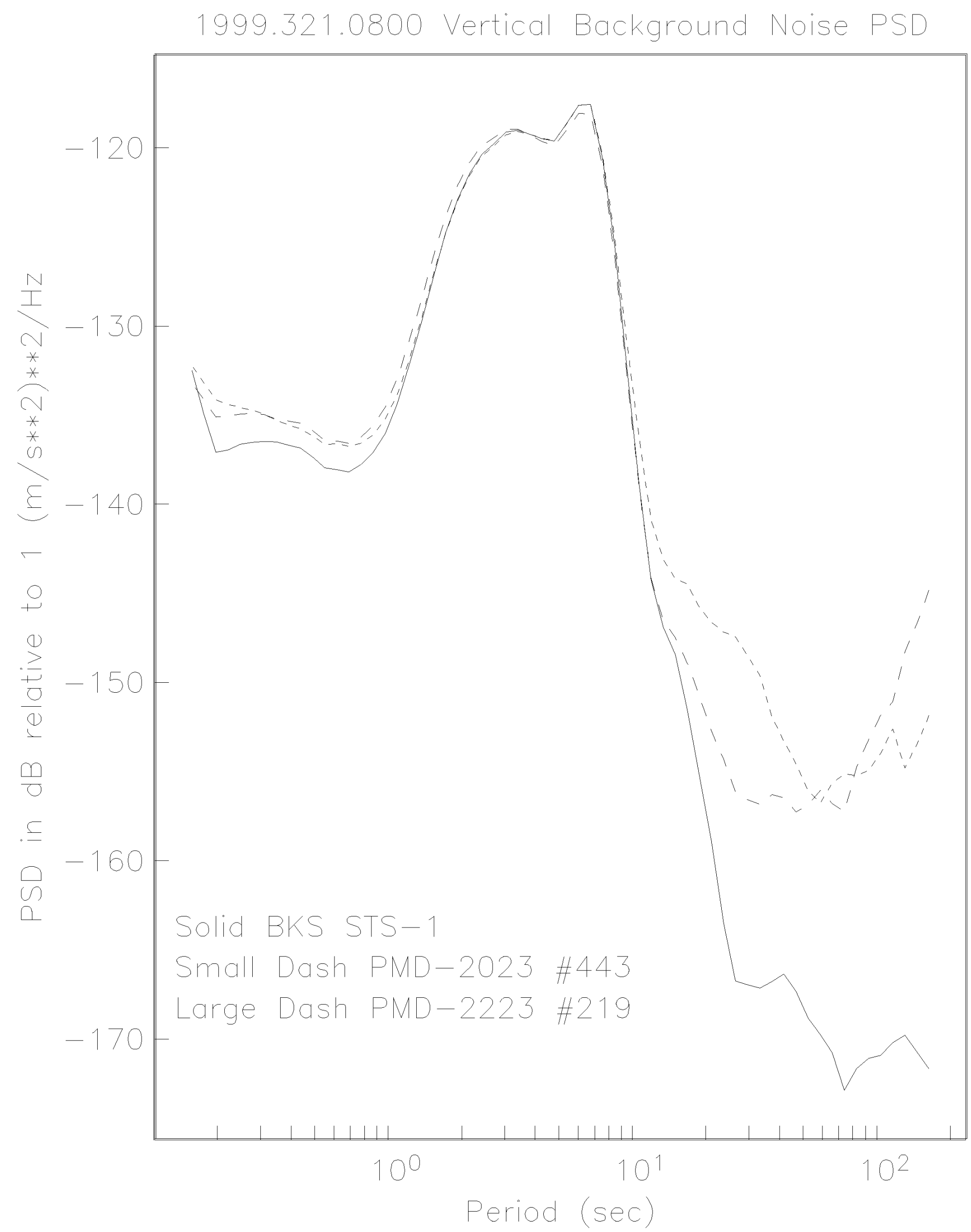


Figure 3. Local Earthquake.

