UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

EXPERIMENTAL INVESTIGATIONS REGARDING THE USE OF SAND AS AN INHIBITOR OF AIR CONVECTION IN DEEP SEISMIC BOREHOLES

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1 INTRODUCTION

Tilt has been the nemesis of horizontal long period seismology since its inception. Modern horizontal long period seismometers with their long natural periods are incredibly sensitive to tilt. They can sense tilts smaller than 10^{-11} radians. To most readers, this is just a very very small number, so we will begin with an example, which should help to illustrate just how small 10^{-11} radians is.

Suppose we have an absolutely rigid rod which is approximately 4170 kilometers long; this just happens to be the Rand McNally map scaled crow flight distance between Los Angeles and Boston. Tilting this rod 10^{-11} radians corresponds to raising one end of the rod 0.0000417 meters. Alas, this is just another very very small number! However, this corresponds to slipping a little less than one third a sheet of ordinary copying paper under one end of this perfectly rigid rod. To clarify, we mean, take a sheet of paper just like the paper this report is printed on and split it a little less than one third in the *thickness* direction, then put it under the end of the 4170 kilometer long rod! This will tilt the rod 10^{-11} radians.

Real world seismometers are nowhere near the length of this rod. A KS-54000 is about two meters long. Tilting a rod only two meters long 10^{-11} radians corresponds to moving one end of this rod a mere 0.00000000002 meters or 0.02 millimicrons. As one of the authors old math teachers used to say, "That's PDS" (PDS = Pretty Damn Small). Unfortunately, the long period seismologist does not have the luxury of ignoring PDS numbers when it suits him as the mathematician frequently does. He must live in the real world in which tilts this small create severe contamination of long period seismic data.

At periods longer than 20 seconds, tilt noise contaminates the long period data from all instruments installed on or near the earth's surface. Many years of experimentation revealed that installing the sensors at depth in deep mines drastically reduced the level of tilt noise in long period data. However, low levels of tilt noise persisted even at great depth; this noise was caused by air convection in the vault in which the sensors were installed. Over the years, methods were developed to control the air motion with mechanical barriers (boxes) around the sensors and by stratifying (creating a situation in which the air temperature increases with height) the air in the vault near the seismometer. These methods decreased tilt noise in deep mines to very low levels. However, deep mines, that are economically and environmentally suitable and accessible to seismology, are not plentiful and are not evenly distributed over the earth's surface. Therefore, the borehole deployable Teledyne Geotech KS-36000 and later the KS-54000 sensor systems were developed to fulfill the need for instruments that could be installed at depth wherever high quality long period data was desired. Early in the development program, it became evident to the Teledyne Geotech personnel that air convection within the borehole was going to be a significant problem in KS deployments. Experimental and theoretical investigations conducted by Teledyne Geotech (see Douze and Sherwin, 1975, and Sherwin and Cook, 1976) produced a list of recommended installation procedures for reducing the effects of air convection. These procedures consisted of wrapping the sensor in a relatively thin layer of foam insulation, filling the free space volume in the vicinity of the centralizer-bail assembly with foam insulation, and the installation of styrofoam hole plugs immediately above the cable strain relief assembly at the top of the sensor package and at the top of the borehole. This technology has performed quite satisfactorily for over 20 years but evidence of tilt noise in the system output has persisted throughout the KS deployment program (the evidence was that the horizontal components were usually noisier than the vertical components) even in deep boreholes. Some deep borehole sites have been plagued by quite high levels of horizontal noise. Therefore, there has been a definite need for a new technique for controlling low level tilt noise in deep boreholes and the use of sand has been under consideration for several years.

Figure 1 contains conceptual illustrations of both the conventional holelock installed KS sensor system and the same sensor installed in sand. This figure demonstrates the major differences between the two installation methods. The curved arrows in the borehole on the left in the figure denote possible air convection cells which are believed to be the source of tilt noise in some of the conventional installations. This air motion is eliminated in a sand installation by filling most of the free air volume surrounding the seismometer with sand as shown in the right hand portion of the figure. The sand actually performs two functions; it prevents air motion and provides a remarkably ridgid clamping of the seismometer in the borehole.

This report presents the results of quantitative experimental investigations into the effectiveness of controlling low level air convection in seismic borehole installations with sand. The main body of the experimental effort consisted of installing two KS-54000I sensor systems in closely spaced shallow boreholes, allowing the sensors to reach equilibrium operation, and then pouring sand into both boreholes to observe any changes caused by pouring sand into the holes. The hypothesis of the experiment was that the sand would fill up the entire free air volume between the sensor package and the borehole walls thereby preventing movement of the air in the vicinity of the sensor package. The validity of this hypothesis had been qualitatively proven by earlier experiments at ASL and by the sand installations at the IRIS/ASL stations ANMO in 1995 and COLA in 1996. This experiment documents the degree of improved noise levels to be expected if KS instruments are installed in sand instead of in the conventional manner.

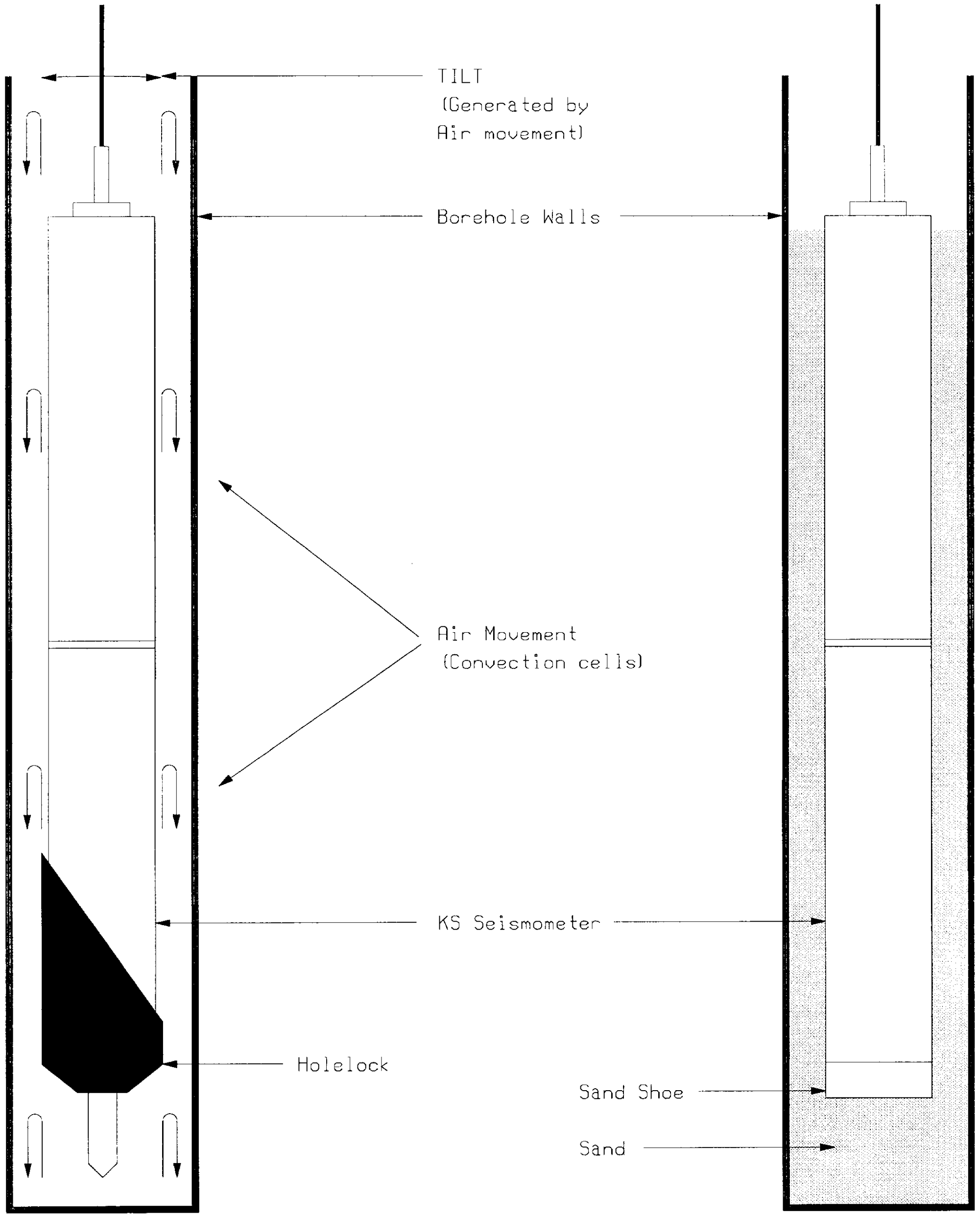


Figure 1. Comparison of a conventional holelock installation and a sand installation.

2 PHYSICAL SETUP

The experiment was conducted at the ASL "Snake Pit" shallow borehole facility. This site consists of two relatively shallow (approximately nine meters deep) closely spaced (about 1.5 meters apart) boreholes located immediately beside a shallow subsurface vault. The two boreholes penetrate about six meters of fractured Precambrian granite and the concrete floor of the vault is poured on the surface of the same granite bedrock about three meters below the surface of the alluvial fill at the site. Surface instruments can be operated in the vault about two and a half meters horizontally from the two boreholes.

Holelocks were installed in both boreholes near the bottom of the hole with enough room below each holelock to prevent the seismometer pilot from touching the bottom of the hole. Two KS-54000I sensors (serial numbers 26 and 114) were installed in the holes in the normal manner except that neither sensor was wrapped with insulation, and no foam plugs were installed immediately above the sensors or at the top of the holes.

An STS-2 was installed in the vault near the wall immediately adjacent to the boreholes. This instrument served mainly as a wind monitor because the horizontal components of the STS-2 were considerably noisier during windy time periods than were the horizontal components of the two KS instruments in the boreholes. During calm conditions, the STS-2 produced high quality quiet horizontal data comparable to that obtained from the two borehole instruments.

Initially, there were concerns about whether or not the shallow boreholes would prove to be quiet enough to permit successful measurements of low level convection generated noise within the borehole. Experience gained during the course of the experiment indicates that the two holes are quite adequate especially during calm wind time periods.

The data were recorded on a twelve channel Quanterra 24 bit digital data system configured to record 80, 20, 1, 0.1, and 0.01 samples per second continuously. The continuous high rate multichannel data filled a 150 megabyte magnetic tape in about 2 days.

3 SEQUENCE OF EVENTS

The sensors were operated for an extended shakedown period to determine if they were behaving properly. During this time period, two major problems were found and corrected. First, it was discovered that one of the sensors (sensor 114) was considerably noisier than the other (sensor 26) and that this noise level was slowly increasing with time. After numerous checks for possible sources of noise, it was discovered that the cable connector at the top of the sensor package had accumulated moisture inside the connector and that the connector pins were slowly corroding due to current conduction between the pins. Careful cleaning of the connector followed by sealing it against further moisture accumulation reduced sensor 114 noise to levels below those for sensor 26. This experience illuminates a potential problem in current and future ASL KS-54000I installations in the field because up to this point in time, this connector has not been sealed; this should be standard practice in the future. Attention then focused on sensor 26 noise levels and it's continuous "burping". At ASL, "burping" means that the data contains randomly distributed excursions which frequently resemble the step response of the sensor system. Burps are usually much more prominent on horizontal components and are believed to be caused by mechanical steps in tilt of the sensor system. We finally discovered that a modified centralizer had been mistakenly installed on sensor 26; for reasons unknown, the three legs had been shortened by someone in the past and we had unknowingly installed a nonstandard centralizer which was not capable of centering and holding the top of the seismometer package in the center of the hole. The top of the sensor had been left free to flop about in the hole at will. The installation of the proper size centralizer eliminated the burps in sensor 26 and reduced it's noise levels considerably.

Continuous undisturbed (undisturbed except for pouring sand into the boreholes) operation for the sand experiment commenced on day 219, 1996 and continued through day 260, 1996. From the beginning, both sensors were remarkably quiet considering the fact that they were not wrapped and that styrofoam plugs were not installed in the borehole. A week of operation revealed that the horizontal components of sensor 26 were noisier than those in sensor 114, so sensor 26 was chosen as the first candidate for sand installation. The borehole was unsealed and a volume of sand calculated to fill the annulus between the sensor and the inner borehole walls to the top of the sensor was poured into the sensor 26 borehole in the morning of day 225. In the afternoon after the dust in the hole settled, visual inspection from the top of the hole using mirror reflected sunlight revealed that more sand was needed. More was added and inspection on the morning of day 226 indicated that the sand had accumulated to near the top of the seismometer package. The borehole was then resealed. Undisturbed operation continued until day 241 when sand was added to the sensor 114 borehole. This time, enough sand was poured into the hole the first time as confirmed by visual inspection during the afternoon of day 241; the hole was then resealed. Undisturbed operation continued through day 260.

