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TECHNICAL REPORT NO. 88-9
TEST REPORT ON THE
MODEL 44000 SEISMOMETER SYSTEM

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ACKNOWLEDGEMENT

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Teledyne Geotech
3401 Shiloh Road
Garland, Texas 75041

August 1988

TEST REPORT

MODEL 44000 SEISMOMETER SYSTEM

Summary

Teledyne Geotech has completed long period subsurface vault tests on four individual 44000 modules; two horizontal and two vertical. Each type of module is tested in tandem by comparing the outputs of aligned sensors. The latest data is outstanding, particularly that of the horizontal. At a period of 20 seconds, both vertical and horizontal channels show incoherent noise power of approximately -180 dB relative to $1 (\text{m/s}^2)^2 / \text{Hz}$. At a period of 64 seconds, the horizontal data is some 20 dB quieter than any previous borehole data and furthermore shows no increase with period, even at periods as long as 250 seconds. This performance is remarkable for a non-borehole installation. The vertical data shows excellent performance, although some temperature effects seem to be present. A detailed explanation of the experimental history and current tests follows.



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1. HISTORY OF THE 44000 SEISMOMETER TEST

1.1 BOREHOLE NOISE PERFORMANCE

After final borehole tests in 1985, we realized that the 44000 seismometer suffered from two major difficulties: (1) long period horizontal noise and (2) short period vertical noise. The long period horizontal noise was characterized by high offset drift rates in the time series data. This time behavior translated to noise frequency spectra that increased with increasing period (decreasing frequency). Figure 1-1 shows the typical noise performance for the 44000 in a borehole at the Sandia Facility for Acceptance, Calibration and Test (FACT). Note that the horizontal incoherent noise power rises at close to 10 dB per decade for periods greater than 1 second. Compare the vertical noise spectrum for the same test. At periods greater than 10 seconds, the vertical channel is approximately 20 dB quieter than the horizontal channel.

In comparison with another high quality long period seismometer, the 44000 horizontal shows its long period weakness. Figure 1-2 depicts spectral data from the 44000 seismometer and the Seismic Research Observatory (SRO) instrument (Teledyne Geotech Model 36000) at the Albuquerque Seismic Laboratory (ASL). While the two seismometers compare favorably at periods from 10 to 20 seconds, the 44000 horizontal is in excess of 20 dB noisier than the SRO seismometer for periods in excess of 40 seconds. The 44000 horizontal was plainly inadequate as a high resolution long period seismometer.

The 44000 vertical also did not perform as hoped. Instead of long period noise problems, the vertical channel produced excessive noise at short periods. The time series of a 44000 vertical channel shows unpredictable impulsive spikes. See figure 1-3 for a comparison of three vertical channels. Note that one channel shows a "spike" at various times that neither other channel reflects. This spike translates to unpredictable increases in noise spectra, depending upon whether the sampled interval contains a spike