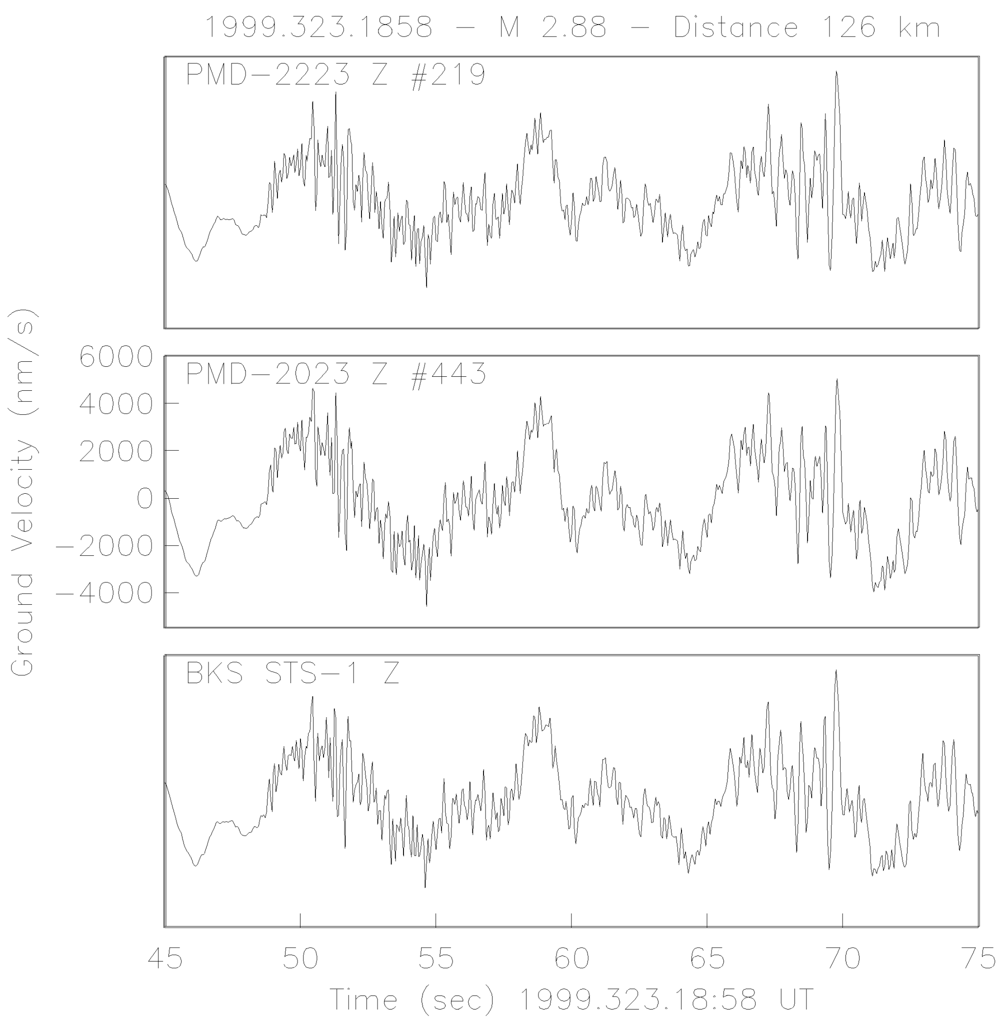


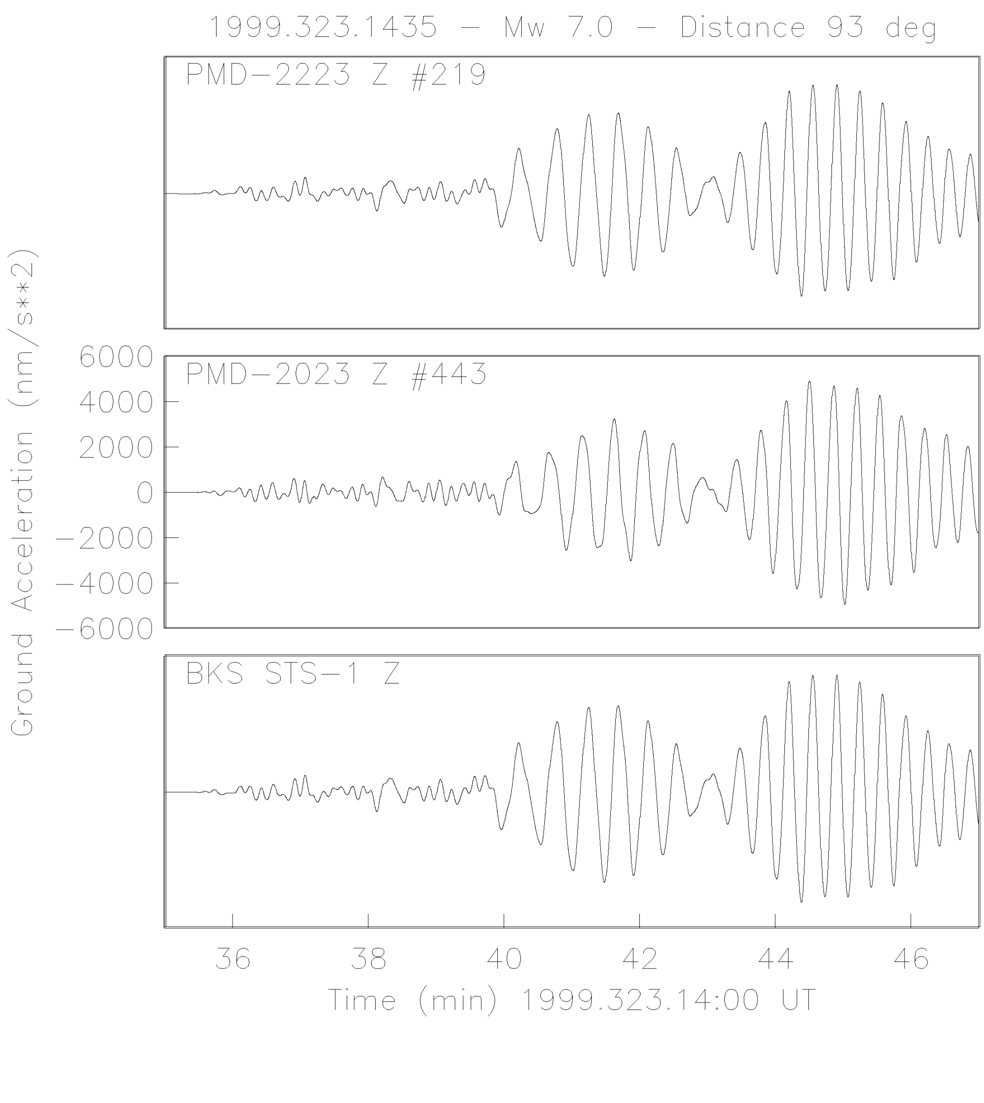
Figure 4 shows the passband filtered (6PBP at 0.01−0.1 Hz) Z−component absolute ground acceleration records, for a Mw 7.0 teleseism which occurred 93 degrees west of BKS in the New Britain of Papua New Guinea, as inferred from the STS−1 and the two PMD sensors. Unlike the case with the traces in Figure 3, obvious differences are visible in the surface waves traces in Figure 4. In particular, the PMD #443 trace exhibits significant differences in both amplitude and phase relative to the other two traces. The linear correlation coefficients between the three traces are:

Table 3. Linear Correlation Coefficients

	STS−1	PMD #443	PMD #219
STS−1	1.000	0.682	0.999
PMD #443		1.000	0.658
PMD #219			1.000

Note that the linear correlation between the PMD #443 sensor and the other two sensors is quite low while the linear correlation between the STS−1 and the PMD #219 is nearly unity. The inference is that the factory supplied transfer function for PMD #443 is inaccurate near the low frequency corner. Figure 1 shows a significant difference in the transfer functions for PMD #443 and the other two PMD sensors at frequencies around 0.03 Hz. For reference, the peak vertical ground acceleration, inferred from the BKS STS−1 Z record, is 5.1 $\mu m/s^2$.

Figure 4. Teleseism.



Linearity and Dynamic Range.

Characterization of the linearity and dynamic range of a broadband seismic sensor is problematic because seismic signals are a wide bandwidth transient phenomena while typical linearity tests utilize a narrow bandwidth continuous signal. One figure of merit that is indicative of the quality with which a seismic sensor can reproduce the ground motion signal is Total Harmonic Distortion (THD). The THD, in percent, is defined as:

$$THD = \frac{\sqrt{\sum_{k=2}^{N} a_k^2}}{a_1} \times 100$$

where: a_1 is the rms level of the fundamental drive signal the a_k are the rms levels of the harmonics that result from non–linear processes in the seismic sensor. Given the difficulties in reliably determining the sum of the a_k's we opted to measure instead the size of the third–order harmonic (a_3) as a function of the sinusoidal drive signal (a_1) and to determine the third–order intercept point. The third–order intercept point, i.e. The projected asymptotic point at which the fundamental and third harmonic signal levels are equal in amplitude, provides a useful figure of merit for the quality of a ground motion signal recorded by a seismic sensor.