4 DATA PROCESSING

The primary method of data analysis was to estimate the signal levels from the instruments using standard power spectral density (PSD) analysis procedures and to estimate the instrument noise levels using the direct method (Holcomb, 1980). First, the time series data for the entire approximately two day duration of each tape was Fast Fourier Transformed using a rectangular window with a 50% overlap between successive segments. These segments were then converted to PSD and corrected for the combined seismometer and instrumentation system amplitude response. The ten percent of these segments for which the PSD level between 30 and 100 seconds were the lowest were retained to calculate a segment averaged PSD estimate of the minimum signal from each channel. Including only the ten percent quietest segments should eliminate time periods during which earthquake signals are present in the data and it should also eliminate time periods during which the wind was blowing. These same simultaneous segments were used to calculate estimates of the noise levels in each channel using the direct method.

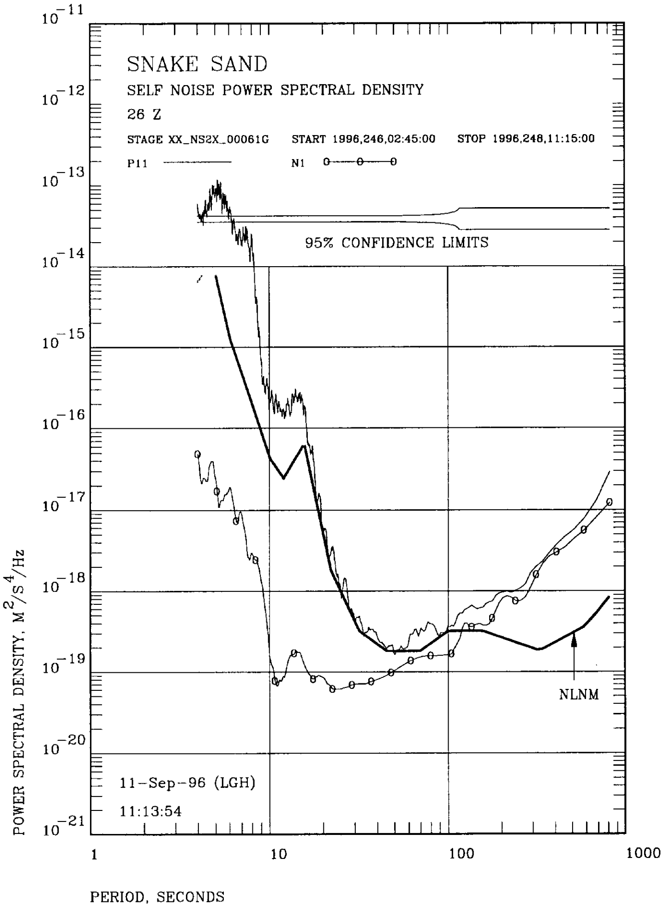


Figure 2. Power spectral density estimates for the total signal (P11) and system noise (N1) for the vertical component of sensor 26 after sand was poured into the borehole.

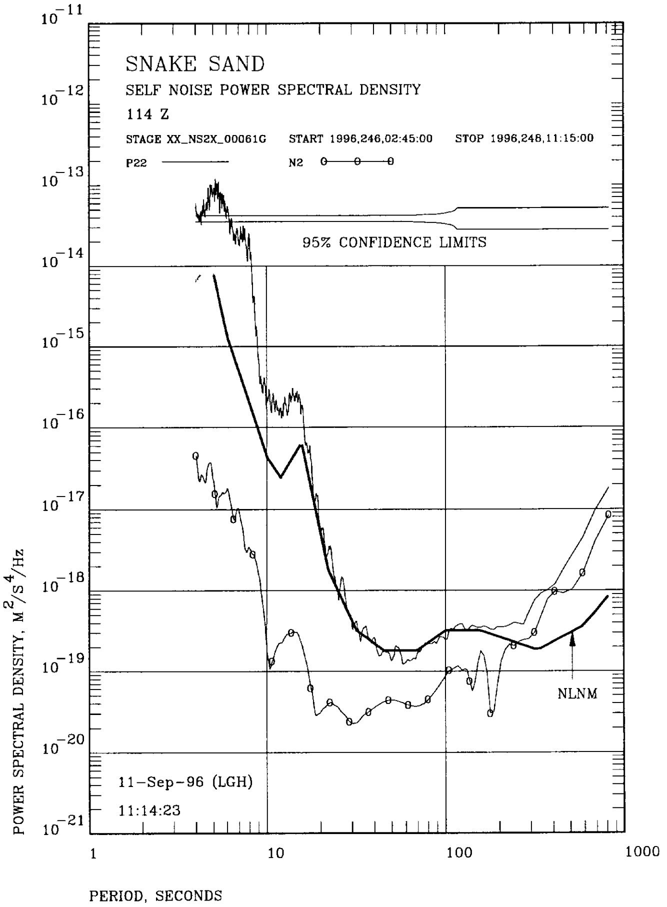


Figure 3. Power spectral density estimates for the total signal (P22) and system noise (N2) for the vertical component of sensor 114 after sand was poured into the borehole.

Examples of the output produced by this analysis is shown in Figures 2, 4, and 6 for sensor 26 and Figures 3, 5, and 7 for sensor 114. In these figures, the thick solid line is the "new low noise model" from Peterson, 1993. The thin solid line (P11 or P22) is the PSD of the total signal (the sum of the coherent ground input to the sensor and the incoherent internal noise generated by the sensor) at the output of the indicated channel and the thin solid line with open circles superimposed (N1 or N2) is the PSD of the estimated system noise level for that channel.

The PSD plots of Figures 2 through 7 present a comprehensive picture of instrument performance as a function of signal period, but it is difficult to visually compare several sequential PSD plots covering an extended period of time to determine trends in PSD levels. Therefore, this report will rely quite heavily on plots of the numeric averages of the PSD levels over preselected bands to illustrate the time behavior of the PSD levels. The bands selected for calculating the averages are 40 to 70, 70 to 100, 100 to 200, 200 to 400, 400 to 700, and 700 to 2048 seconds. The average PSD levels over each of these bands will be assumed to be indicative of the instrument performance for the time period under analysis. Plots of these averages should portray trends in overall instrument performance. Figure 8 contains a definition of the symbols used to plot the various bands in Figures 9 through 20.

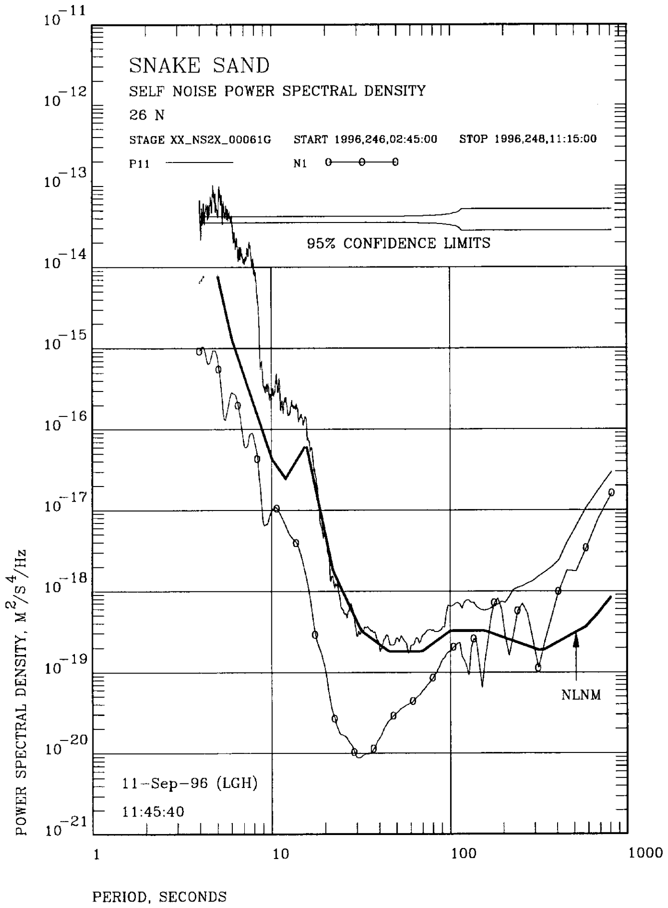


Figure 4. Power spectral density estimates for the total signal (P11) and system noise (N1) for the north component of sensor 26 after sand was poured into the borehole.

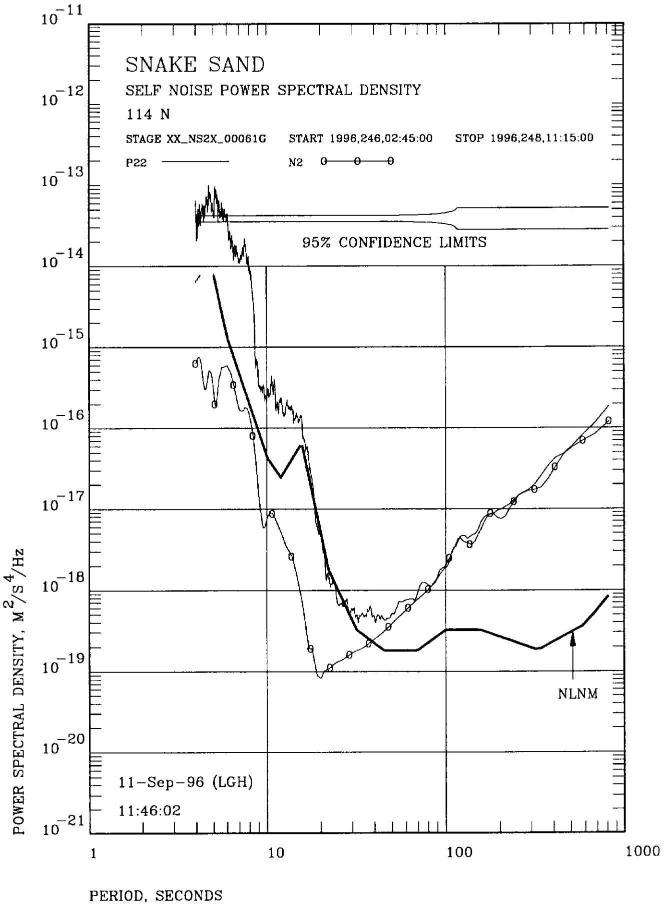


Figure 5. Power spectral density estimates for the total signal (P22) and system noise (N2) for the north component of sensor 114 after sand was poured into the borehole.

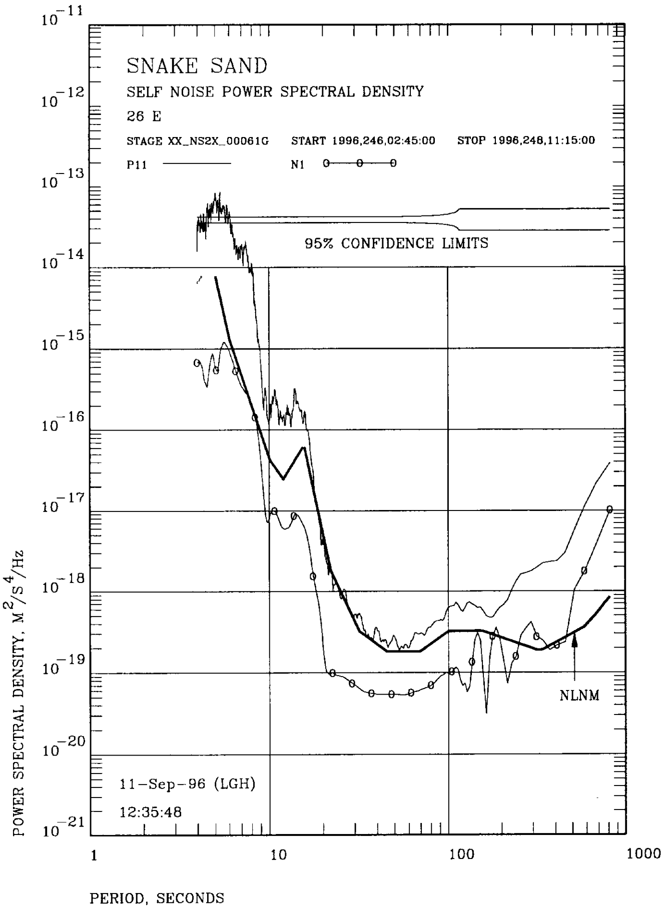


Figure 6. Power spectral density estimates for the total signal (P11) and system noise (N1) for the east component of sensor 26 after sand was poured into the borehole.