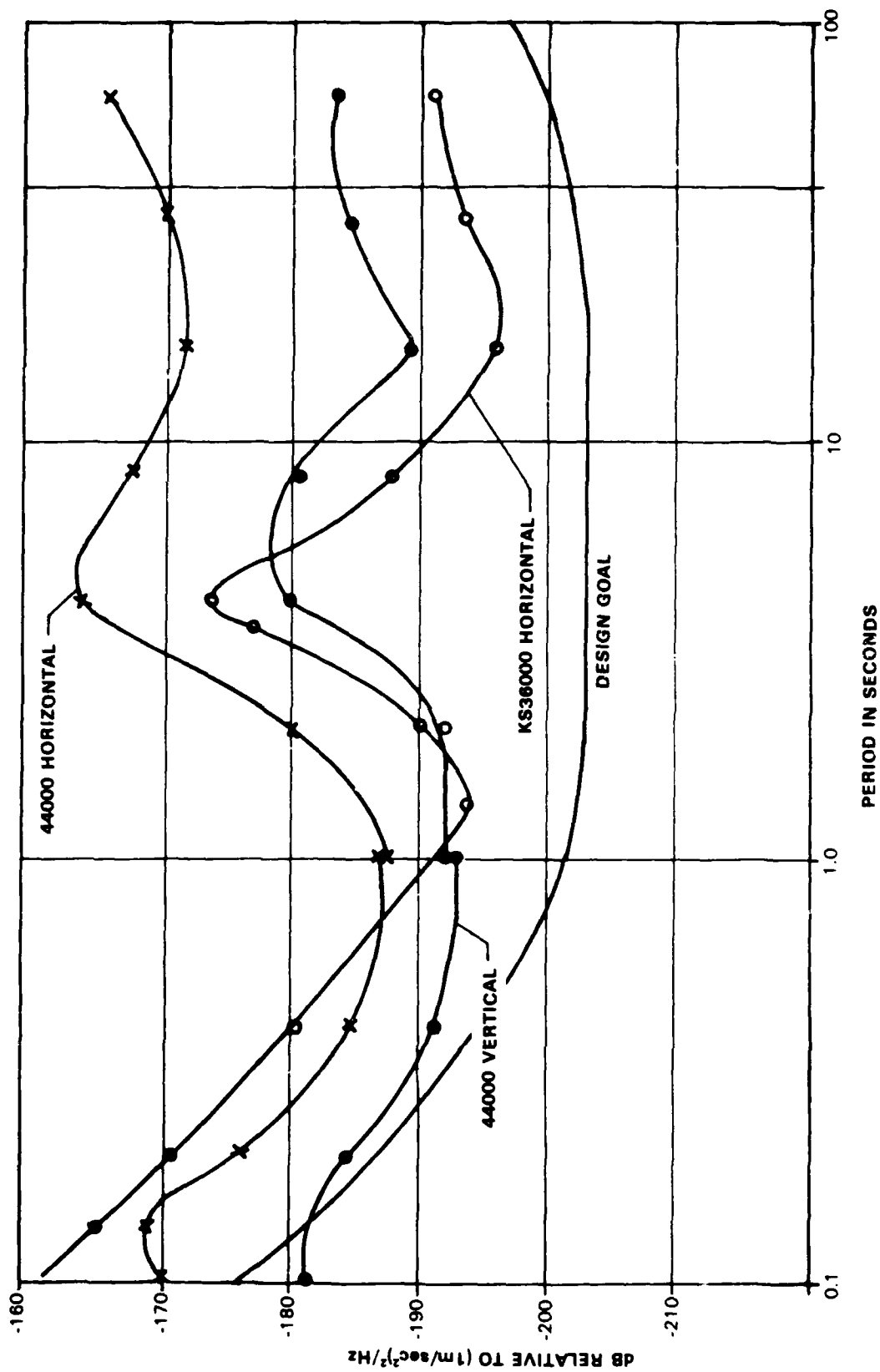


Figure 1-1. Sandia FACT Site Test Summary

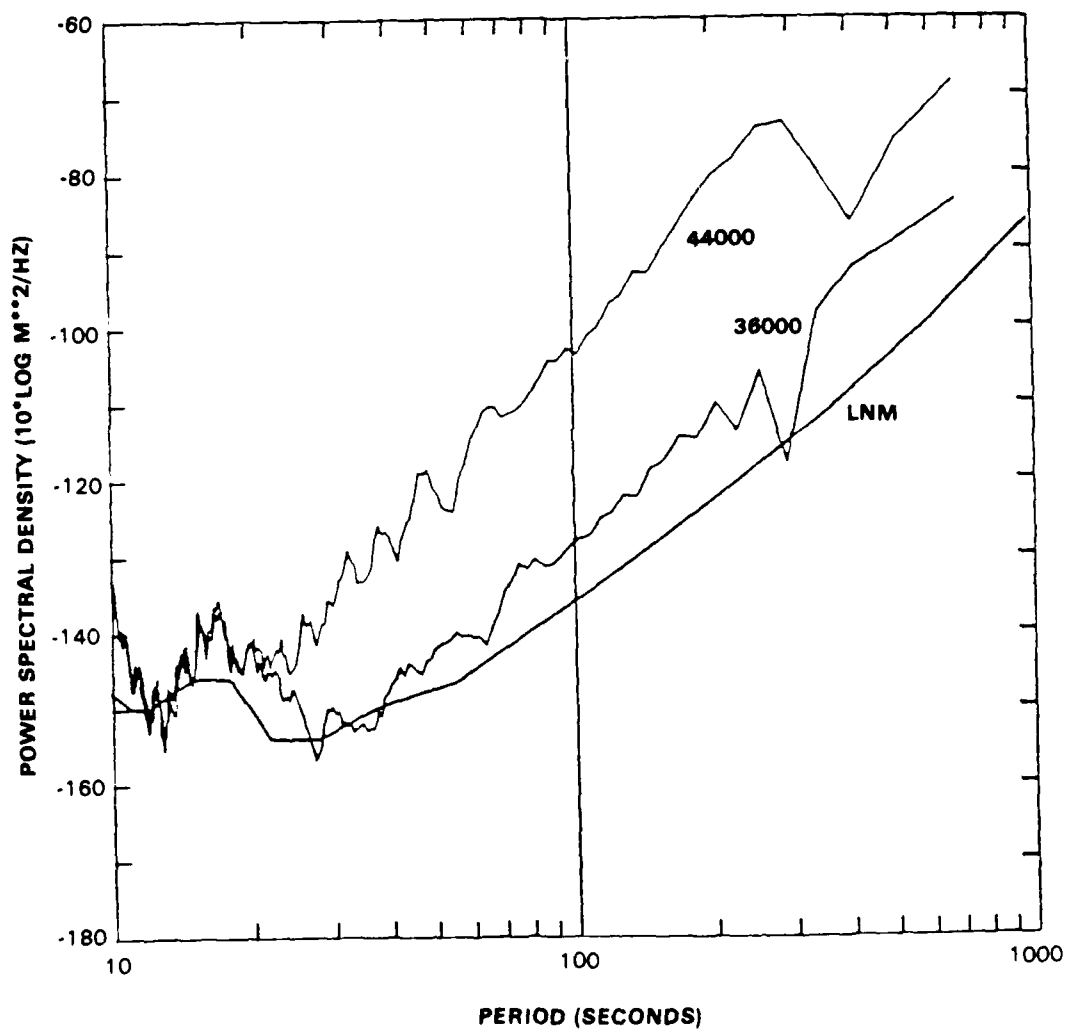


Figure 1-2. 44000 North vs. 36000 North (SRO) ASL

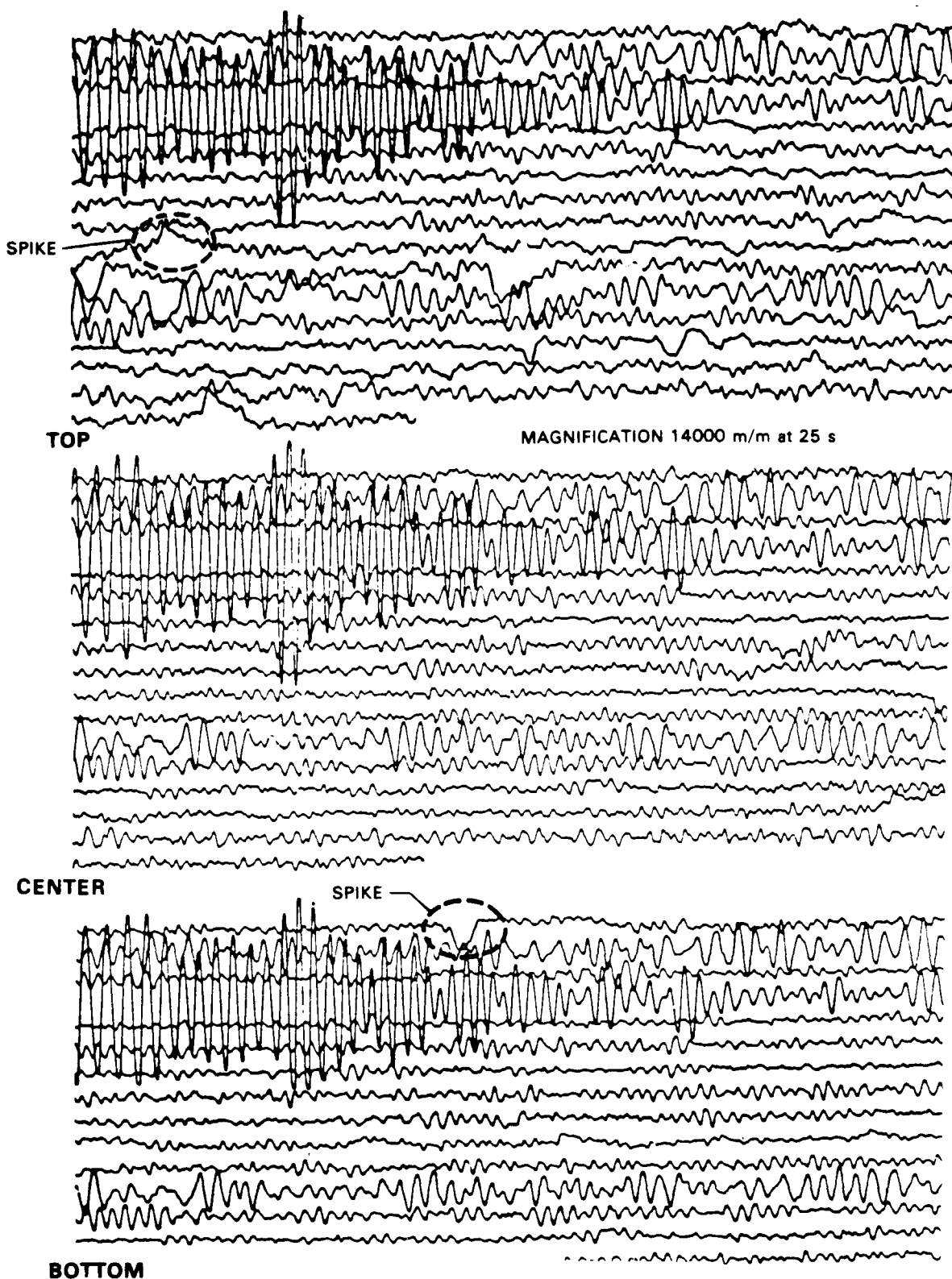


Figure 1-3. Triple Vertical LP Record

or not. Obviously, one cannot count on events of interest occurring only during spike-free intervals.

The 44000 vertical, however, performs well at long periods. Figure 1-4 shows the SRO vertical and 44000 vertical power spectral densities. Note the similarity in amplitudes at all measured frequencies. We knew that if we could solve the noise "spike" problem, the 44000 vertical would serve well as a high resolution long period seismometer.

1.2 NOISE SOURCES

1.2.1. Vertical

We believe that the module suspension causes the vertical noise. Figure 1-5 shows a cross section of the 44000 vertical module. The proof mass moves linearly (no pivot points) with a helical spring counterbalancing the gravitational force. This spring is one of the critical differences between the horizontal and vertical modules. Since the horizontal modules show no noise spikes, we believe the vertical spring-based suspension is the vertical noise source. This theory comports with spring related problems we have experienced in the past with the 36000 vertical module.

The vertical noise impulses are characteristic of materials defects or spring termination imperfections. A polycrystalline material, like the 44000 vertical spring, has many crystal boundaries. Microcracks are often located at these boundaries. Further cracking at these interfaces causes a small shift in the total spring length. This shift is impulsive in time and has an essentially white noise spectrum for frequencies small in comparison with the reciprocal of the time it takes for the crack to form. Hence, small cracking events may produce the observed spikes in the seismometer output time series.

Spring termination may also be the culprit. As the spring stretches or contracts, this force is transmitted to the ends of the spring. Each end of