The problem of how to shake the PMD sensors in order to test the linearity was solved by constructing a vertical component shake table using a Johnson–Matheson (J–M) Model 6840 short–period vertical seismometer. A platform to hold the PMD sensor and extra springs to support the additional weight were added to the J–M seismometer so that vertical shaking could be induced by actively driving the signal coil. The natural frequency of the resulting shake table was ~1.6 Hz. We found that the shake table could be driven over a useful range of ~50 dB, from ~3.4×10^{-6} m rms (limited by the ~1 Hz background noise PSD level of ~–136 dB at BKS as seen in Figure 2) to ~10^{-3} m rms (limited by the shake table suspension travel), and over a 0.2–5 Hz frequency range by driving the signal coil sinusoidally with a WaveTek function generator. Vertical and horizontal Wilcoxon 731A accelerometers were attached to the PMD sensor housing to directly measure the amplitude and spectral characteristics of the induced shaking. The table and sensors were arranged so that their center of mass was on the center line of the J–M suspension axis in order to minimize cross–axis coupling. The MET transducer has a peaked response with its greatest output at ~1 Hz and thus the electronics are most likely to saturate at a frequency of ~1 Hz (Abramovich, personal communication, 1999). Thus the shake table is a reasonable match for testing the PMD sensors.

After one of the PMD sensors (#218) was installed on the shake table, it was left on the shake table for a few days and a M_L 4.28 earthquake, which occurred in the Geysers area 114 km NW of BKS, was recorded. The resulting record is shown in Figure 5 where the lower three traces are the three components of ground velocity recorded by the PMD seismometer and the upper three traces, given for comparison, are the corresponding components of ground velocity recorded by the BKS STS−1 broadband seismometers. Due to the suspension of the shake table being unclamped at the time, the vertical component PMD trace (BH1) is primarily registering the response of the shake table suspension to the ground shaking while the PMD horizontal components (BH2 and BH3) track the ground velocity inferred from the corresponding STS−1 components (BHN and BHE). This indicates that the J−M seismometer suspension is not being adversely effected by the the added mass of the shake table and the PMD sensor. The amplitude spectra of the vertical component ground velocity recorded by the PMD on the shake table and by the vertical component BKS STS−1 are shown in Figure 6. The ~40 dB resonance peak at ~1.6 Hz is due to the fundamental suspension resonance of the shake table. The smaller peak at ~4.8 Hz is the third harmonic of the suspension resonance and it is ~43 dB below the amplitude of the fundamental. The third−order peak is indicative of non−linear behavior in the shake table suspension and/or the PMD sensor. For reference, the peak ground velocities, inferred from the BKS STS−1's, are 8.9×10^{-5} m/s (vertical) and 1.2×10^{-4} m/s (horizontal).

The methodology for determining the third−order intercept point is shown in Figure 7 where the fundamental and third harmonic output velocities are plotted as a function of the sinusoidal input velocity at a given frequency. Asymptotes are drawn through the fundamental and third harmonic slopes and their intersection is the third−order intercept point. The third−order intercept point for the vertical component on PMD−2123 #218 at a frequency of 4 Hz is 0.000185 m/s or −74.6 dB relative to 1 m/s. Note that at larger input velocity the fundamental and third harmonic velocities deviate significantly from the asymptotes as the sensor saturates. At input velocities of ~0.0003 m/s and higher, the sensor is saturated and the third harmonic signal is actually larger than the fundamental. Spectral analysis of the shake table motion, recorded by a vertical component Wilcoxon 731A mounted on top of the PMD housing, shows that the amplitude of the third harmonic is 70 dB below the amplitude of the fundamental drive signal at an input velocity of 0.0002 m/s. Likewise, spectral analysis of the shake table motion, recorded by a horizontal component Wilcoxon 731A mounted on top of the PMD housing, shows that amplitude of the horizontal shaking induced by non−linearity in the shake table suspension is 50 dB below the fundamental vertical amplitude and the third harmonic amplitude is below the noise floor. Thus the PMD sensor and not the shake table is the source of the observed harmonic distortion.

Figure 5. PMD on Shake Table versus STS−1 Recording of Local Event.