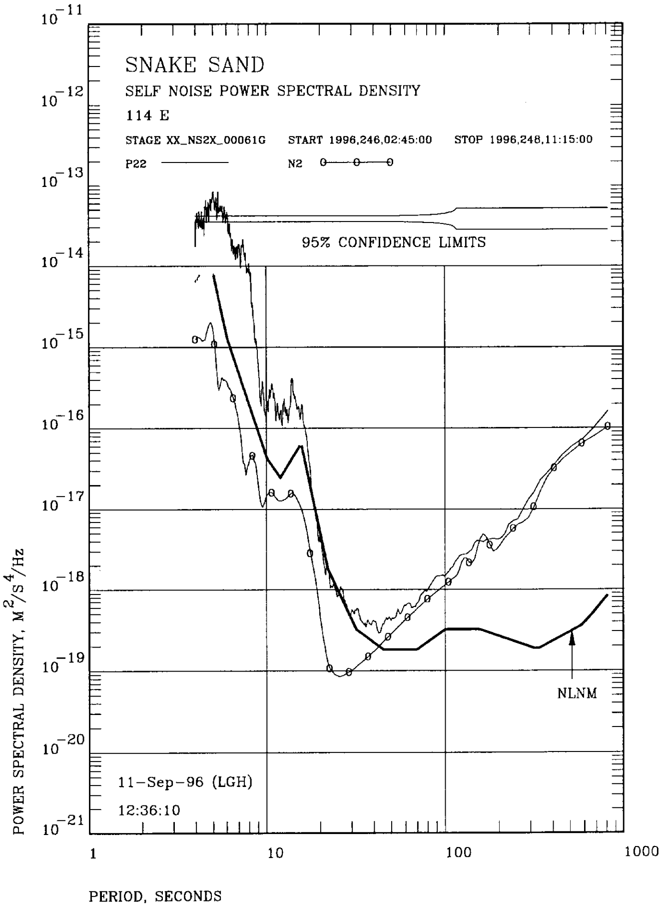


Figure 7. Power spectral density estimates for the total signal (P22) and system noise (N2) for the east component of sensor 114 after sand was poured into the borehole.

▲ = 700 TO 2048 SECONDS

△ = 400 TO 700 SECONDS

■ = 200 TO 400 SECONDS

◉ = 100 TO 200 SECONDS

□ = 70 TO 100 SECONDS

○ = 40 to 70 SECONDS

Figure 8. Definition of the symbols used to plot the estimated band averaged PSD levels in the various bands.

5 BAND AVERAGED PSD RESULTS

The time dependence of the lower levels of the total signal at the seismometer output for both sensors 26 and 114 for the duration of the experiment are plotted in Figures 9 through 14. Each plotted point in these figures represents the average PSD level for the appropriate band (see Figure 8) for the time period beginning at approximately the time at which the point is plotted extending to approximately the time at which the next point is plotted. The times at which the sand was poured into each of the boreholes are shown in all of the appropriate figures.

The time behavior of the vertical band-averaged signal PSD of sensors 26 and 114 throughout the duration of the experiment are shown in Figures 9 and 10 respectively. There does not appear to be any general overall trend in the vertical signal levels. They remain quite constant throughout the test period with small apparently random day to day variations. There was no detectable change in the minimum vertical signal levels of either sensor at the times when sand was poured into their respective boreholes. Note that the minimum signal levels for sensor 114 (Figure 10) are lower than those for sensor 26 (Figure 9). This is probably indicative of lower internal electronic system noise in the vertical channel of sensor 114.

The time behavior of the north band-averaged signal PSD of sensors 26 and 114 throughout the duration of the experiment is somewhat different as shown in Figures 11 and 12 respectively. There is a significant drop ranging from 5.09 to 10.08 db (see Table 7 on page 42 for details) in the band averaged PSD signal levels for sensor 26 at the time sand was added to the sensor 26 borehole (see Figure 11). In contrast, there is no apparent change in the slowly increasing trend of the band-averaged PSD signal levels for sensor 114 when sand was added to the sensor 114 borehole (see Figure 12).

The behavior of the east band-averaged signal PSD of both sensors (see Figures 13 and 14) is quite similar to that of the north. There is an even larger decrease in the minimum east signal levels ranging from 8.78 to 15.64 db (see Table 8 on page 43 for details) for sensor 26 when the sand was poured into sensor 26's borehole. However, as was true for the 114 north component, the minimum 114 east averaged PSD signal levels do not show a change in the overall slightly increasing trend when sand was poured into the sensor 114 borehole (see Figure 14).

Minimum total signals averaged over the various bands are composed of the sum of both the coherent true groundmotion signal and the incoherent apparent internal system noise of the seismometer. True grondmotion is probably not absolutely constant as a function of time thereby increasing the difficulty of assessing the performance of the instrument system itself. The apparent instrument selfnoise (N1 and N2 in Figures 2 through 7) is an estimate of the incoherent noise level in the combined instrument/borehole system. If convection in the borehole is contributing to this incoherent noise level and if sand suppresses convection noise, the incoherent noise level should drop if sand is added to the borehole. Figures 15 through 20 contain plots of the band averaged estimates of the incoherent noise PSD levels for all three components of sensors 26 and 114.

The vertical band-averaged incoherent noise levels for both sensors remain relatively constant throughout the test period (see Figures 15 and 16). There was no detectable change when sand was poured into either borehole and the estimated noise levels for sensor 114 are considerably lower than those for sensor 26.

The decrease in the band-averaged incoherent noise levels for the north component of sensor 26 when sand was added to sensor 26's borehole ranged from 5.23 db to 16.83 db (see Figure 16 and Table 10 on page 45 for details). However, there was no discernable immediate change in the general overall increasing trend in the north incoherent noise levels for sensor 114 when sand was added to that borehole (see Figure 18).

The largest decrease in the band-averaged incoherent noise levels caused by adding sand occurred in the serial number 26 east component as shown in Figure 19. This decrease ranged from 10.8 db to 21.74 db (see Table 11 on page 46 for details) Once again, there was no discrenable change in the east incoherent noise levels for sensor 114 when sand was added to the serial number 114 borehole (see Figure 20).

The reader may ask why there was no decrease in noise levels when sand was poured into the sensor 114 borehole. The answer to this question probably lies in the fact that the noise levels in sensor 114 were already very low before sand was poured into the hole; they were much lower than were the noise levels for sensor 26. Both of these two sensors were initially installed in a conventional manner with a holelock, an operational centralizer, an azimuth ring, a pilot etc.; not all conventional KS installation have equal noise levels. Some conventional field sites have very quiet horizontals whereas some conventional field site horizontals are very noisy. Apparently, for reasons not understood even after over 20 years of experience with KS installations, there was little or no air convection in sensor 114's borehole before sand was poured into the hole. Conventional installations have always been erratic. Sand installations should be more reliable because they make it impossible for air to move in the vicinity of the sensor.

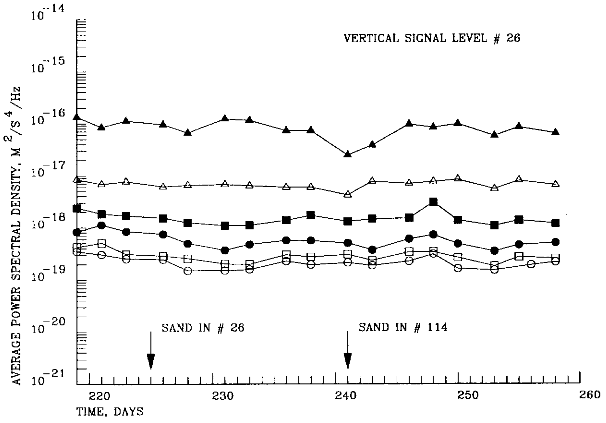


Figure 9. Time dependence of the vertical band averaged signal PSD for sensor 26.

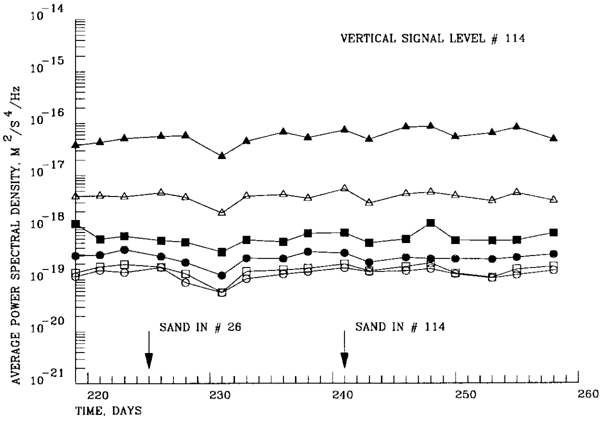


Figure 10. Time dependence of the vertical band averaged signal PSD for sensor 114.

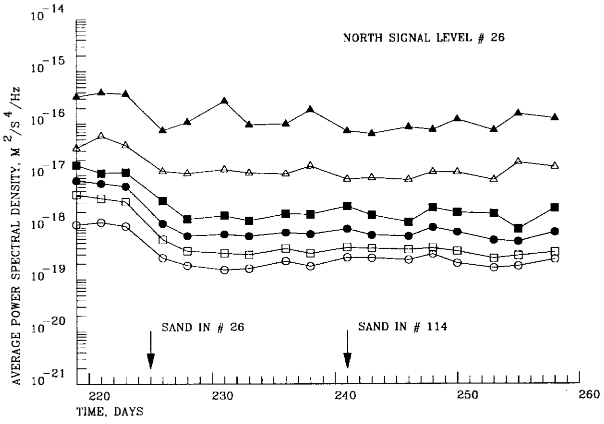


Figure 11. Time dependence of the north band averaged signal PSD for sensor 26.

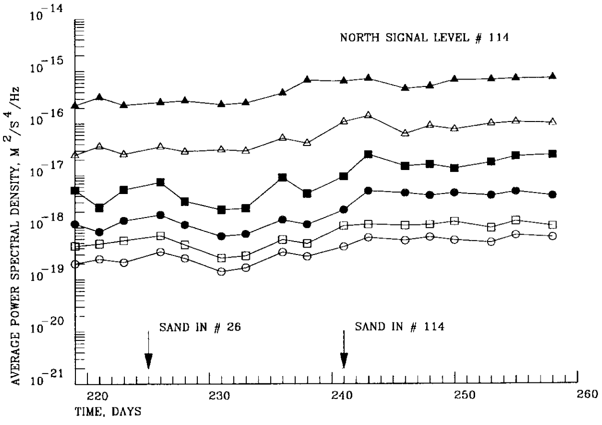


Figure 12. Time dependence of the north band averaged signal PSD for sensor 114.

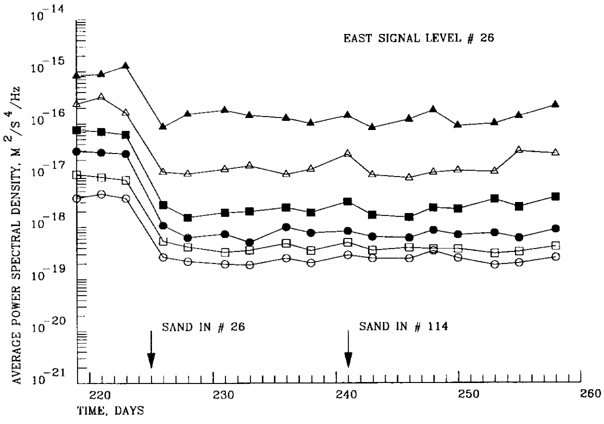


Figure 13. Time dependence of the east band averaged signal PSD for sensor 26.

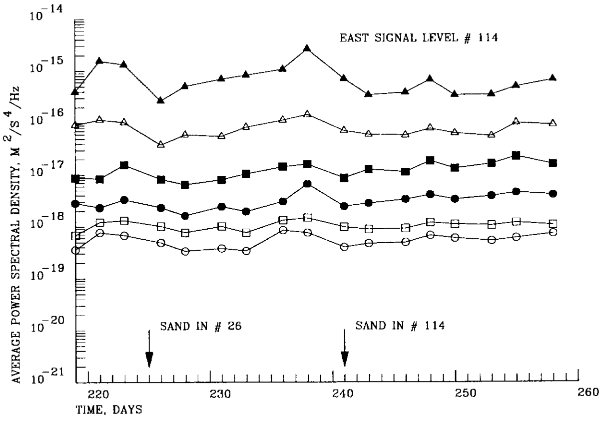


Figure 14. Time dependence of the east band averaged signal PSD for sensor 114.

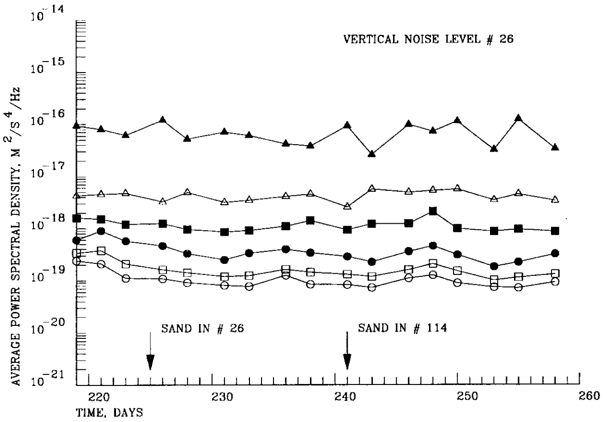


Figure 15. Time dependence of the vertical band averaged incoherent noise PSD for sensor 26.