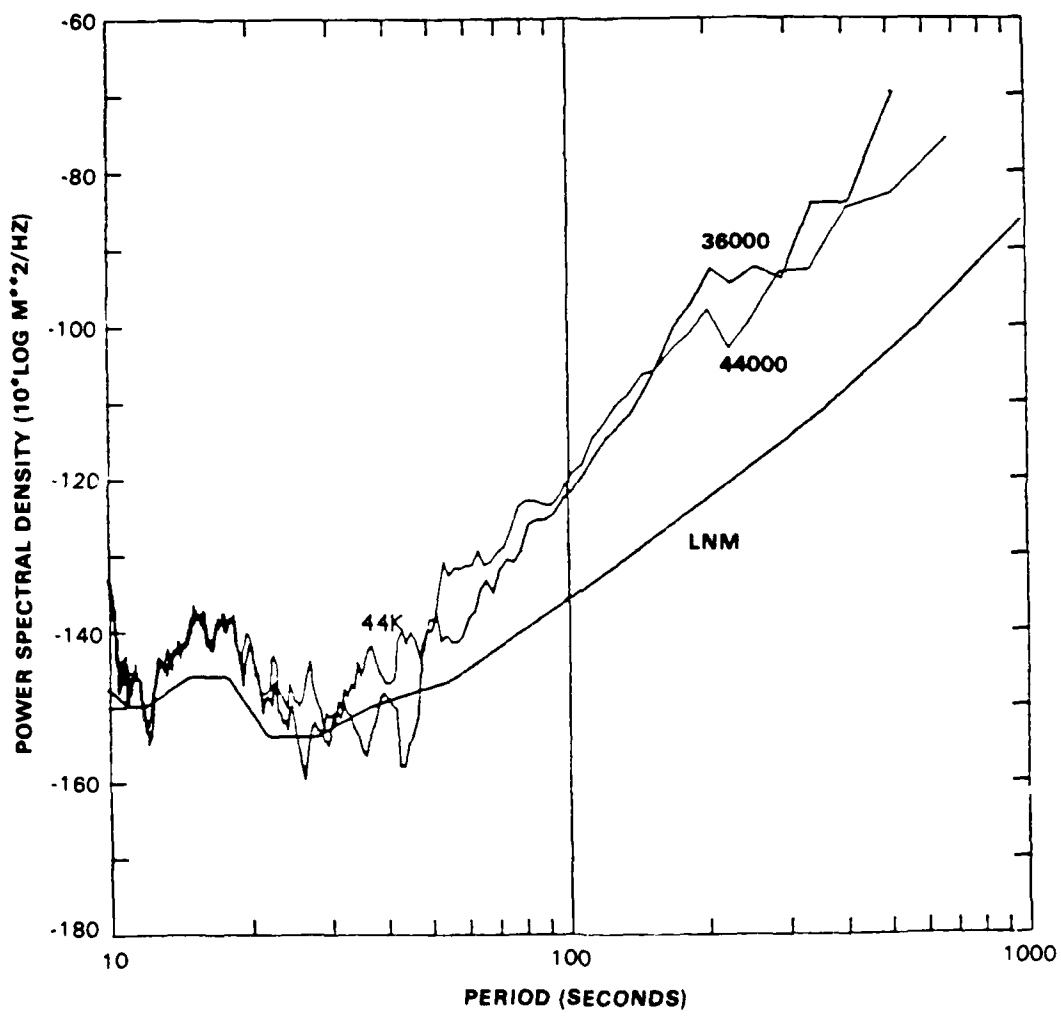


Figure 1-4. 44000Z vs. 36000Z (SR0) ASL

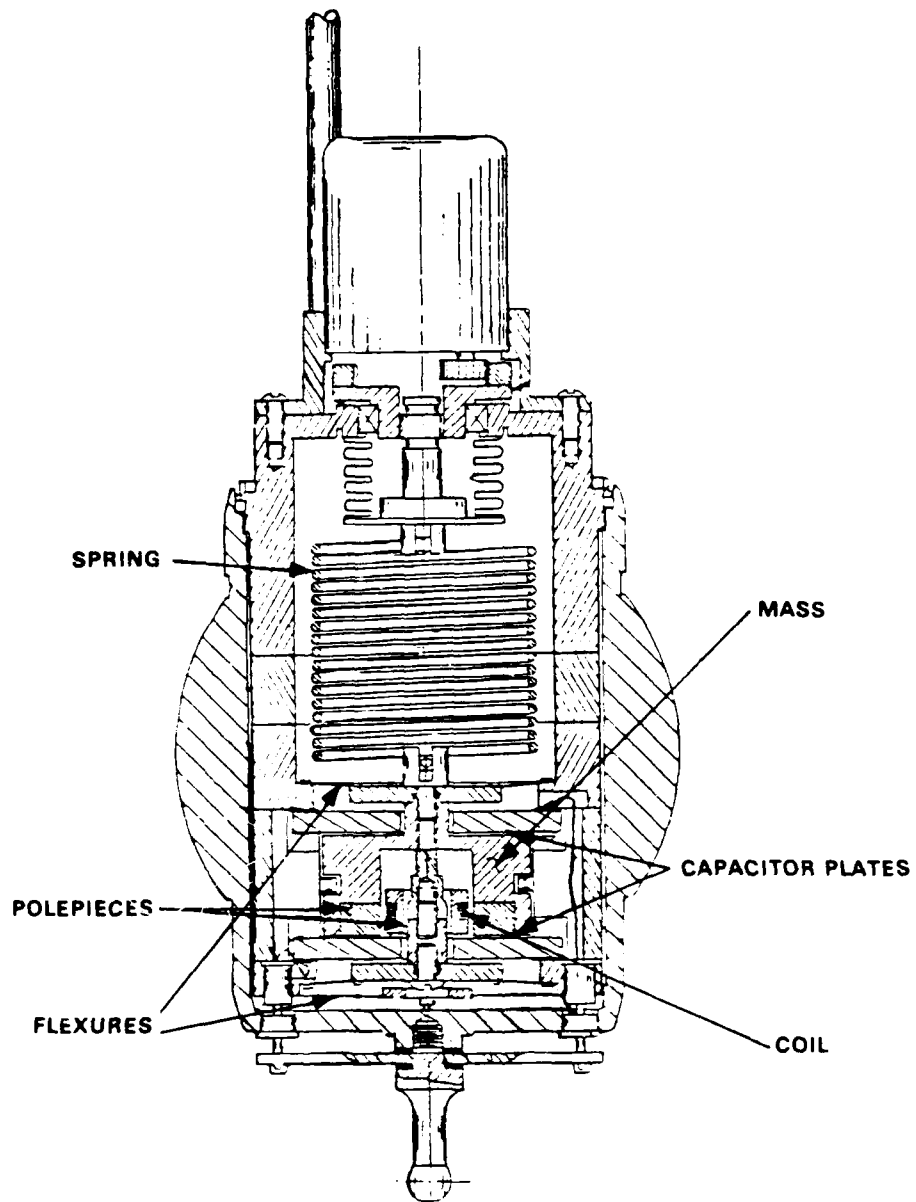


Figure 1-5. 44000 Vertical Module Cross Section

the spring is attached to an adapting terminator, which in turn connects to the frame at one end and proof mass at the other. The transmitted force has both linear and torsional components. The spring end tries to twist in the terminator as the spring length changes. If this torsional force builds up and then the spring suddenly twists a tiny amount, this will cause an impulsive change in the overall length of the spring. Like the microcracking, this will produce a spike in the seismometer output.

The forces and distances are tiny: generally less than 10^{-8} meters. It is difficult to abstractly visualize the processes at work. The closest real-life analogy is a garage door with a counterbalancing spring. When opening a garage door, the helical counterbalance spring often "pops" during the process. The theoretical 44000 vertical noise process is similar, although on a vastly smaller scale.

The tests we have performed at Garland are long period and do not effectively address this potential noise source. We feel that the cost in changing design and/or material of the vertical module internal parts is prohibitive, especially considering the time and money constraints for this follow-on work. The test data discussed in section 3 reflects this decision.

1.2.2 Horizontal

We believe that the horizontal noise is caused by a form of creep. This creep causes a time dependent tilt of the module with respect to the mechanical stack. The horizontal module shows creep noise more than the vertical since any tilt causes gravity to become part of the horizontal signal. While the vertical module is also sensitive to tilt, this sensitivity is second order in comparison to the horizontal module's sensitivity. The vertical module thus shows much less long period noise than the vertical module.

The 44000 module has an integral 2.5 inch spherical surface, which is used to hold the module in the mechanical stack. See figure 1-6 for a cross section of the module. The module's spherical surface contacts a conical seat ring