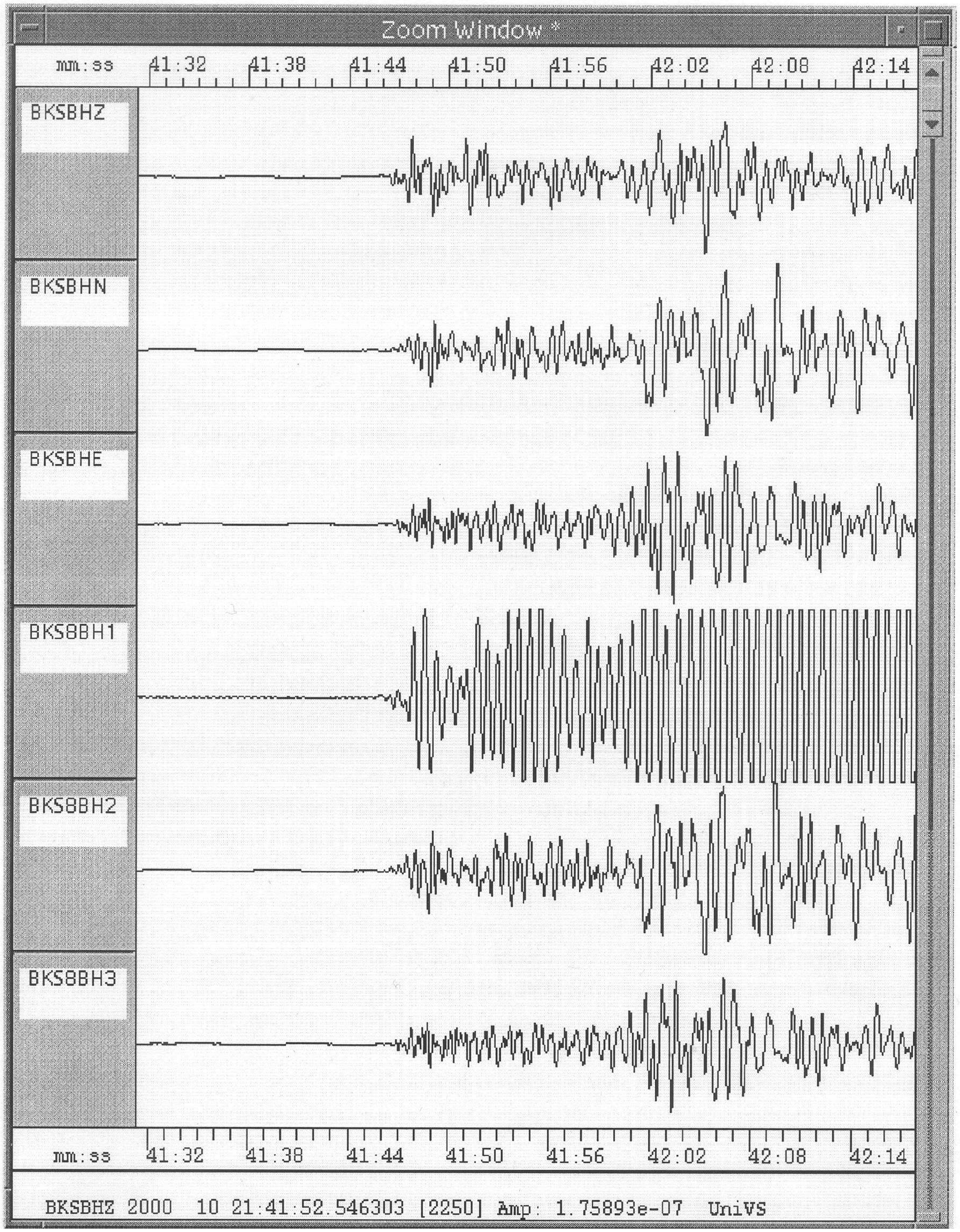


Figure 6. PMD versus STS–1 Z–component Amplitude Spectra.