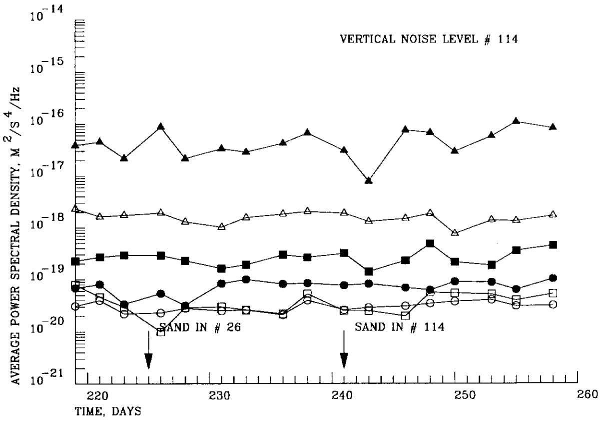


Figure 16. Time dependence of the vertical band averaged incoherent noise PSD for sensor 114.

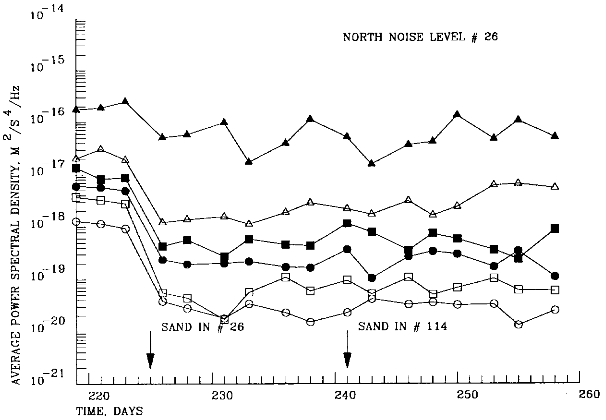


Figure 17. Time dependence of the north band averaged incoherent noise PSD for sensor 26.

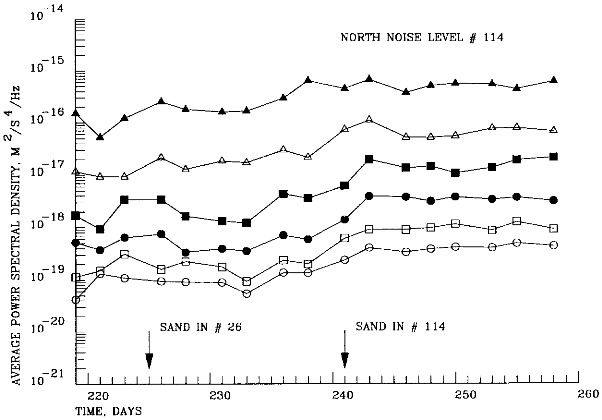


Figure 18. Time dependence of the north band averaged incoherent noise PSD for sensor 114.

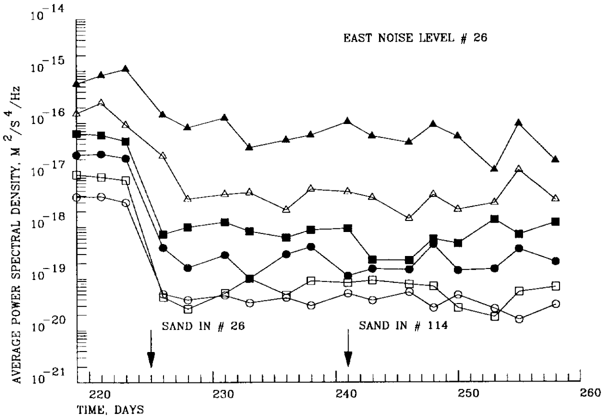


Figure 19. Time dependence of the east band averaged incoherent noise PSD for sensor 26.

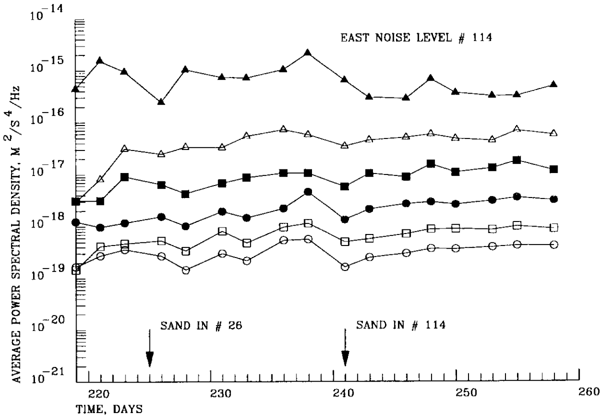


Figure 20. Time dependence of the east band averaged incoherent noise PSD for sensor 114.

6 RMS LEVELS IN THE 20 TO 600 SECOND PASSBAND

Another method of evaluating the long period performance of seismological instruments is to simply calculate the root of the mean square (RMS) value (see Bendat and Piersol, 1971) of the total signal in the 20 to 600 second passband for each data channel. This parameter is routinely calculated every half hour by the SHEAR software in all IRIS/ASL Quanterra systems and is subsequently stored as part of the station log. This quantity can be used to compare the relative performance of sensor systems with the same response functions. It provides a characterization of the signal level in the form of a single number; it is much easier to quantitatively compare numbers than PSD data when evaluating relative system performance. The data presented in this report has been slightly refined beyond the Quanterra procedure. Only the quietest 25% of the possible total of 48 RMS values per day has been retained and averaged together to provide a number representative of the quietest portions of each day. These 12 point averages for each day from the three channels of sensors 26 and 114 are plotted for the duration of the experiment in Figures 21 through 26 and the same averages for the same time period from IRIS/ASL stations ANMO and COLA are presented in Figures 27 through 32. All four of these KS-54000I sensors were installed in sand.

Figures 21, 22, 27, and 28 contain the 20 to 600 second RMS signal levels for the vertical components of serial numbers 26 and 114 plus ANMO and COLA respectively. Note the great similarity in these four sets of data. The RMS values remain at a relatively constant value day after day. Note the simultaneous increase in the indicated vertical noise levels for the essentially collocated #26, #114, and ANMO sensor systems on day 219 and near day 250. The fact that these higher RMS levels occur on all three borehole systems at the same time indicates that an external source caused the higher noise levels. A possible external source could be increased event activity during that particular time period; if event generated ground motion is present in the earth's background more than 75% of the time during a particular day, a higher RMS signal level will result. This also may be the reason that the RMS signal levels of all three components at COLA exhibit more variation than they do at ANMO because COLA is much closer to a highly active earthquake source region.

The 20 to 600 second RMS signal levels for the north and east components are plotted in Figures 23 through 26 and Figures 29 through 32. The most obvious character of these figures is that the RMS levels for the horizontal components of serial numbers 26 and 114 vary considerably more than those from ANMO and COLA. This is probably due to the fact that serial numbers 26 and 114 were installed in quite shallow boreholes (about 9 meters deep) whereas AMMO and COLA were installed at about 152 and 120 meters depth respectively. Low levels of locally generated surface tilt probably contaminates the data from serial numbers 26 and 114 a significant portion of the time. Note the decreases in the RMS signal levels in both the north and east components of serial number 26 when sand was poured into the number 26 borehole. Note also that the RMS signal level for serial number 114 north component probably increased when sand was poured into the serial number 114 borehole (see Figure 24); it is difficult to tell for sure because the 114 RMS signal level had temporarily reached quite high levels 6 times prior to putting sand in the 114 borehole. Therefore, the higher levels after sand was poured into the borehole may or may not be due to pouring sand into the hole. The RMS signal level for the east component of serial number 114 in Figured 26 appears to remain essentially constant as sand was added to the borehole.

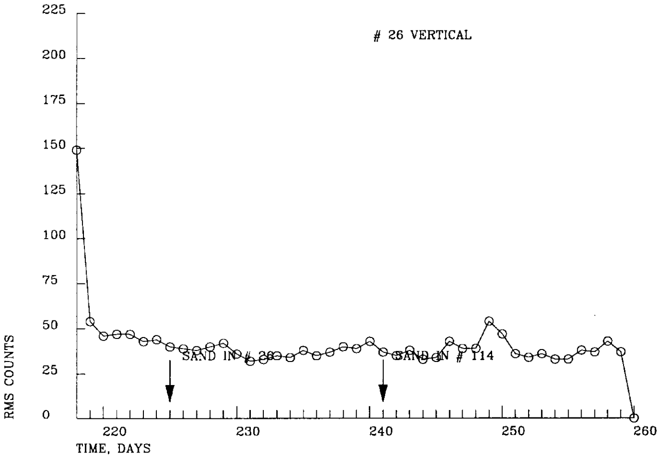


Figure 21. Vertical # 26 RMS signal in the 20 to 600 second band.

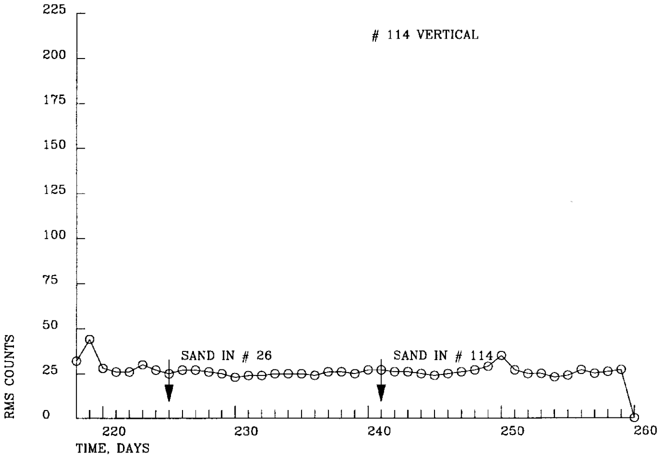


Figure 22. Vertical # 114 RMS signal in the 20 to 600 second band.

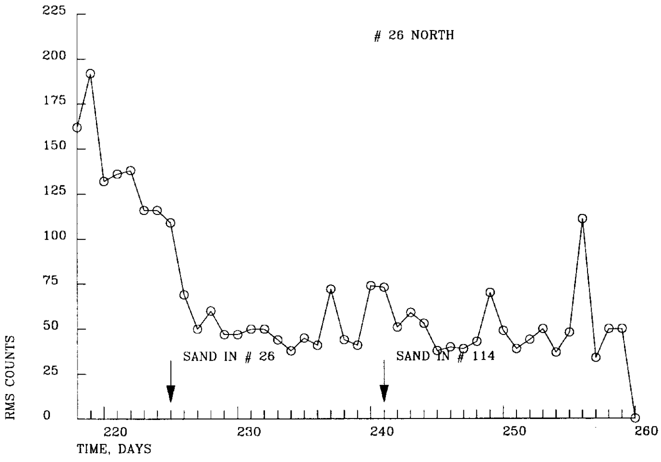


Figure 23. North # 26 RMS signal in the 20 to 600 second band.

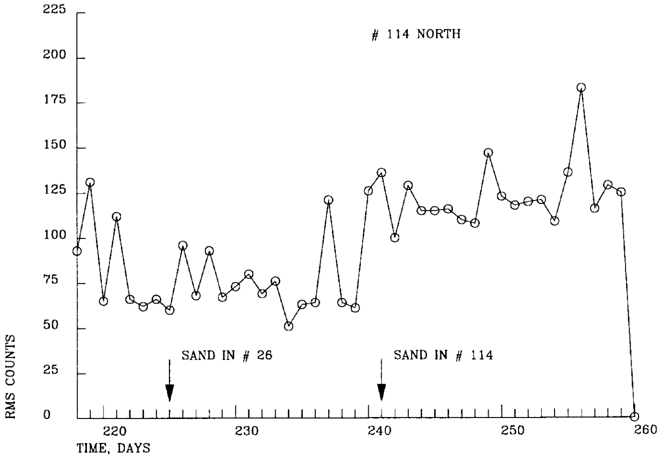
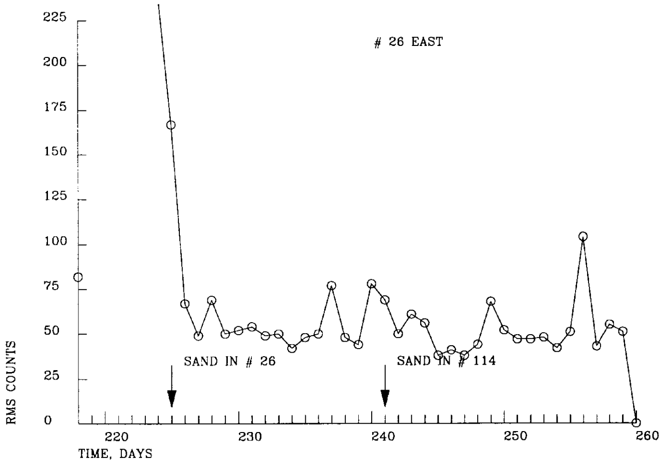


Figure 24. North # 114 RMS signal in the 20 to 600 second band.