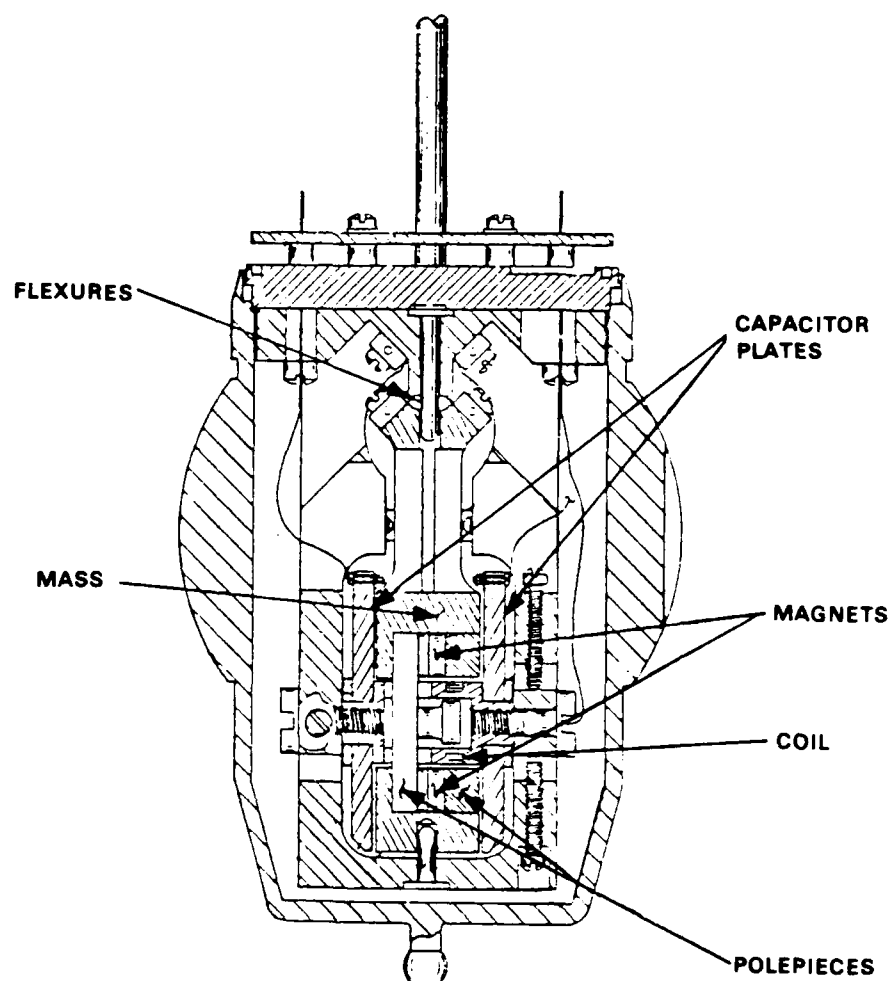


Figure 1-6. 44000 Horizontal Module Cross Section

in the mechanical stack. Another conical ring, directly above the seat ring, is spring loaded and also contacts the module. See figure 1-7 for a simplified diagram of the current module-to-mechanical stack interface (seat) design. To level the module, the leveling assembly slides the module relative to the conical seat until the module's center axis is aligned with the local gravity vector. After the leveling process, the leveling mechanism backs away from the module to remove any further force from the module. Instead of staying in position, however, the module slowly slides or creeps with time along the surface of the seat ring. Any force tending to push the module away from its initial position increases this creep rate. Furthermore, any significant vertical forces temporarily reduce the gravitational force of the module seat against the ring. Since the sliding surfaces thereby have a momentarily smaller contact force, they slide across one another more quickly. Thus, high vertical background signal, including high frequency vibrations, increase the creep rate.

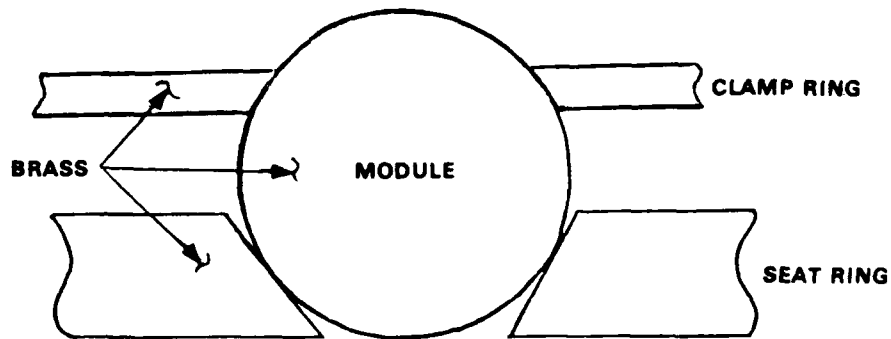
The spring-loaded upper clamping ring can add to the overall creep rate. As the module slides during the leveling procedure, the clamping ring's sliding friction causes the ring to move along with the module until the force applied by the leveling mechanism overcomes this friction. Even after the leveling procedure, the spring on the upper clamp ring will tend to force the module in the direction opposite to that moved in the last leveling operation. This nonzero force will therefore induce a sliding creep.

We believe the solution to the 44000 horizontal noise lies in reducing the tendency of the module to creep relative to the seat ring. Our approach in the tests that follow relies upon reducing the forces tending to push the module away from the leveled position. While material and design changes might also be effective, we felt that identification of the noise source at a low cost was the appropriate first step.

1.3 Testing At Sandia Facility for Acceptance, Calibration and Test (FACT)

Teledyne Geotech has performed little work on the 44000 borehole seismometer

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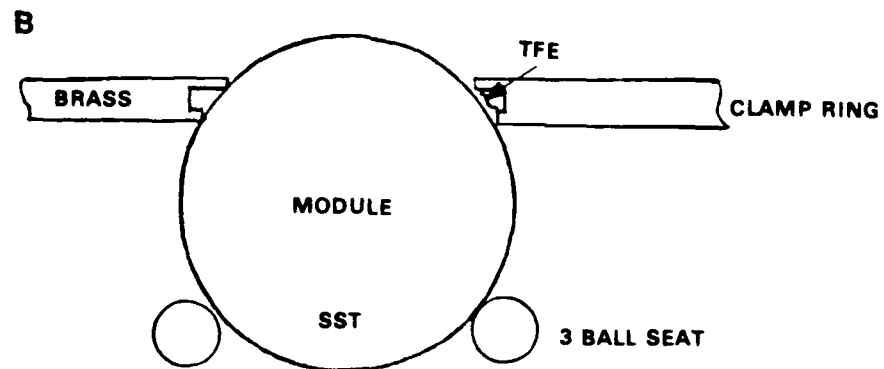
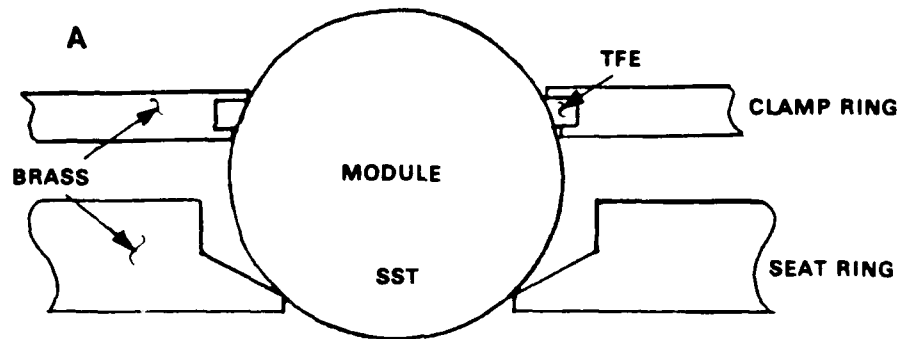


Figure 1-7. 44000 Module Seat Options

test project since the spring of 1985. The 44000 seismometer system has not performed as hoped, particularly at long periods (periods greater than 5 seconds). As noted above, this long period noise is particularly prevalent on the horizontal axes.

In order to identify the long period horizontal noise sources, Geotech devised a five step test plan to identify suspected noise sources. This plan involves a series of different configurations set up in a subsurface vault, rather than a borehole. The steps are briefly outlined below:

- Step 1: Mechanical stack, without steel cover, set up on test stand in vault to provide baseline data.
- Step 2: Loop parameter changed in electronics to provide minimum electronic noise, mechanical setup unchanged.
- Step 3: Each element of mechanical stack broken down and individually mounted to pier in vault. The only other change from step 2 is removal of the spring-loaded upper clamp ring on each module. A fourth module (vertical) added to provide two channels of vertical and horizontal data.
- Step 4: Each element removed from its stack mounting location and leveling mechanism. The four modules will be placed in a common metal plate and leveled as a unit.
- Step 5: Similar to step 4, except that each module will be leveled in a bed of anhydrous, uniformly sized sand or glass beads.

The basic premise of this test plan is that the excessive horizontal noise results from the module to stack interface, namely the brass module sliding along the sintered bronze seat. Thus, the test plan involves several changes in element mounts.

Geotech, with the cooperation of Jim Durham and George Patton at Sandia National Labs, substantially completed steps one through three at the Sandia Facility for Acceptance, Calibration and Test (FACT) in Albuquerque, New Mexico. The most notable aspect of the data is a comparison of the stack

baseline and the separated modules without clamp rings. Figure 1-8 shows spectral data for the modules in the stack and for separated modules at periods from .1 second to 100 seconds. At periods greater than 10 seconds, the separated modules perform significantly better than those in the stack. At 50 seconds, for example, simply removing the clamp ring and placing the modules separately on the vault floor reduced the incoherent noise by 10 dB.

Figure 1-9 compares the separate module data with FACT borehole data on the same modules. Note that even in the vault, without the protective environment of casing and borehole, the noise levels are very similar. Such a significant change in noise for a small change in experimental setup was promising. We believe this data supports the seat noise source theory. As the Garland data shows, we have further reduced the horizontal noise by avoiding creep-inducing forces.