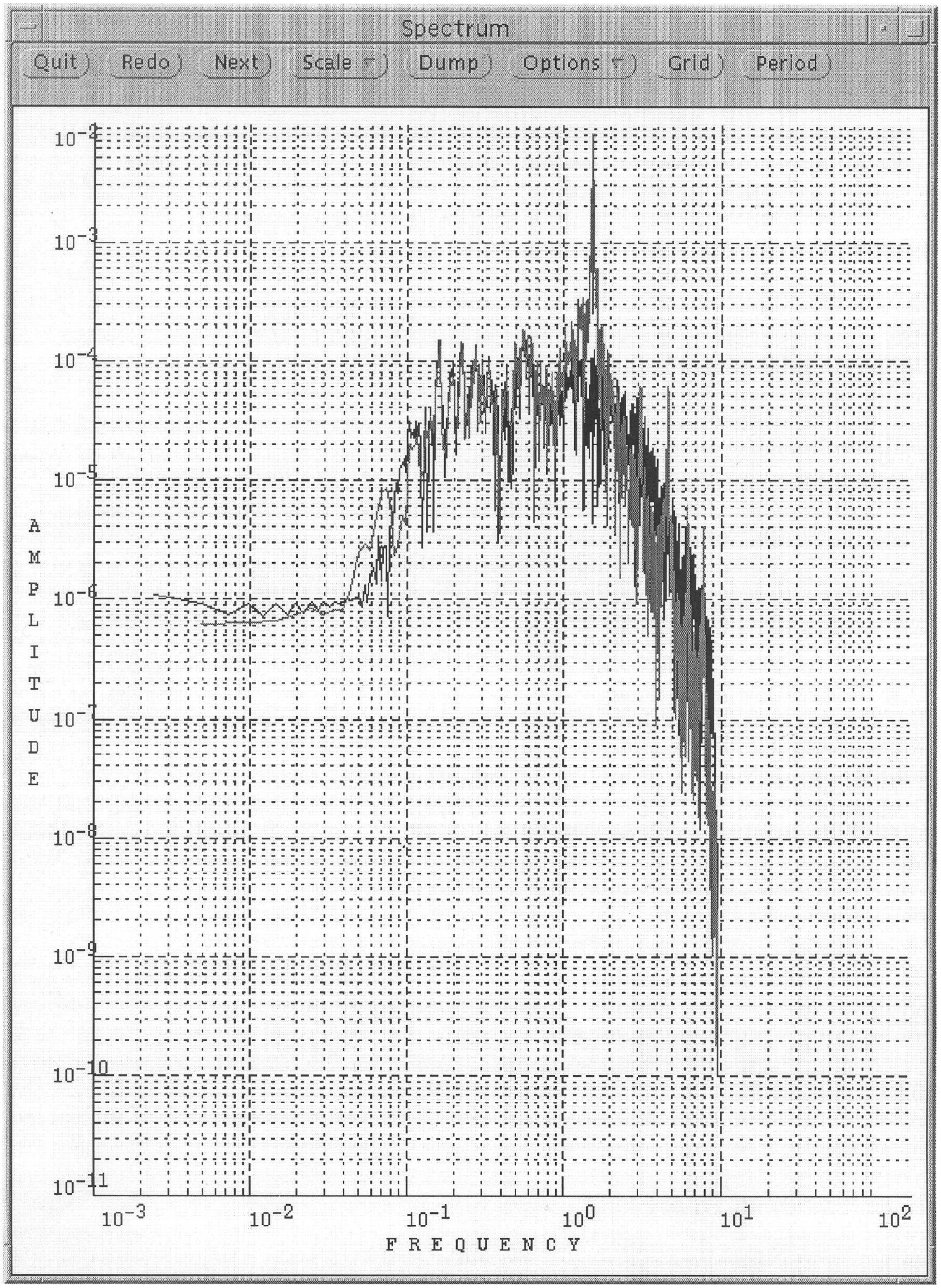
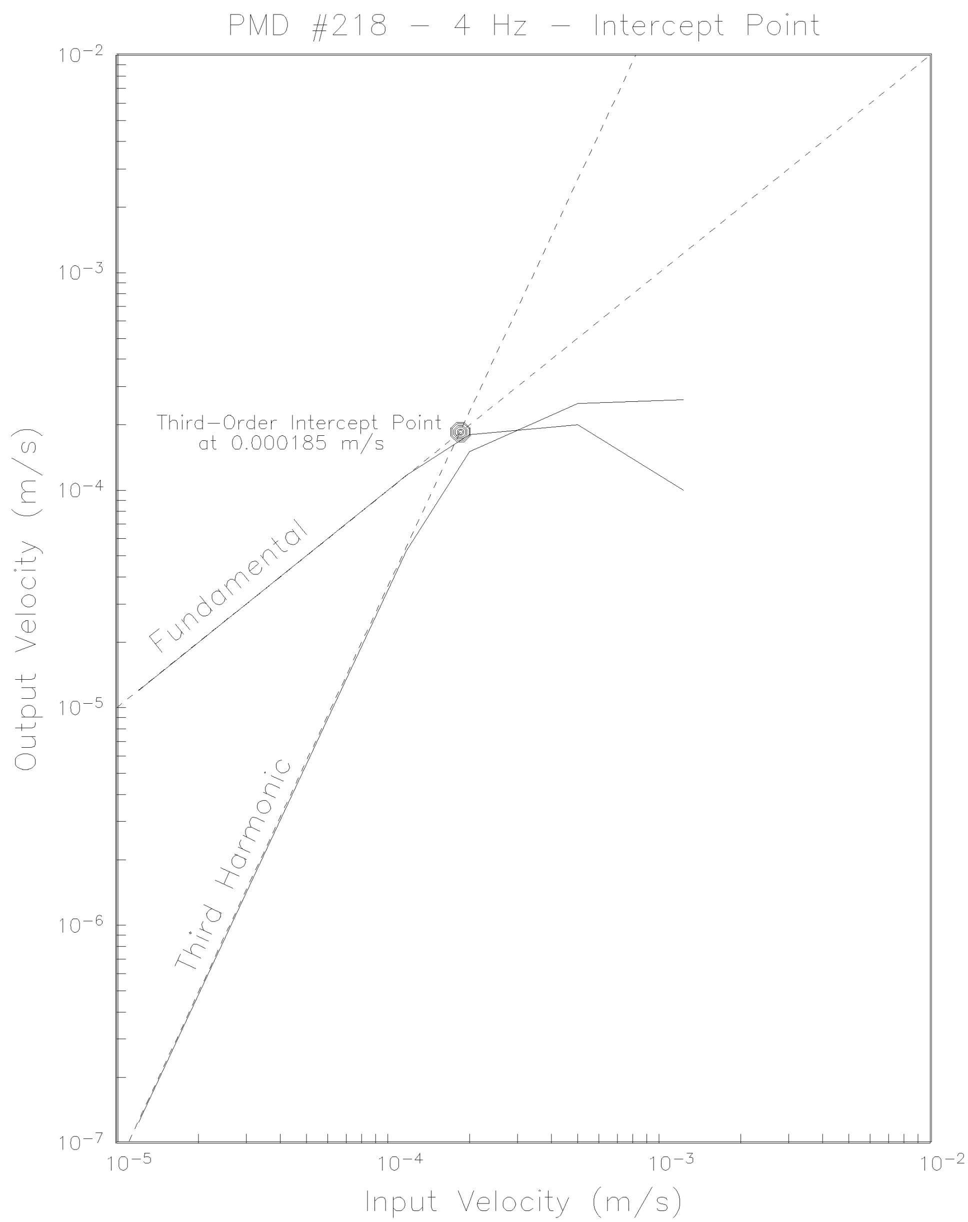