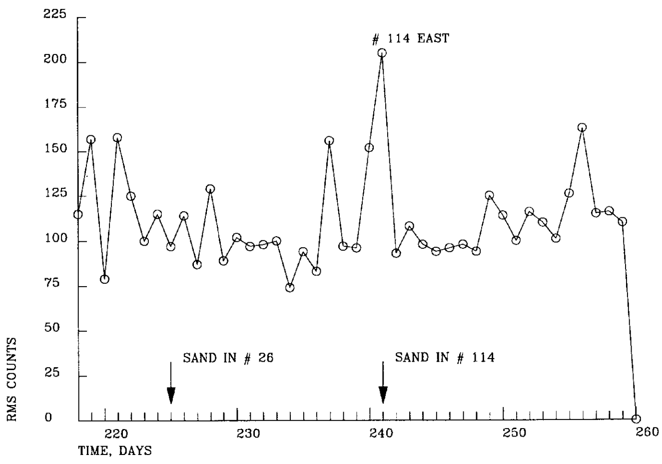


Figure 25. East # 26 RMS signal in the 20 to 600 second band.

Figure 26. East # 114 RMS signal in the 20 to 600 second band.

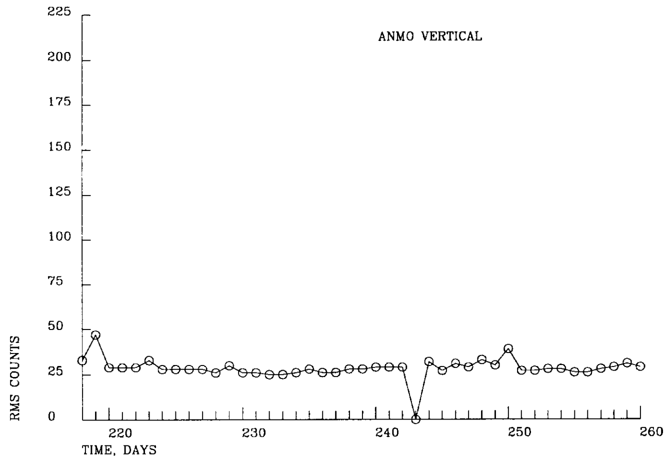


Figure 27. Vertical ANMO RMS signal in the 20 to 600 second band. Data for day 243 is missing.

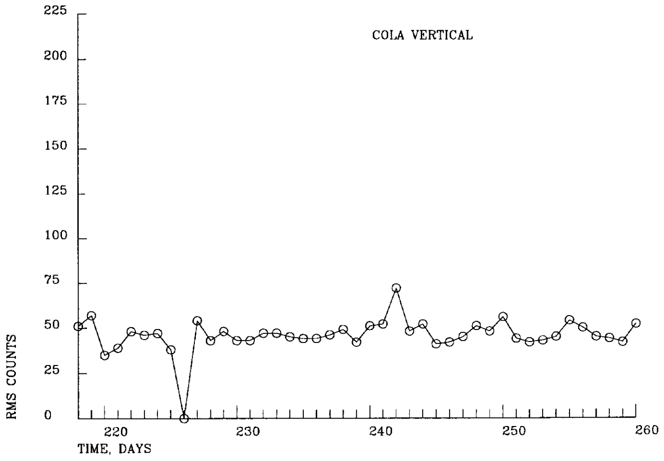


Figure 28. Vertical COLA RMS signal in the 20 to 600 second band. Data for day 226 is missing.

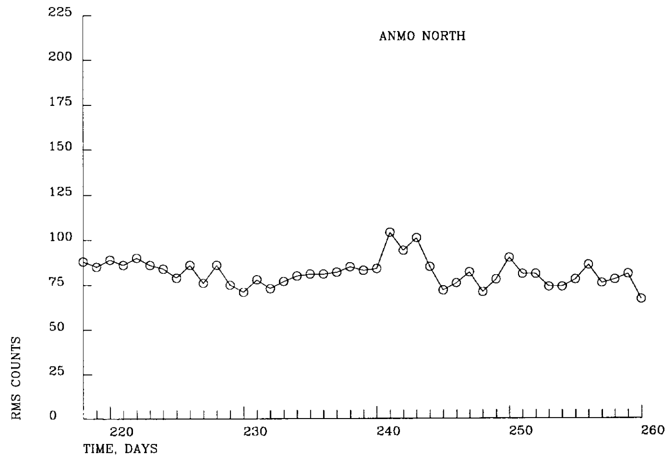


Figure 29. North ANMO RMS signal in the 20 to 600 second band.

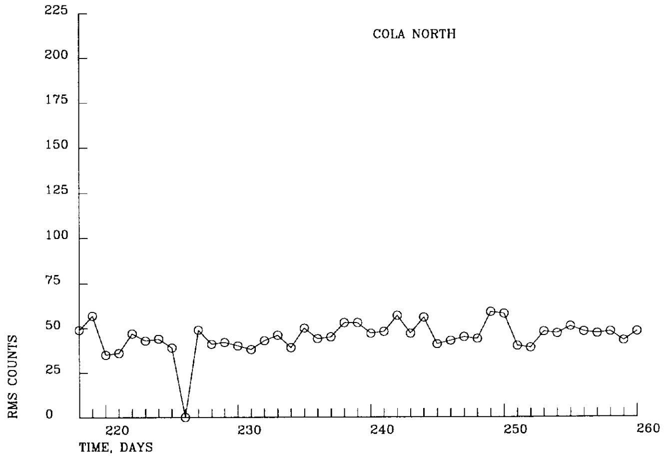
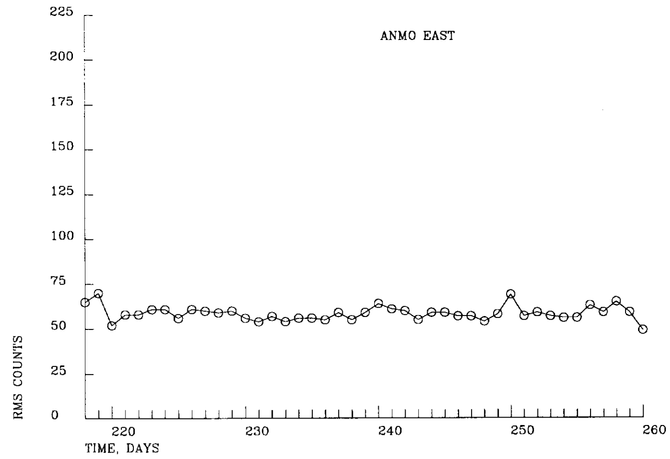


Figure 30. North COLA RMS signal in the 20 to 600 second band. Data for day 226 is missing.



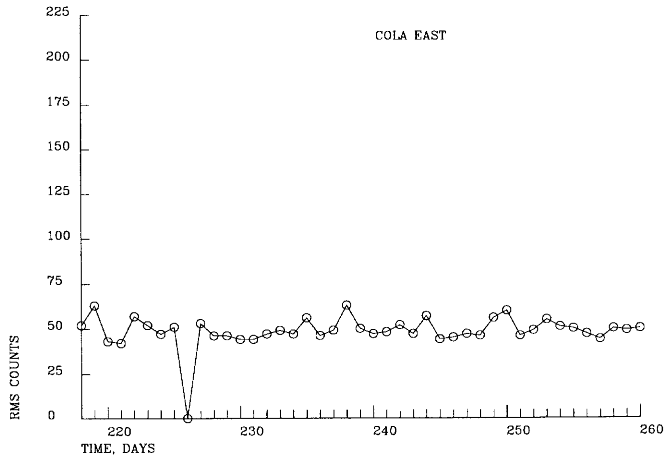


Figure 31. East ANMO RMS signal in the 20 to 600 second band.

Figure 32. East COLA RMS signal in the 20 to 600 second band. Data for day 226 is missing.

It should be very informative to compare the 20 to 600 second RMS signal levels from the four ASL sand installations in Figures 21 through 32 with the RMS signal levels from other borehole sites around the world. Table 1 summarizes the RMS signal levels at all the GTSN and IRIS/ASL borehole installations. The GTSN RMS values in the table were calculated from time series data recorded at the stations during days 001 through 080, 1995 and was corrected for the difference in the overall sensitivities between the GTSN and the IRIS/ASL recording systems. The IRIS/ASL RMS values in the table were calculated from time series data recorded at the stations during 1995. All of these sensors are installed at depths of 100 meters or greater with the single exception of BOCO which is much shallower (only 25 meters deep). Also included in Table 1 for comparison purposes are "eye ball" averages of the RMS levels for #26 and #114 in sand from Figures 21 through 26.

The RMS signal levels of the vertical components at all of the GTSN and IRIS/ASL borehole sites are all less than or equal to 200. That fact that the vertical RMS signal levels of the KS-36000I sensors tend to be larger than those for the KS-54000I sensors may be significant because the KS-36000I sensors are all older than the KS-54000I instruments. The individual modules in the KS series are evacuated to reduce thermal convection noise generated within the module itself. Vertical modules have become noisy in the past when they lost vacuum. All of the KS sensor modules may be slowly losing their vacuum over the years; if so, the older KS-36000I verticals would tend to be noisier. Note the wide range in the RMS signal levels covered by the horizontal components in Table 1. There is no known physical reason to expect true horizontal ground motion levels at a given site to be significantly greater than vertical ground motion levels at that site. Therefore, horizontal RMS signal levels in the table which are significantly greater than their corresponding vertical level are indicative of excess noise in the horizontals at that station. Some of the stations have quite noisy horizontals (BDFB, CPUP, LBTB, and VNDA for GTSN, and CHTO, RAR, SNZO, and TATO for IRIS). Several others are somewhat noisier than they should be. On the positive side, stations such as LPAZ, ANMO, COLA, GRFO, and PTGA all have RMS signal levels below 100 for both horizontals. Obviously, the data in Table 1 indicates that we (IRIS/ASL) are not controlling the noise levels in the horizontal components very well with current installation procedures. All of the sensors at the "AIR" type stations are installed in the same manner as far as is known. Yet the horizontal noise levels are quite variable.

The RMS signal levels at the IRIS/IDA borehole sites are listed in Table 2. These signal levels have been converted to IRIS/ASL sensitivity levels so these numbers can be compared approximately with those in Table 1. At most sites, the RMS levels were calculated from data recorded in early 1996; the single exception was MSEY for which data from 1995 was used. In general, the IRIS/IDA borehole sensor noise levels in Table 2 are comparable to the levels for the ASL-operated boreholes in Table 1. The vertical IRIS/IDA RMS signal levels are approximately equal to those found at the IRIS/ASL sites. It is noteworthy that the RMS signal level of the vertical at NIL is higher than those for the two horizontal sensors at that station; this may indicate a problem with the vertical but it may also be the result of the particular data segment selected to calculate the RMS levels. At three of the stations (BORG, MSEY, and SHEL), the horizontal components are quite noisy which indicates the possibility of significant air convection noise in these three boreholes. At the IRIS/IDA borehole installations, 100% of the horizontal RMS noise levels are greater than 100 counts, whereas 23% (5 out of 22) of the ASL borehole stations have horizontal noise levels below 100.

STATION ID CODE	SENSOR	TYPE	VERTICAL RMS	NORTH RMS	EAST RMS
GTSN BOREHOLE STATIONS					
BGCA	KS-54000	AIR	24	140	146
BDFB	KS-54000	AIR	55	1200	1600
BOSA	KS-54000	AIR	32	150	320
CPUP	KS-54000	AIR	65	5400	2800
DBIC	KS-54000	AIR	32	130	430
LBTB	KS-54000	AIR	90	1000	600
LPAZ	KS-54000	AIR	32	50	45
PLCA	KS-54000	AIR	30	60	170
VNDA	KS-54000	AIR	50	3200	1200
IRIS/ASL BOREHOLE STATIONS					
ANMO	KS-54000I	SAND	30	80	55
ANTO	KS-36000I	AIR	130	120	120
BOCO	KS-54000I	AIR	70	200	300
CHTO	KS-36000I	AIR	100	600	500
COLA	KS-54000I	SAND	46	43	52
GRFO	KS-36000I	AIR	27	70	70
GUMO	KS-36000I	AIR	90	110	130
HNR	KS-54000I	AIR	60	150	100
NWAO	KS-36000I	AIR	140	120	120
PTGA	KS-54000I	AIR	186	54	54
RAR	KS-36000I	AIR	170	1500	1500
SNZO	KS-36000I	AIR	200	1500	1400
TATO	KS-36000I	AIR	190	1150	2200
SNAKE PIT BOREHOLE TEST SENSORS					
# 26	KS-54000I	SAND	35	40	50
# 114	KS-54000I	SAND	25	115	100

Table 1. Summary of the RMS signal levels in the 20 to 600 second band for all the GTSN and IRIS/ASL borehole installations plus the two "Snake Pit" sand test sensors. All table RMS entries are in units of IRIS/ASL sensitivity digital tape counts.