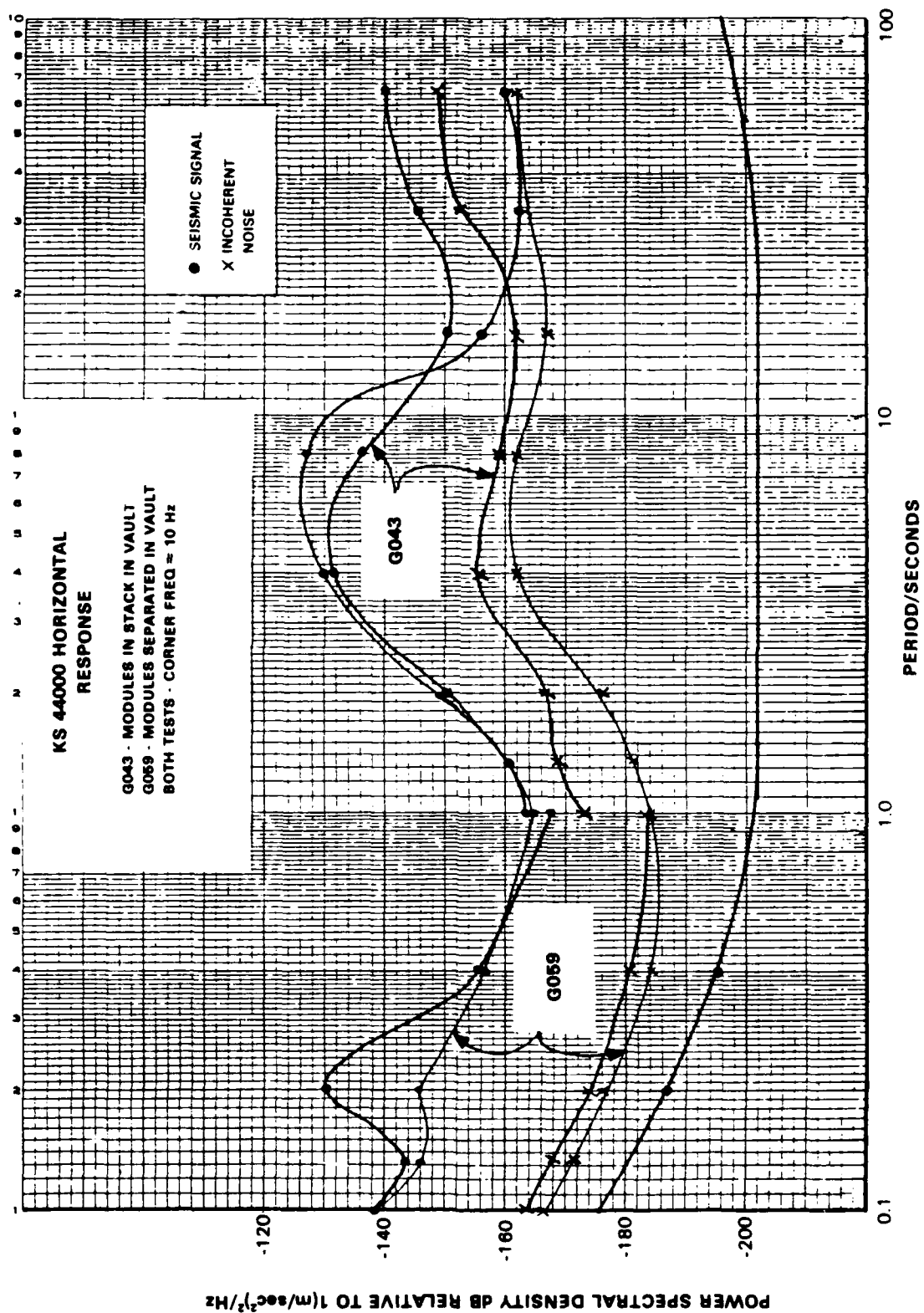


Figure 1-8. Comparison of 44000 Modules In the Stack and Modules Separated

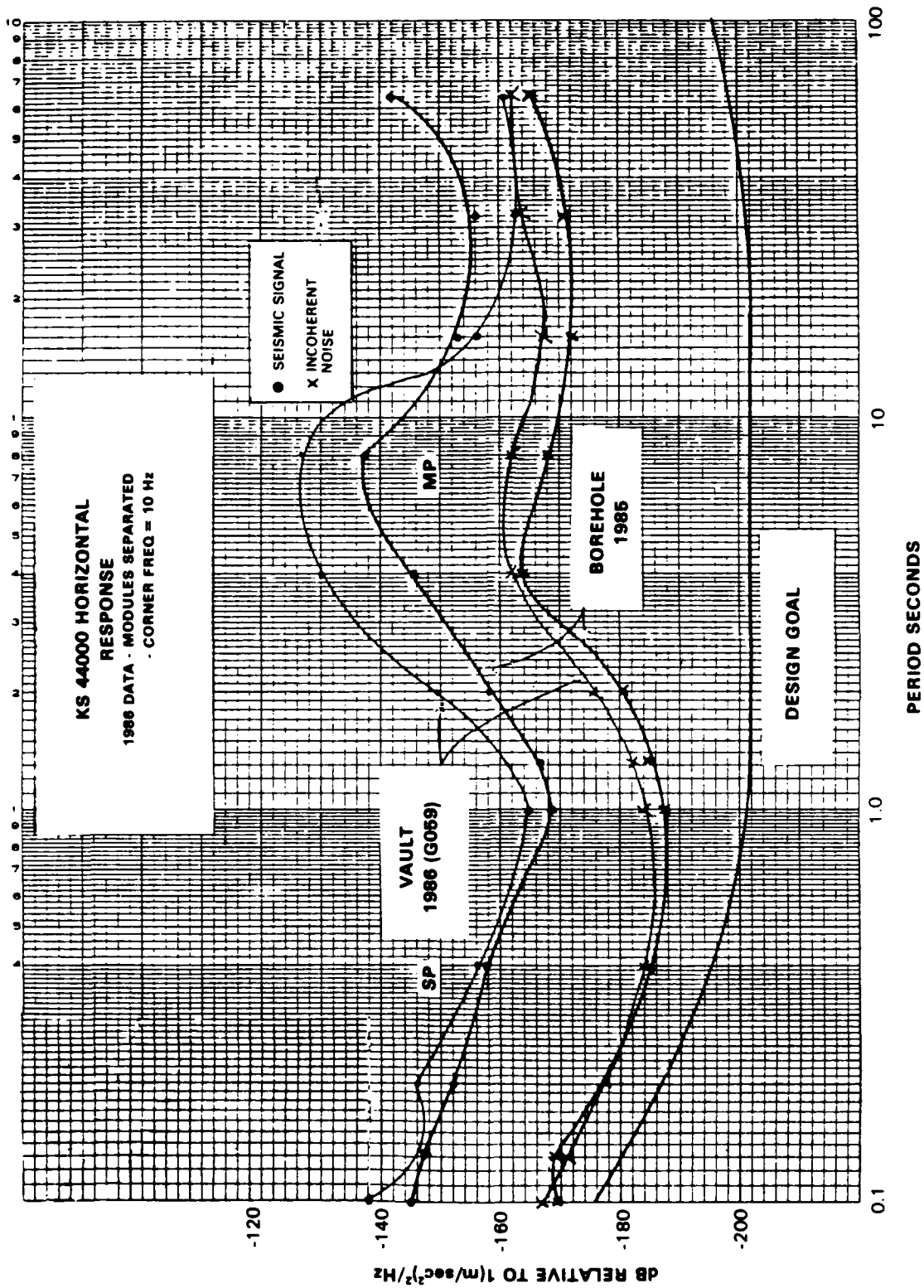


Figure 1-9. Comparison of 44000 Separate Modules With Borehole Installation

2. CURRENT TESTING

2.1 CONFIGURATION AND EQUIPMENT

We have recently duplicated the step 3 configuration at our Garland, Texas facility. Each seismometer element is securely bolted to a plate which is in turn grouted to a pier in our underground test vault. The horizontal element's sensitive axes are aligned, as are the vertical axes. We ran into some difficulty at the setup stage, as the horizontal module damping had increased to unacceptable levels (the modules, now over four years old, contained excessive gas). We simply pumped the modules down to high vacuum and baked them out again.

The modules and loop electronics are each set up with a nominal loop gain of 2×10^4 V/m/s² from dc to 4.0 Hz. This gain, while slightly low, is suitable for the higher short period background at Garland. Significantly higher gain causes leveling, drift and clipping problems.

In the results reported below, we have performed no magnetic, electrostatic or temperature shielding other than what the vault naturally provides. The dramatic improvement in the horizontal data is so outstanding that we feel that there is no benefit to be gained in carrying out steps 4 and 5 of the original plan, and that immediate analysis and reporting is appropriate.

Above the vault, the broadband seismic data passes through long period filters and on to helicorder records. The filtered data also goes to our data acquisition system.

The data acquisition system is centered around an 8 channel, 16-bit, analog to digital converter. The software oversamples the data and digitally filters and decimates down to one sample per second. We then analyze the data via DADiSP™. The coherence estimate is based upon the technique explained in

Samuel D. Stearns, Application of the Coherence Function in Comparing Seismometers, Sand 79-1633 (December 1979) [especially equations (5), (7), and (11)].

2.2 RESULTS

2.2.1 Vertical

Figure 2-1 depicts the time series for a pair of vertical modules in the early morning hours of March 23, 1988. The differences between the signals is noticeable, as the coherence measurement of figure 2-2 quantitatively shows. Figure 2-3 contains the auto spectrum and incoherent noise estimate for channel one.

For frequencies above 0.08 Hz, the incoherent power is comparable to that of the borehole data. Compare figure 1-1 to figure 2-3. The longer period data increases with period, however, reaching a peak of approximately -160 dB re $1 \text{ (m/s}^2\text{)}^2 \text{ /Hz.}$ at periods in excess of 50 seconds. As the time series for these calculations is 512 seconds long, the frequency data extends down to approximately 0.004 Hz.