Figure 7. Third−Order Intercept Plot.



Third–order intercept points are given in Table 4. The intercept points are in dB relative to a velocity of 1 m/s.

Table 4. Third–Order Intercept Points for PMD–2123 #218.

Frequency (Hz)	Intercept Point (dB)
0.2	–17.6
0.5	–32.3
4.0	–74.6

The signal clipping level in the PMD electronics is approximately 0.002 m/s or approximately –54 dB. Thus the PMD sensors are limited by the signal clipping at frequencies below ~1 Hz and by harmonic distortion (non–linearities) at frequencies above ~1 Hz. The –74.6 dB third–order intercept at 4 Hz implies that the PMD–2123 #218 vertical component sensor would provide a distorted record when the 4 Hz ground velocity exceeded ~0.0002 m/s. The other two PMD sensors behaved in a like manner.

The –74.6 dB level would typically be exceeded by the following local events in Table 5.

Table 5. Events Producing ~200 μm/s (–74.6 dB) ground velocity at 4 Hz.

Distance (km)	M_L
10	2.7
20	2.9
50	3.8
100	4.2
200	4.7

These M_L versus distance thresholds are more than a magnitude below the typical signal handling capabilities of broadband feedback seismometers which utilize velocity transduction. The harmonic distortion seen in the PMD sensors with MET transducers should be significantly reduced when feedback is employed.