STATION ID CODE	SENSOR	TYPE	VERTICAL RMS	NORTH RMS	EAST RMS
IRIS/IDA BOREHOLE STATIONS					
ASCN	KS-54000I	AIR	193	317	276
BORG	KS-54000I	AIR	258	9613	2177
CMLA	KS-54000I	AIR	64	340	286
EFI	KS-54000I	AIR	31	209	222
MSEY	KS-54000I	AIR	74	1761	1277
MSVF	K3-54000I	AIR	103	238	249
NIL	KS-54000I	AIR	341	177	268
SHEL	KS-54000I	AIR	66	519	680
WRAB	KS-54000I	AIR	37	254	139

Table 2. Summary of the RMS signal levels in the 20 to 600 second band for the indicated IRIS/IDA borehole installations. All table RMS entries are in units of IRIS/ASL sensitivity digital tape counts.

7 POTENTIAL SOURCES OF EXCESSIVE HORIZONTAL NOISE

There are several possible causes for high horizontal noise. First, the sensor electronics themselves could be excessively noisy. The data in Tables 1 and 2 argues against this possibility because in most cases horizontal noise appears to occur at about the same level in both horizontal components at a given site. It is not likely that excessive electronic noise would either always occur in both horizontal sensors at once or not at all; it would seem that a mixture of one quiet and one noisy horizontal would occur occasionally if electronic noise was the source of the excessive noise levels. In addition, note that none of the vertical sensors are excessively noisy. The electronic circuitry for the vertical channel in KS-36000I's and KS-54000I's is identical to the circuitry for the horizontal channels. It is unlikely that all of the vertical channels would be relatively quiet whereas several horizontal channels exhibit high levels of noise in pairs. The data in Tables 1 and 2 strongly suggests that the source of the noise arises not from electronic sources, but from tilt. Recall that the horizontal components are very sensitive to tilt whereas the vertical components are relatively insensitive to tilt.

Tilt of the sensor package can arise from several possible sources. First, it is possible that the borehole may not be cemented properly at the depth of the seismometer installation thereby allowing the borehole casing to "swing free" to generate tilt. Poor cementing near the bottom is highly probable if the hole was cemented from the top. Drillers are notorious for cutting corners if left unmonitored on the job for any length of time. If voids exist between the rock walls and the outside of the casing at the installation depth, the casing will probably tilt continuously especially if water is present in the void. This could explain the fact that high levels of noise only occur in pairs on the horizontals in Tables 1 and 2 and not at all on the vertical channels. It is possible that one or more poorly-cemented boreholes are responsible for some of the high horizontal noise but it is not probable that all of the noisy holes are poorly cemented.

A myriad of possible mechanical malfunctions within the stabilizer - seismometer - holelock - borehole system could be sources of tilt. These possible malfunctions include poor spring tension in the centralizer, poor mechanical contact between the three centralizer centering legs and the borehole walls due to rust build up, dirt etc., poor mechanical contact between the seismometer base and the three stainless steel balls in the holelock due to debris build up on the balls, poor mechanical contact between the borehole walls and the casehardened holelock locking jaws due to rust build up, dirt etc., or movement in one or more of the many mechanical interfaces found throughout the system. If any of these possibilities is the source of tilt noise, a sand installation eliminates most of them because the centralizer and holelock are not utilized in a sand installation.

The most likely source of tilt noise in deep seismic boreholes lies in air convection driven by temperature gradients within the free air space around the seismometer. Personnel at Teledyne Geotech were well aware of air convection as a potential source of tilt noise during the KS product development years in the early 1970's. Numerous copies of internal company memoranda (most of them were written by J. C. Cook) dating from that era, which were given to ASL personnel over the years by Teledyne Geotech, are devoted to theoretical discussions of the effects of various gasses, the effect of varying the gas pressure, and the effects of varying casing diameters on the onset temperature gradient required for starting convection. According to these documents, the natural earth heat flow temperature gradient at most sites is theoretically equal to just about the gradient required to start air convection in a 7 inch inside diameter borehole. Adding an active component seismometer to the borehole greatly complicates theoretical calculations because the geometry of the seismometer package increases the difficulty of modeling the free air space and the active sensor electronics adds heat to the space around the package thereby greatly increasing the local temperature gradient in the vicinity of the package. Air convection in a borehole can generate tilt in the seismometer package in two ways. First, the action of the air motion itself acts as a wind blowing on the package thereby creating a force which moves the package. Second, the air convection is the result of a temperature gradient; therefore, the air motion generates temperature changes in the mechanical parts of the sensor - borehole system causing unequal expansion and contraction of these mechanical parts which in turn tilts the sensor package. A change in the temperature of one of the approximately one inch long steel legs of a KS stabilizer of only FOUR TENTHOUSANDTHS of a degree Fahrenheit will create a tilt of the package of 10^{-11} radians! These forces and temperature changes are very small but the tilt sensitivity of the horizontal sensors is extremely high.

8 CONCLUSIONS

Excessive long period noise in the horizontal components is present at many of the KS borehole installations around the world. Excessive horizontal noise at most sites is probably generated by air motion in the vicinity of the sensor which introduces tilting of the sensor package thereby generating noise. Current sensor installation technology has proven to be insufficient for controlling low level borehole noise. This experiment investigated the effectiveness of the use of sand as a means of preventing air motion near seismometer systems installed in boreholes.

Controlled experiments at ASL yielded definite decreases in horizontal noise levels when sand was added to the borehole. Conversion of SNZO from a conventional installation to a sand installation produced a significant reduction in horizontal noise levels at a station which had had noisy horizontals for many years. The new sand installation at COLA has the quietest horizontal components of any site in the world. ANMO has operated in sand for over two years with very quiet horizontals.

The combination of this evidence demonstrates that the use of sand as an installation medium inhibits air convection and associated tilt noise in KS installations. The reduction in horizontal noise levels can be very large if existing noise levels are high. Horizontal noise levels should approach the vertical noise level in continental sand installations; noise levels in coastal sand installations will probably be higher because of tilt noise from sources external to the borehole.

9 ACKNOWLEDGMENTS

The authors appreciate the assistance of several individuals during this experiment. Vern Stoup helped clean up the "Snake Pit" to convert it from a dark and rodent infested dungeon to a bright comfortable recording facility. In addition, Vern and Tyler Storm built a barbed wire fence around the boreholes to keep the local Isleta Pueblo "instrumentation cable eating cows" away from the boreholes. Alvin Garcia and Derrick Serrano performed numerous tasks to support the effort. Ken Oliver conducted all of the seismometer locking, unlocking, and leveling operations. Bob Woodward spent at least a couple of days extracting time series data from CMLA and EFI. Caryl Peterson set up the digital data system configuration file and assisted in interpreting the system's occasional strange operating behavior.

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11 APPENDIX

SEISMOMETER REMOVAL EXPERIMENTS

Several people in the seismic community have expressed considerable concern about the possibility that a sand installed sensor system might become "stuck" in the hole if the sand becomes wet and or is "cemented" with an unknown cementing agent. We agree that it is quite likely that sand in most boreholes will become wet.

Therefore, during June, 1996 an experiment was performed at ASL to determine the difficulty of removing a KS sensor system from wet sand. A dummy package which was approximately the same size as a KS sensor was installed in a shallow borehole and completely submerged in sand to a depth of at least 4 to 5 inches above the top of the package. Water was then added to the hole until the sand remained submerged underwater and allowed to stand for three days.

The package was 5.5 inches in diameter and 65 inches long and it weighed 80 pounds. A 5000 lb capacity scale was used to monitor the lifting cable tension as the dummy package was pulled from the sand. A total of 540 pounds of force was required to pull the package from the wet sand. This force was composed of the package weight plus a vacuum force plus the friction of the sand against the package minus the buoyancy.

Force = 540 lbs (measured with uphole cable tension scale)
Weight = -80 lbs (measured with platform scale)
Vacuum force = -349 lbs (assuming sea level air pressure)
Friction = -169 lbs (calculated by summing the remaining forces)
Buoyancy = 58 lbs (calculated from known package volume)

For a real KS-36000 or KS-54000, these numbers are expected to vary slightly because these instruments weigh more than the dummy package and the real instruments have slightly different mechanical dimensions. The biggest change should be in the weight (a KS-54000 weighs about 145 pounds) so the total force required to remove a real instrument should increase by about 65 pounds. For a real instrument in the bottom of a deep borehole (100 meters), the force will also increase by an estimated 100 more pounds due to the added weight of the soft and hard cables.

The "vacuum" and the "buoyancy" forces are undoubtedly functions of the rate at which the package is pulled from the wet sand. If the package is pulled out quite rapidly, the vacuum force should approach that given above whereas the buoyancy force will approach zero. If the package is pulled out slowly enough to allow the water to percolate downward through the sand and fill the space being created at the bottom of the package as the package is withdrawn, the vacuum force should approach zero and the buoyancy force will be near that quoted above. Therefore, slow pulling should result in the smallest overall removal force.

Assuming that the package is removed very rapidly thereby creating the maximum vacuum force and the minimum buoyancy force, the forces indicated above total to about 763 pounds of cable tension required to remove a deep borehole installed KS-54000 if it is in water saturated sand. This force is well within the capability of the hard cable (2800 pounds) and GoLo winches (1200 pounds) which are currently in use at most IRIS/ASL borehole sites. Rapid removal is not recommended! It is not prudent policy to try to hurry when working in boreholes.

Efforts to simulate "cementing" have been less successful. First of all, it is impossible to conduct a truly realistic test of "cementing" because no one is sure just what "cementing" is. No one knows what material or materials may become mixed with the sand to create a hardened mixture or just how much time might be involved in this hypothetical process. During the spring of 1995, a dummy KS package was coated with silicone grease and cemented in a short piece of borehole casing with Portland Cement

Concrete. The intention was that concrete would simulate a worst case cementing situation, and that the silicone grease would serve as a mold release and allow the dummy package to slip out of the concrete after it had cured. The annulus between the dummy package and the casing wall was filled with concrete to the top of the dummy package and allowed to cure for three days. This experiment failed because we were not able to pull the dummy package from the concreted piece of casing. A postmortem disassembly of the casing revealed that the silicone grease had indeed prevented adhesion of the concrete to the dummy package. The mode of failure appeared to be radial pressure generated by the expansion of the concrete between the two cylinders.

Therefore, in June of 1996, a new experiment was performed in which the dummy seismometer package was first coated with silicone grease, then wrapped with thin rubber sheet and finally cemented in a short piece of casing. The purpose of the rubber sheet was to provide a compliant medium to absorb the expansion of the concrete and thereby reduce the radial pressure on the dummy package. This time, the dummy package was successfully pulled from the concrete with a peak force of about 1000 pounds.

This configuration solved the cementing problem but questions remained about whether this configuration was quiet. Therefore, on day 265, 1996, KS-54000 serial number 26, which had been coated with silicone grease and wrapped with a thin (1/16" thick) rubber sheet, was installed in a shallow borehole in a holelock and with a centralizer. Two days later on day 267, sand was poured into the borehole. The minimum signal levels for this experiment are tabulated in the lower portions of Tables 6, 7, and 8, and the minimum noise levels are tabulated in the lower portions of Tables 9, 10, and 11.

Both the minimum vertical signal and minimum vertical noise levels in Tables 6 and 9 with the seismometer wrapped in rubber sheeting are approximately the same in all of the bands as they were with no rubber sheeting (days 226 through 260) both before (days 265 through 267) and after (days 267 through 275) the sand was poured in the borehole. However, the north signal and noise minimum levels in Tables 7 and 10 with the rubber sheeting are much higher both in air (days 265 through 267) and after (days 267 through 275) the sand was poured into the borehole than they had been in the earlier installation (days 226 through 260). Similarly, the east signal and noise minimum levels in Tables 8 and 11 with the rubber sheeting on the sensor are also greater than they had been with no rubber sheeting both in air and after the sand was poured into the borehole. It is not surprising that the levels are higher in air because the air is free to convect in this configuration, but the high levels after sand was poured into the hole seems to indicate that sand does not suppress air convection. Or does it?

At the time the experiment was conducted, the results were puzzling but subsequent work revealed an explanation for the high level noise from a sand installed sensor. Later, the same sensor, still wrapped in the rubber sheeting, was installed in sand without a holelock and with no centralizer. No holelock and no centralizer is the configuration being proposed as the standard sand installation configuration. The horizontals were quite noisy and surprisingly the noise levels increased significantly when the wind was blowing; the increased noise levels during windy periods were much greater than had been observed previously. This suggested that air pressure variations were involved; since the borehole packoff unit had not been correctly installed, therefore, it was reinstalled with great care to seal the borehole properly. This change eliminated most of the increased noise levels during windy time periods and reduced the noise levels significantly. However, the sensor was still noisier than it had been without the rubber sheeting.

This suggested that the probable source of the noise lies in the rubber sheeting. Remember that the sheeting was wrapped on a silicone greased sensor. It is highly probable that air bubbles were trapped between the sensor and the rubber sheeting by the grease. An air bubble will act as a "air pressure change to mechanical motion transducer" which generates lateral forces between the sensor and the surrounding sand thereby tending to tilt the sensor package even though it is immersed in sand. Pressure changes within the borehole are quite large if the packoff assembly is not properly assembled. Sealing the top of the borehole eliminates pressure variations due to wind but much smaller pressure changes, which are generated by temperature gradient driven air convection in the sand free portion of the borehole, are large enough to create tilt noise.