The long period noise on the vertical channels is somewhat troubling, but probably results from the non-optimal installation in the vault. The borehole environment has more temperature stability and the package is filled with helium to prevent convection. The vault has a much lesser degree of thermal stability and the air can support convection. The 44000 spring in the vertical module may therefore simply be sensing these temperature changes.

Environmental variation can also influence secondary long period noise processes in the mechanisms discussed for the vertical suspension.

Microcracking can produce a long period spectral component. The data does not show the typical spikes that we have noticed before. We feel confident,

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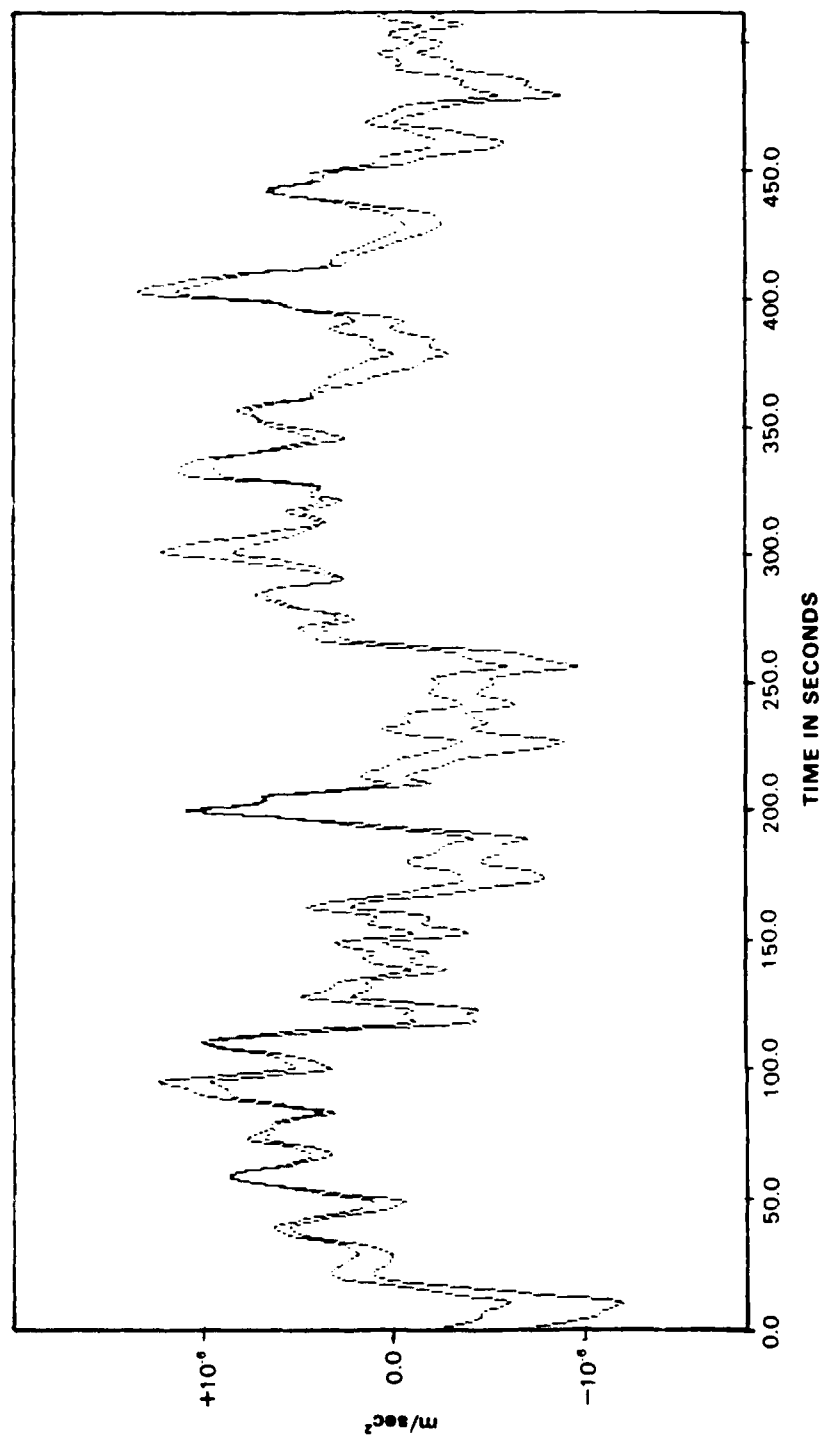