Appendix A. PMD description of the MET sensor is provided for reference.

Improved, Wide-Band Molecular Electronic Seismometer and Data Acquisition System

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How does an MET Transducer Work?

An **MET Transducer Cell** is shown in Fig. 1**.** Spacers *4* with microscopic capillaries are installed within a ceramic tube *1* filled with electrolyte *3*. Thin platinum wires connect electrodes, *5 & 6*, with the external electronics. The electrodes between the spacers are cathodes; the outer electrodes are anodes. The **electrolyte** is a highly concentrated aqueous solution of potassium iodide with a small amount of iodine as an additive. The neutral iodine reacts with the I^- ions producing I^{-3} ions.

When a small dc offset is applied between the anodes and cathodes, the flow of ions of each type is given by the following expression:

$$\mathbf{j}_a = -D \cdot \nabla c_a + q_a \cdot c_a \cdot \mu \cdot \mathbf{E}$$

where D = diffusion coefficient, μ = mobility, c_a = concentration of ions of the type "a", **E** = the electrical field vector. At the electrodes, the reversible chemical reaction $I_3^- + 2e \leftrightarrow 3I^-$, provides a charge transfer over the electrolyte-metal interface.

With a highly concentrated electrolyte, the electric field is non-zero only in a narrow boundary layer adjacent to the electrodes. In this case, the electric current in the absence of electrolyte flow is fully determined by the diffusion.

An acceleration, **a,** along the cell's axis creates a pressure differential, **ΔP,** across the cell, which puts the liquid in motion with a velocity, **v**. This flow of electrolyte entrains ions and causes an additional charge transfer between the electrodes:

$$\mathbf{j}'_a = \mathbf{v} \cdot c_a$$

The cell thus generates an electrical signal in response to an input motion. The symmetric geometry of the cell ensures its linear behavior over a wide range of input signals.

Since it is ionized molecules that *transfer charges* causing the electric current to flow into the external electronic circuit, we call this transducer a **MOLECULAR ELECTRONIC TRANSFER** cell, or **MET**.

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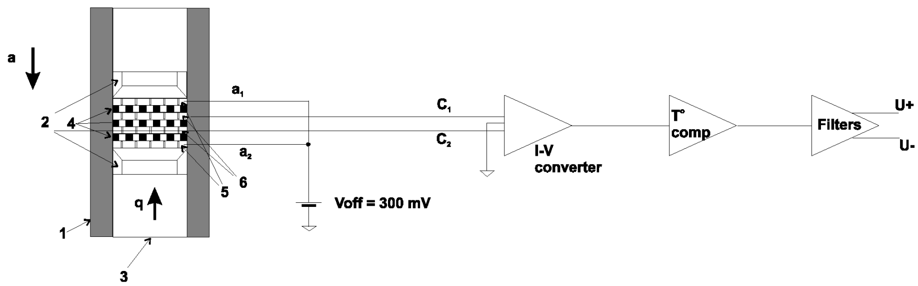
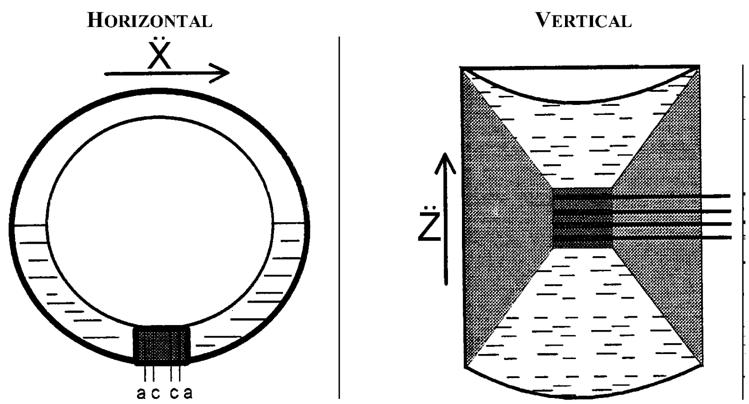
Figure 1: 1 = ceramic channel; 2 = clamping washers; 3 = electrolyte; 4 = microporous spacers; 5 = anodes; 6 = cathodes.



How do MET Seismic Sensors Work?

Figure 2: Vertical and Horizontal MET sensors have different designs :



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