To confirm this theory, the sensor was pulled from the hole, the rubber sheeting was removed from the sensor, and the silicone grease was rubbed off the sensor with rags. After reinstallation in sand, several days of operation confirmed that the horizontal noise levels once again assumed the levels produced earlier by this sensor (days 226 through 260).

Finally, members of the seismological community had expressed concern that sand might slowly compact with time thereby gripping the sensor tighter and tighter as time went by. This is a difficult concept to address experimentally because of the long time periods necessary to conduct meaningful experiments. However, we were able to obtain one data point by measuring the force necessary to remove the ANMO KS-54000I sensor after it had been installed in sand for nearly two years. The force required to pull the sensor from the sand was quite small being on the order of 60 pounds or less. In this case at least, there was no evidence that the sand tends to compact with time.

FIELD SAND INSTALLATION PROCEDURES

Installing a KS instrument in sand is a relatively easy procedure compared to the installation procedure used in the past because the holelock, the holelock key, the pilot, the foam hole plugs, the foam wrapping, and the centralizer are not needed. A typical field sand installation would not use a holelock, as was done in the "Snake Pit" installation described in Section 2, because the holelock would probably be buried in sand and lost if the sensor system is ever removed from the hole in the future. Instead of utilizing the holelock to orient the sensor system in the conventional north-south east-west directions, the horizontal components of the sensor are installed at an arbitrary but known azimuth. The holelock key and pilot are not needed because there is no mating holelock. The foam hole plugs and the foam wrapping are not needed because we are controlling air convection generated tilt with the sand. The centralizer is not required because the sand holds the sensor package quite firmly within the borehole. In addition, the complex mechanical linkages in the centralizer are excellent possible sources of additional noise.

The following steps are major changes from previous procedures; they are things that are no longer required.

1. Do not install the holelock key at the bottom of the sensor.
2. Do not install the pilot at the bottom of the sensor.
3. Do not install the holelock in the borehole.
4. Do not wrap the seismometer with foam.
5. Do not install foam plugs anywhere in the borehole.

As far as is known, the type of sand to use is not critical. However, the only sand that has been used to date is ordinary "play ground sand", which is available at most building supply centers in the United States. The sand must be pure sand; impurities that might tend to harden with time such as clay, cement, carbonate containing minerals, etc. must be studiously avoided. To be on the safe side, it probably should be standard policy to ship all sand from ASL to the borehole site in order to maintain control on the quality of the sand.

The following steps are required to install a KS sensor system in a new borehole. These instructions refer to a "standard coffee can". A 39 ounce (2 pound 7 ounce) Folgers coffee can is a "standard coffee can". This can holds about 183.8 cubic inches of sand. If this can is not available, any container of known volume can be used to measure the sand.

1. Install a sand foot cup on the bottom of the sensor package (where the pilot attached previously). Hand tightening should be sufficient.
2. Measure the distance from the bottom of the sand foot to the top of the sensor package in inches (HI in Figure 33 and Tables 3 and 4). Record this distance for use later in Step 12. Measure the inside diameter of the borehole and record this diameter for use later in Steps 3 and 12.
3. Pour enough <u>DRY</u> sand into the borehole to accumulate to about one foot deep on the bottom. For a 6.5" inside diameter borehole, 398 cubic inches (2.1 standard coffee cans) of sand are required. Note: Any foreign object at the bottom should be buried to a depth of about one foot above the top of the object.
4. Install the centralizer on the top of the package. Secure with the nut. Do not install the three springs on the centralizer. Instead, tie the three centralizer legs back with a heavy tie wrap to prevent them from extending.

5. Assemble the remaining hardware (bail, strain relief, soft and hard cables, borehole packoff unit, Golo winch assembly etc.) as is standard procedure.
6. Lower the sensor assembly into the borehole while clamping the soft cable to the hard cable at regular intervals until the sensor just rests on the sand at the bottom of the hole (reduced hard cable tension will be your only clue that the sensor has reached bottom).
7. Lower about 2 more feet of cable into the borehole.
8. Install the packoff assembly - do not tighten it up completely because it will need to be removed later.
9. Unlock and level the sensor modules.
10. Check the data output to see that the sensor system is operating properly. The horizontal components will probably be very noisy at this point.
11. If the sensor appears to be operating, remove enough of the packoff assembly to permit pouring sand down the hole.
12. Pour in enough sand to completely fill the volume between the sensor and the borehole walls to the top of the sensor package.

    Use the inside diameter of the borehole and the sensor height "HI" which were measured and recorded in Step 2 above and <u>Table 3</u> to determine the volume of sand required for a <u>KS-54000</u> installation.

    Use the inside diameter of the borehole and the sensor height "HI" which were measured and recorded in Step 2 above and <u>Table 4</u> to determine the volume of sand required for a <u>KS-36000</u> installation.

    <u>DO NOT PUT IN TOO MUCH SAND!!!</u>

    Too much sand above the top of the package will tend to anchor the sensor in the borehole. We don't want this to happen.
13. After all of the sand is poured down the hole, shake the downhole cable to knock some of the sand off the cable and hopefully the strain relief. Moderate shaking only - don't break anything!
14. Lower about 2 more feet of cable into the borehole.
15. Reinstall the packoff assembly - tighten it up this time.
16. Relevel the sensor modules if necessary.
17. After things settle down (a few hours - preferably overnight), look at the data to see if everything seems to be functioning properly. The lowest VH RMS noise levels printed on the station log for the horizontal components for a given day should be near that being calculated for the vertical component (not more than two or three times the vertical level).
18. Measure the orientation of the sensor system.

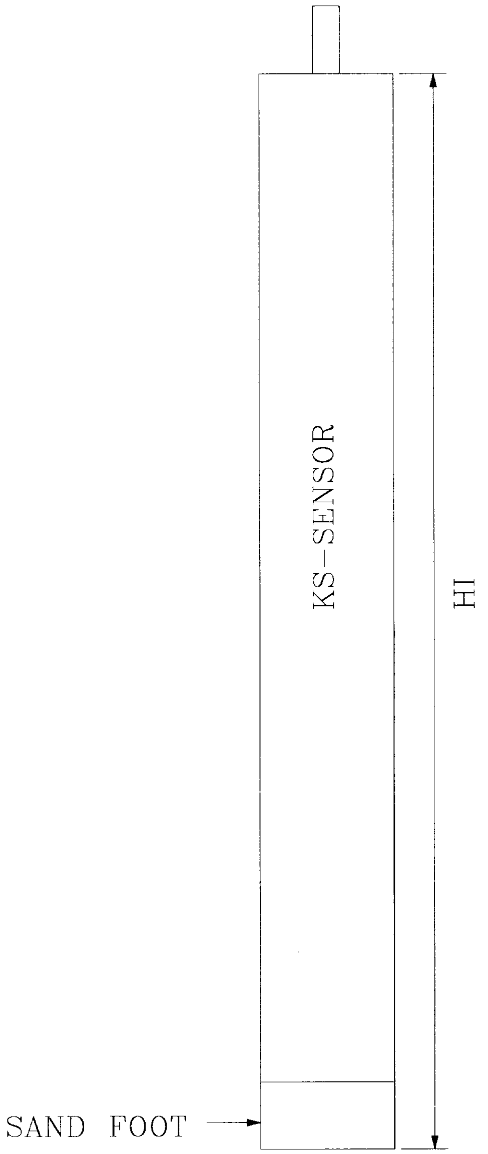

Figure 33. Illustration of the measurement of the dimension "HI" which is defined as the distance from the bottom of the sand foot to the top of the sensor package.

	Diameter = 6.50"			Diameter = 6.75"			Diameter = 7.00"			Diameter = 7.25"		
HI	VOL	CAN	LOST	COL	CAN	LOST	VOL	CAN	LOST	VOL	CAN	LOST
40	420	2.2	12.5	524	2.8	14.6	623	3.4	16.4	744	4.0	18.0
42	441	2.4	13.3	550	2.9	15.4	663	3.6	17.2	781	4.2	18.9
44	462	2.5	13.9	576	3.1	16.1	695	3.7	18.1	818	4.4	19.8
46	483	2.6	14.5	602	3.2	16.8	727	3.9	18.9	855	4.6	20.7
48	504	2.7	15.2	629	3.4	17.6	758	4.1	19.7	892	4.8	21.6
50	525	2.8	15.8	655	3.5	18.3	790	4.2	20.5	930	5.0	22.5
52	546	2.9	16.4	681	3.6	19.0	821	4.4	21.3	967	5.2	23.4
54	567	3.0	17.1	707	3.8	19.8	853	4.6	22.2	1004	5.4	24.3
56	588	3.1	17.7	733	3.9	20.5	884	4.7	23.0	1041	5.6	25.2
58	609	3.3	18.3	759	4.1	21.2	916	4.9	23.8	1078	5.8	26.1
60	630	3.4	19.0	786	4.2	22.0	948	5.1	24.6	1116	6.0	27.0
62	651	3.5	19.6	812	4.4	22.7	979	5.2	25.4	1153	6.2	27.9
64	672	3.6	20.2	838	4.5	23.4	1011	5.4	26.3	1190	6.4	28.8
66	693	3.7	20.9	864	4.6	24.2	1042	5.6	27.1	1227	6.6	29.7
68	713	3.8	21.5	890	4.8	24.9	1074	5.8	27.9	1264	6.8	30.6
70	734	3.9	22.1	917	4.9	25.6	1106	5.9	28.7	1301	7.0	31.5
72	755	4.0	22.8	943	5.1	26.3	1137	6.1	29.5	1339	7.2	32.4
74	776	4.2	23.4	968	5.3	27.1	1168	6.4	30.4	1375	7.5	33.3
76	797	4.3	24.0	995	5.4	27.8	1200	6.5	31.2	1412	7.7	34.2
78	818	4.5	24.7	1021	5.6	28.5	1231	6.7	32.0	1450	7.9	35.1
80	839	4.6	25.3	1047	5.7	29.3	1263	6.9	32.8	1487	9.1	36.0
82	860	4.7	25.9	1073	5.8	30.0	1295	7.0	33.7	1524	8.3	36.9

Table 3. Sand volumes required to bury a KS-54000 to the indicated depths in 6.50, 6.75, 7.00, and 7.25 inch inside diameter boreholes. Column HI is the height of the sand around the sensor measured from the bottom of the sand foot in inches. VOL is the volume of sand required in cubic inches. CAN is the number of "standard coffee cans" required to hold VOL cubic inches of sand. LOST is the length of borehole in inches which will be lost (remain filled with sand) when the sensor is removed from the borehole if the sand is not removed.

	Diameter = 6.50"			Diameter = 6.75"			Diameter = 7.00"			Diameter = 7.25"		
HI	VOL	CAN	LOST	COL	CAN	LOST	VOL	CAN	LOST	VOL	CAN	LOST
40	542	2.9	16.3	646	3.5	18.1	754	4.0	19.6	866	4.6	21.0
42	569	3.0	17.1	678	3.6	19.0	792	4.2	20.6	909	4.9	22.0
44	596	3.2	18.0	711	3.8	19.9	829	4.4	21.6	952	5.1	23.1
46	623	3.3	18.8	743	4.0	20.8	867	4.6	22.5	996	5.3	24.1
48	650	3.5	19.6	775	4.2	21.7	905	4.8	23.5	1039	5.6	25.2
50	677	3.6	20.4	807	4.3	22.6	942	5.1	24.5	1082	5.8	26.2
52	705	3.8	21.2	840	4.5	23.5	980	5.3	25.5	1126	6.0	27.3
54	732	3.9	22.0	872	4.7	24.4	1018	5.5	26.4	1169	6.3	28.3
56	759	4.1	22.9	904	4.8	25.3	1056	5.7	27.4	1212	6.5	29.4
58	786	4.2	23.7	937	5.0	26.2	1093	5.9	28.4	1256	6.7	30.4
60	813	4.4	24.5	969	5.2	27.1	1131	6.1	29.4	1299	7.0	31.5
62	840	4.5	25.3	1001	5.4	28.0	1169	6.3	30.4	1342	7.2	32.5
64	867	4.6	26.1	1034	5.5	28.9	1206	6.5	31.3	1385	7.4	33.6
66	894	4.8	26.9	1066	5.7	29.8	1244	6.7	32.3	1429	7.7	34.6
68	921	4.9	27.8	1098	5.9	30.7	1282	6.9	33.3	1472	7.9	35.7
70	948	5.1	28.6	1130	6.1	31.6	1319	7.1	34.3	1515	8.1	36.7
72	975	5.2	29.4	1163	6.2	32.5	1357	7.3	35.3	1559	8.4	37.8
74	1003	5.4	30.21	1195	6.4	33.4	1395	7.5	36.2	1602	8.6	38.8
76	1030	5.5	31.0	1227	6.6	37.0	1433	7.7	37.2	1645	8.8	39.9
78	1056	5.8	31.8	1259	6.9	35.2	1470	8.0	38.2	1688	9.2	40.0
80	1083	5.9	32.7	1291	7.0	36.1	1507	8.2	39.2	1731	9.4	42.0
82	1110	6.0	33.5	1324	7.2	37.0	1545	8.4	40.2	1775	9.7	43.0

Table 4. Sand volumes required to bury a KS-36000 to the indicated depths in 6.50, 6.75, 7.00, and 7.25 inch inside diameter boreholes. Column HI is the height of the sand around the sensor measured from the bottom of the sand foot in inches. VOL is the volume of sand required in cubic inches. CAN is the number of "standard coffee cans" required to VOL cubic inches of sand. LOST is the length in inches of borehole which will be lost (remain filled with sand) when the sensor is removed from the borehole if the sand is left in the hole.