Figure 2-1. Comparison of Two 44000 Vertical Modules

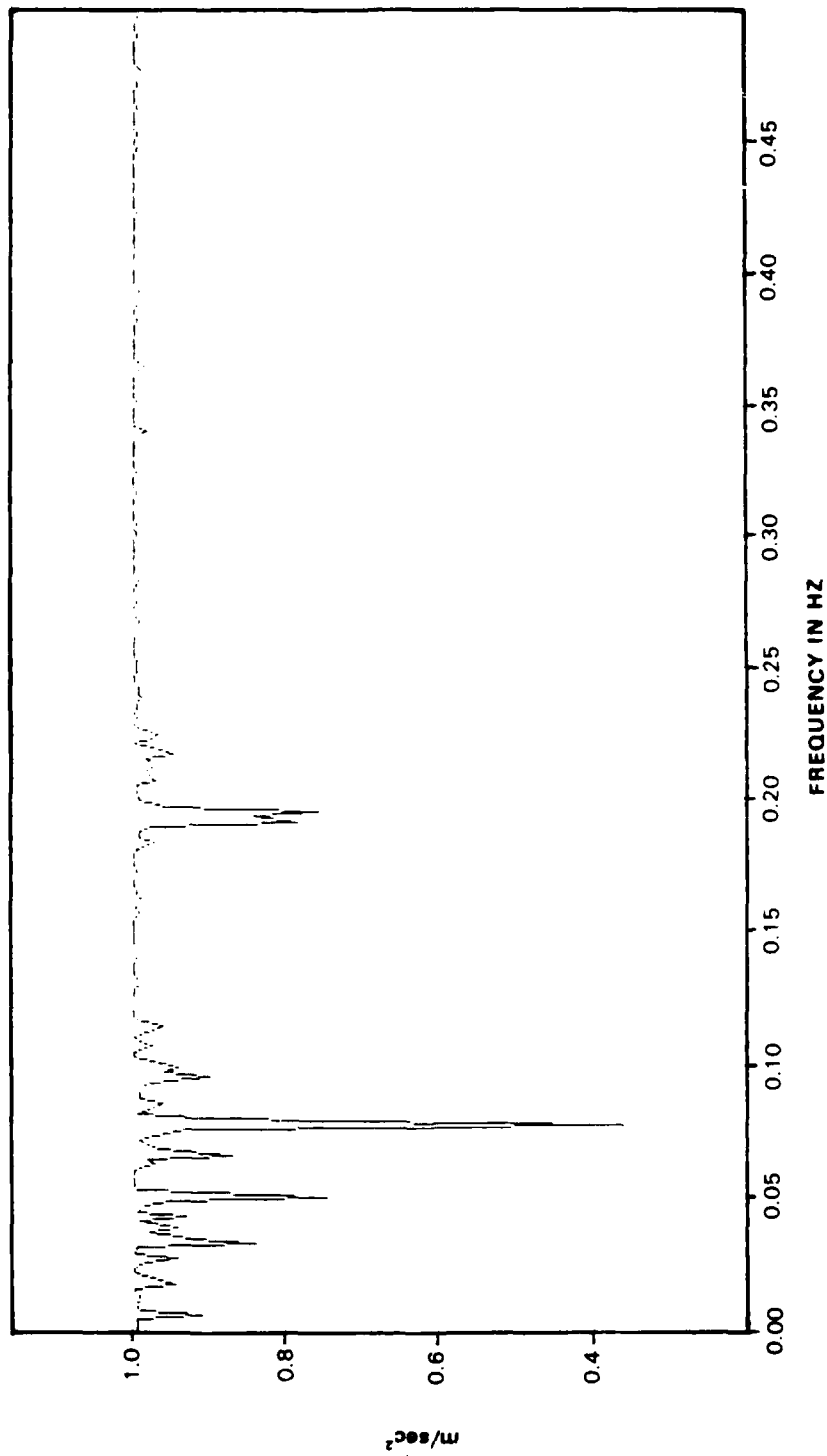


Figure 2-2. Coherence of Signals in Figure 2-1

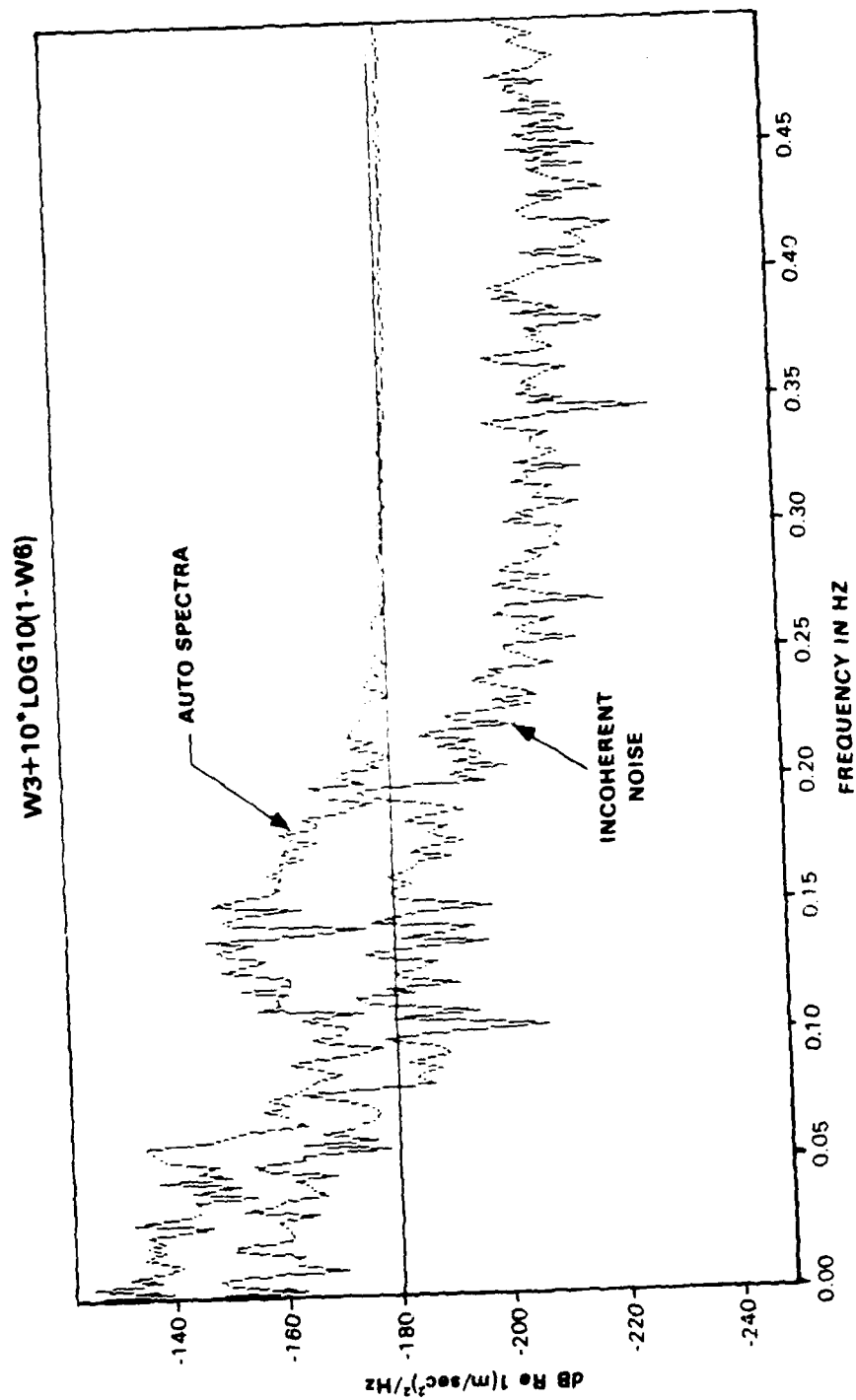


Figure 2-3. Autospectra and Incoherent Noise Estimate of Vertical 44000
in Vault Test At Teledyne Geotech, Garland, Texas

therefore, that the vertical noise is a function of this particular installation.

2.2.2 Horizontal

The horizontal performance has dramatically improved over any we have measured before. Figure 2-4 shows time series data taken during the early morning hours of March 26, 1988. The two channels overlay almost perfectly, as the long period coherence in figure 2-5 quantitatively shows. The incoherent noise is no greater than -180 dB relative to $1 \text{ (m/s}^2\text{)}^2/\text{Hz}$ from .004 Hz to 0.5 Hz as shown in figure 2-6. At 100 seconds, this surface data at the Garland site is over 70 dB quieter than the 1985 borehole data at ASL. The Garland noise data at 64 seconds is some 20 dB less than any ever taken at FACT (see figure 1-1) and, more importantly, shows no increase with period. The earth background during these tests is approximately equal to the ASL low noise model.

We believe that this dramatic improvement is due solely to changes in the module installation technique. During leveling, we removed the leveling mechanism to avoid any possible contact with the module. We further set up all wiring leading to the module so that it applied no force tending to pull the module away from level. Finally, we accelerated any drift by setting up vibrations in the frame and adjusting the module so that high levels of vibration caused no appreciable drift.

As a result of this modified installation and leveling procedure, we have seen drift rates smaller than those in earlier borehole installations. We have reduced the incoherent noise power almost beyond our ability to measure at long periods. The noise estimate data shows no appreciable tendency to increase with increasing periods.

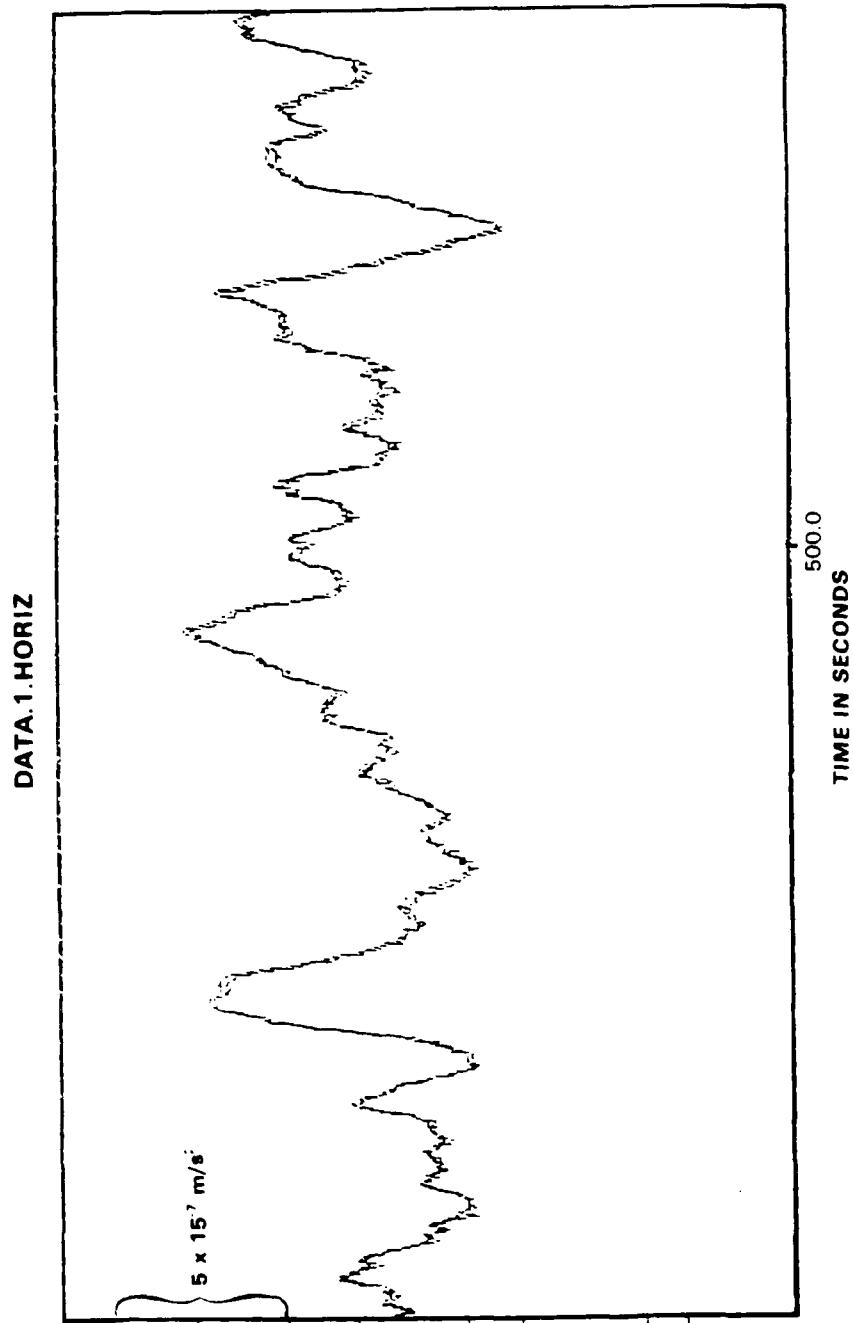


Figure 2-4. Comparison of Two 44000 Horizontal Time Traces

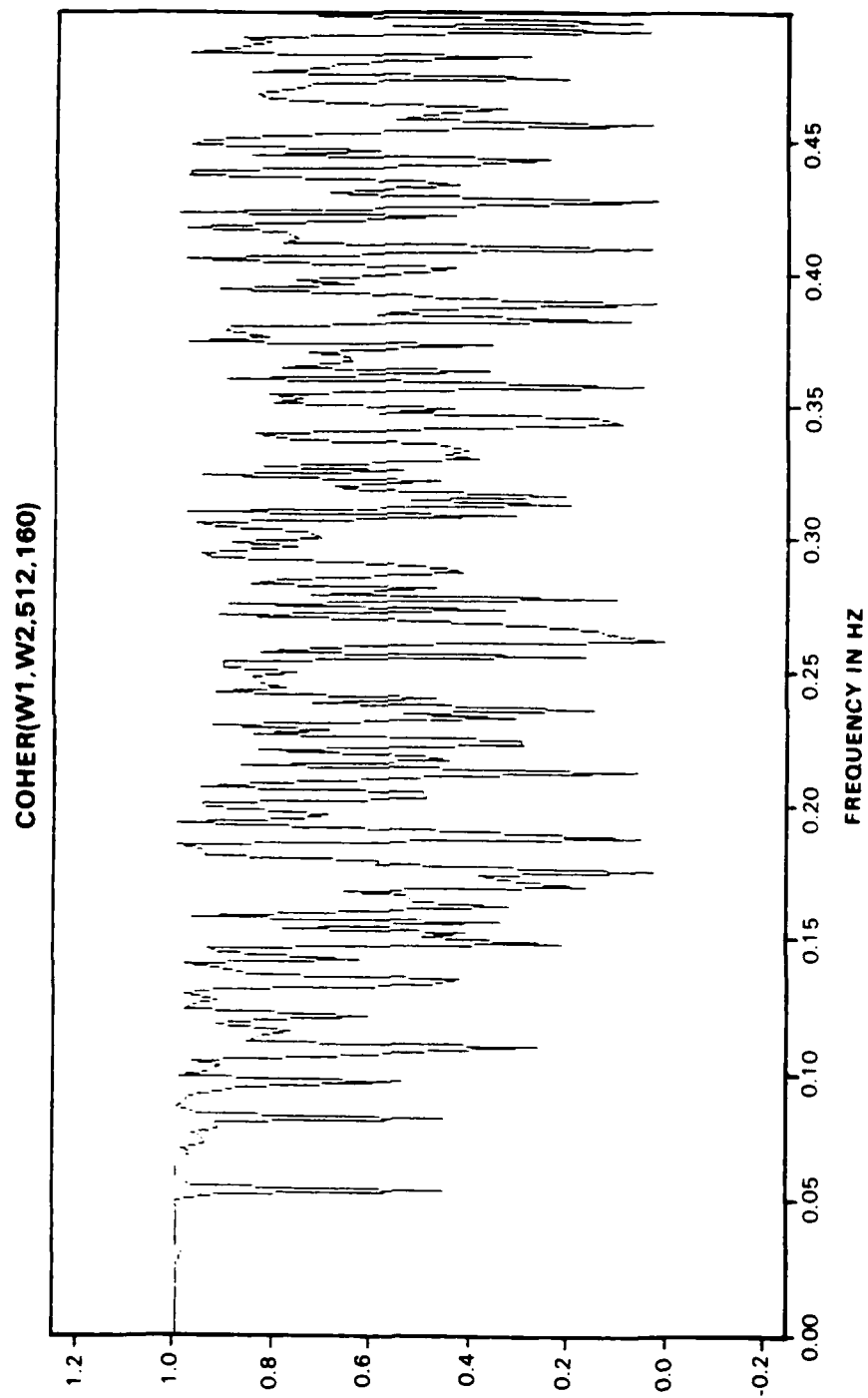


Figure 2-5. Coherence of Figure 2-4 Signals

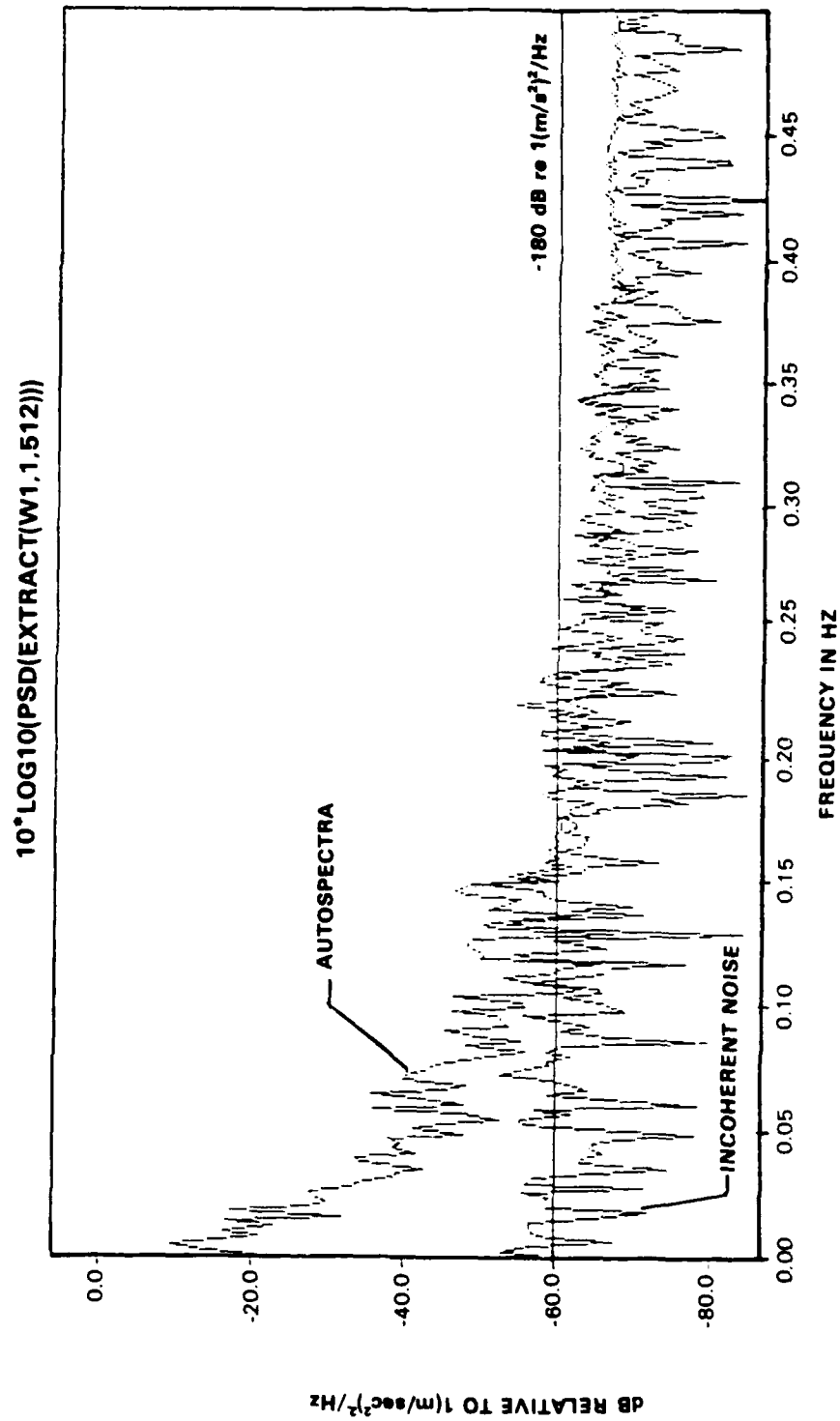


Figure 2-6. Incoherent Noise of 44000 Horizontal Modules For Vault Test At Teledyne Geotech, Garland Texas

3. CONCLUSION

3.1 HORIZONTAL RECOMMENDATIONS

The horizontal noise performance shows dramatic improvement. Since the improvement followed specific efforts planned to reduce the noise, we believe that we have identified the most significant noise source on the 44000 Horizontal modules.

To take advantage of this information, we must change the design of the seismometer system. The upper clamping ring must be eliminated from the system. Furthermore, we must minimize all non-equilibrium forces on the modules. Electrical connections cannot be permitted to apply forces. We should consider different materials for the seat to avoid the typically high coefficient of friction between like materials. Finally we should test these changes in the vault environment where we have good baseline data from the tests to date.

3.2 VERTICAL RECOMMENDATIONS

We have not performed a controlled test on the vertical module to determine the source of the short period noise. To do so, we must disassemble subject modules and make internal changes. We may need to weld the spring terminations and/or change the spring material. Furthermore, the mass position adjustment mechanism may require modification. A piezoelectric stepper motor may provide adequate resolution in movement without the present mechanical parts.

In the long period passband, the vertical module has historically performed adequately. The seat design improvements should further improve this operation. We feel confident that the vertical module can be made to perform at least as well as the model 36000 at all frequencies.

After publication and distribution of this report, some funding will remain from budgets for field travel, step 4 and step 5. This funding should be sufficient for the purchase, and preliminary evaluation of , a piezoelectric micropositioning assembly. To our knowledge, this is a relatively new drive method which may provide important benefits in seismic instrumentation.