THE SNZO PROOF OF CONCEPT EXPERIMENT

The results of the snake pit sand installation experiment and the COLA station installation were presented at the IRIS Standing Committee meeting at Harvard on November 12-13, 1996. The Standing Committee requested that the technique be demonstrated at an existing borehole site that had been producing relatively noisy horizontal data for a long time. The station at South Karori, New Zealand (SNZO) was chosen as the site because the horizontals had been noisy since the station was first installed in the mid 1970's.

The necessary equipment and supplies were shipped to New Zealand and AlliedSignal Field Engineer Chuck Cazier arrived at the site in late January, 1997. The existing KS-36000 seismometer was removed from the borehole, converted to a sand installation configuration, and reinstalled in sand February 8 (day 39) 1997. A few days of data system software modification and station calibration followed with routine undisturbed operation beginning on about day February 11 (day 42) of 1997.

The results of installing the sensor in sand are presented in Figures 34, 35 and 36. The RMS noise level for the vertical component remained unchanged by the sand (see Figure 34). However, the RMS noise levels for both the north and east components decreased approximately 15 db after the sand was put in the hole (see Figures 35 and 36 respectively). With sand in the hole, the horizontals are only slightly noisier than the vertical component (See SNZO in Figure 37). These results are exactly what should be expected if air convection generated tilt was causing the horizontal noise because tilt should not cause nearly as much noise in the vertical component; therefore, it was quiet to begin with. Filling up the volume around the seismometer with sand prevents air convection thereby decreasing tilt generated horizontal noise.

The results of adding sand to the SNZO borehole are also shown in the frequency domain PSD surfaces in Figures 38, 39, and 40. These surfaces are constructed from daily median PSD estimates calculated as follows. First, a given day of 1 sample per second time domain data from a given channel was divided into 2048 second segments with a 50% overlap between segments. The FFT of each segment was then converted to PSD and the FFT bin wise median of these 84 PSD segments was evaluated. This yielded the "daily median" PSD estimate for that channel and day; these spectra are plotted on a logrithemic acceleration PSD scale between 30 and 2048 seconds over a 125 day period to create the PSD surfaces in the figures. At this point, it should be mentioned that the source of the peak near 500 seconds in all three figures both before and after sand was added to the borehole is unknown.

To assist in determining the levels of the PSD surfaces, the daily PSD levels at 127 and 256 seconds have been highlighted in all three figures and straight line segment fits have been "eyeballed" through these PSD levels at these two periods.

Note the essentially constant PSD level across the long period band which is evident in the PSD surface for the SNZO vertical in Figure 38 both before and after sand was put in the borehole. The performance of the vertical component was not influenced by the sand. However, note the decrease in the north and east horizontal PSD levels between 30 and 600 seconds produced by the sand installation (Figures 39 and 40 respectively). Also note that the horizontal long period PSD levels before the sand installation were very constant and smooth whereas the horizontal PSD levels after the sand installation show some variation and roughness with time. The constant PSD levels before the sand installation were probably due to steady state air convection generated tilt noise within the borehole in the vicinity of the sensor. The variation of the PSD level after the sand installation probably arises from tilt sources external to the borehole system; the chief source of this variation is quite probably due to changes in the state of the sea which is only about 4 kilometers from the site.

The decrease of the PSD level after the sand was put in the hole in the horizontal PSD surfaces in Figures 39 and 40 at 128 and 256 seconds is 12.4 and 14.4 db for the north component and 11.5 and 12.5 db for the east component. The PSD decrease at 128 seconds was determined by calculating the db decrease between the average of the PSD level at 128 seconds (circles) before sand was poured into the borehole to the average of the PSD level after sand was poured in. The PSD decrease at 256 seconds was determined in the same manner. The PSD surface estimated changes in the noise level are approximately equal to the 15.3 db decrease for both components as calculated by the 25 minimum averaged RMS noise level method. In contrast, the same calculation for the vertical channel yields a change of only 0.4 db at 128 seconds and 0.3 db for 256 seconds; vertical noise levels were essentially unchanged by the sand installation.

The results of the SNZO experiment were presented to the IRIS Standing Committee at their meeting at Disney World on March 5-6, 1977. The committee agreed that the experiment was a success and that in the future ASL could install KS sensors in sand at it's own discretion.

The data in Figure 37 provides an estimate of how much improvement that should be expected by converting several of the existing borehole sites to sand installations. Reinstalling the sensors in sand should produce horizontal noise levels equal to or slightly greater than the noise level for the vertical component at that site. At BDFB, CPUP, LBTB, VNDA, SHEL, and MSEY the vertical noise levels are rather low so a sand installation should result in a large improvement in the horizontal noise levels. The potential reductions of horizontal noise levels are tabulated in Table 5 for all of the non sand borehole stations in Figure 37. Smaller but quite significant decreases in noise levels should be expected at additional sites not shown in Figure 37 and Table 5.

CHTO	RAR	TATO	BDFB	CPUP	LBTB	VNDA	BORG	SHEL	MSEY
14.3	19.1	20.8	28.9	38.0	20.0	36.0	31.4	20.0	27.2

Table 5. Potential horizontal noise reduction figures in db which could be produced by converting these stations to sand installations.

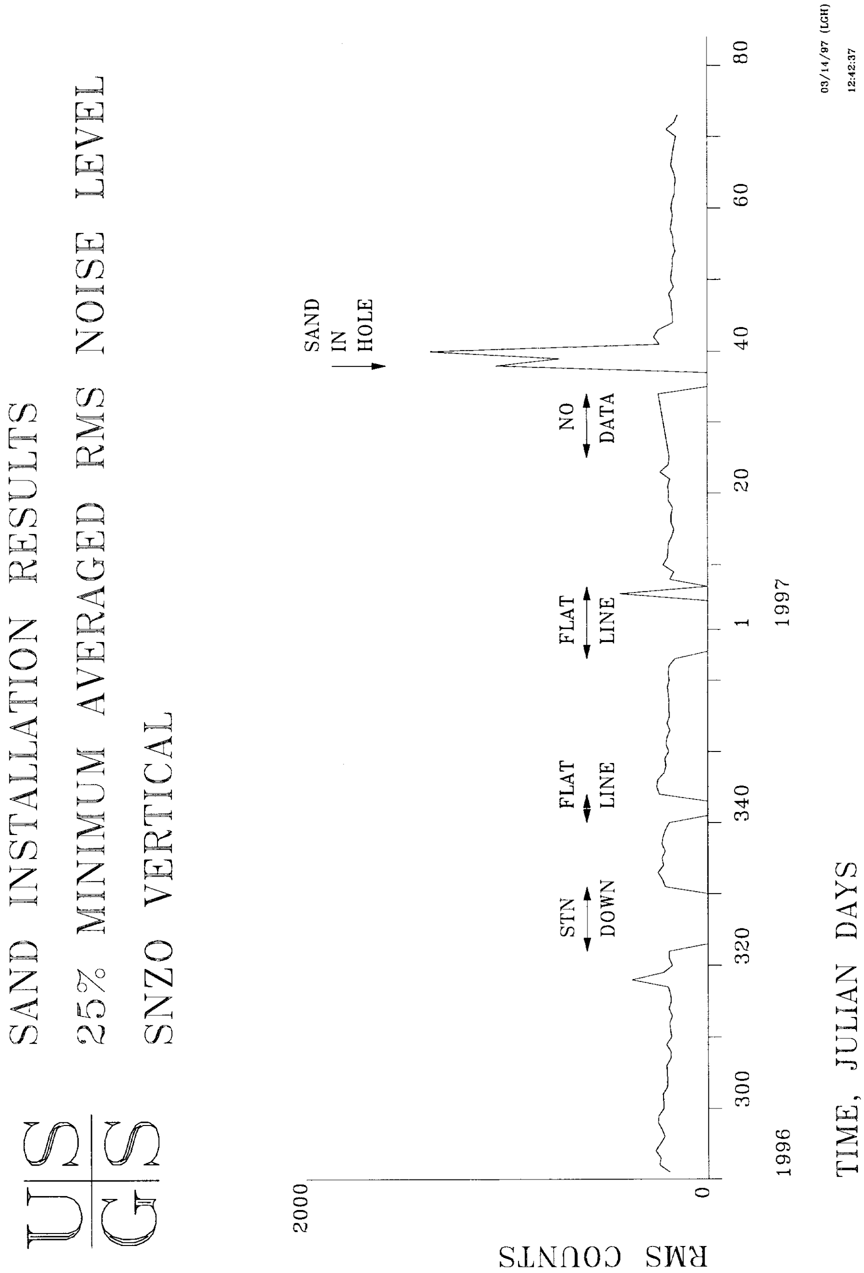

Figure 34. The 25% minimum averaged RMS vertical noise level at SNZO before and after the sensor was installed in sand.

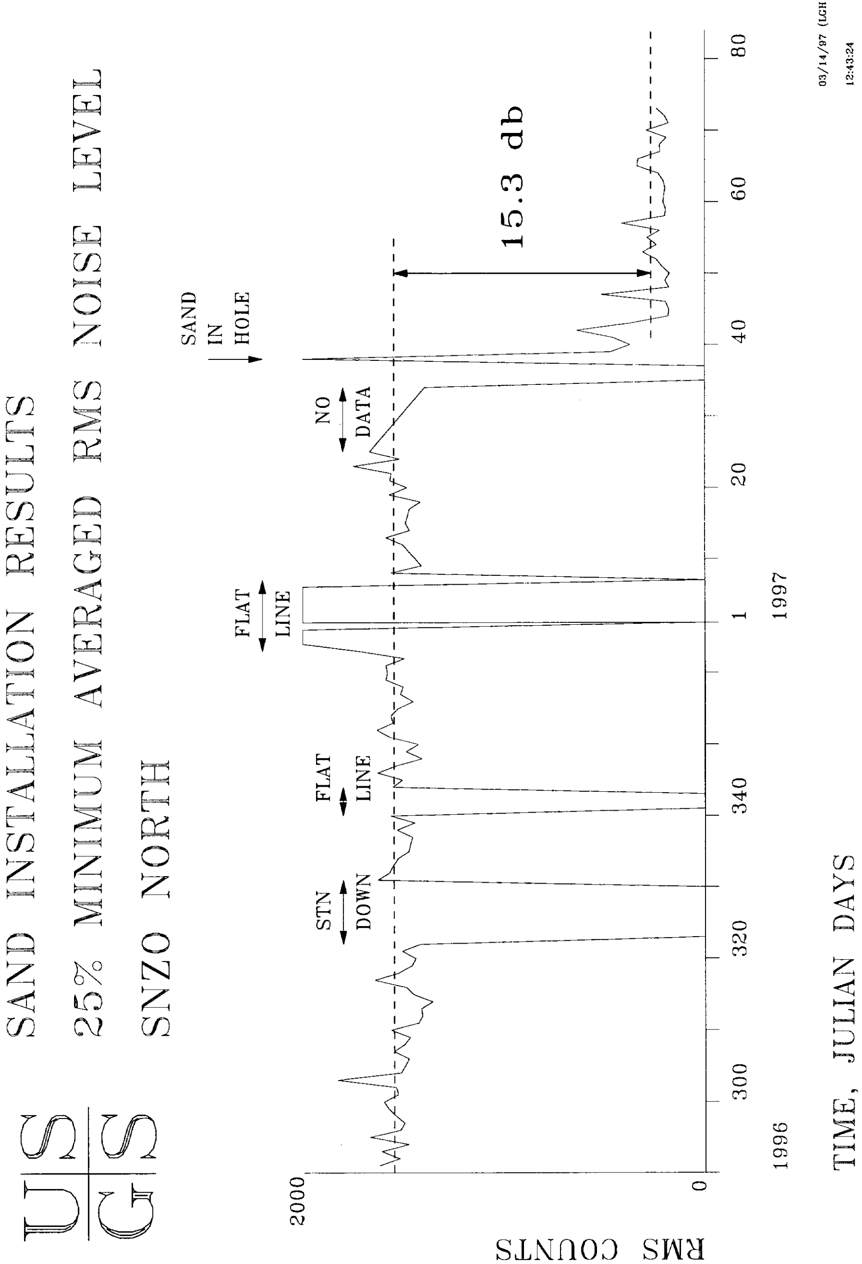

Figure 35. The 25% minimum averaged RMS north noise level at SNZO before and after the sensor was installed in sand.

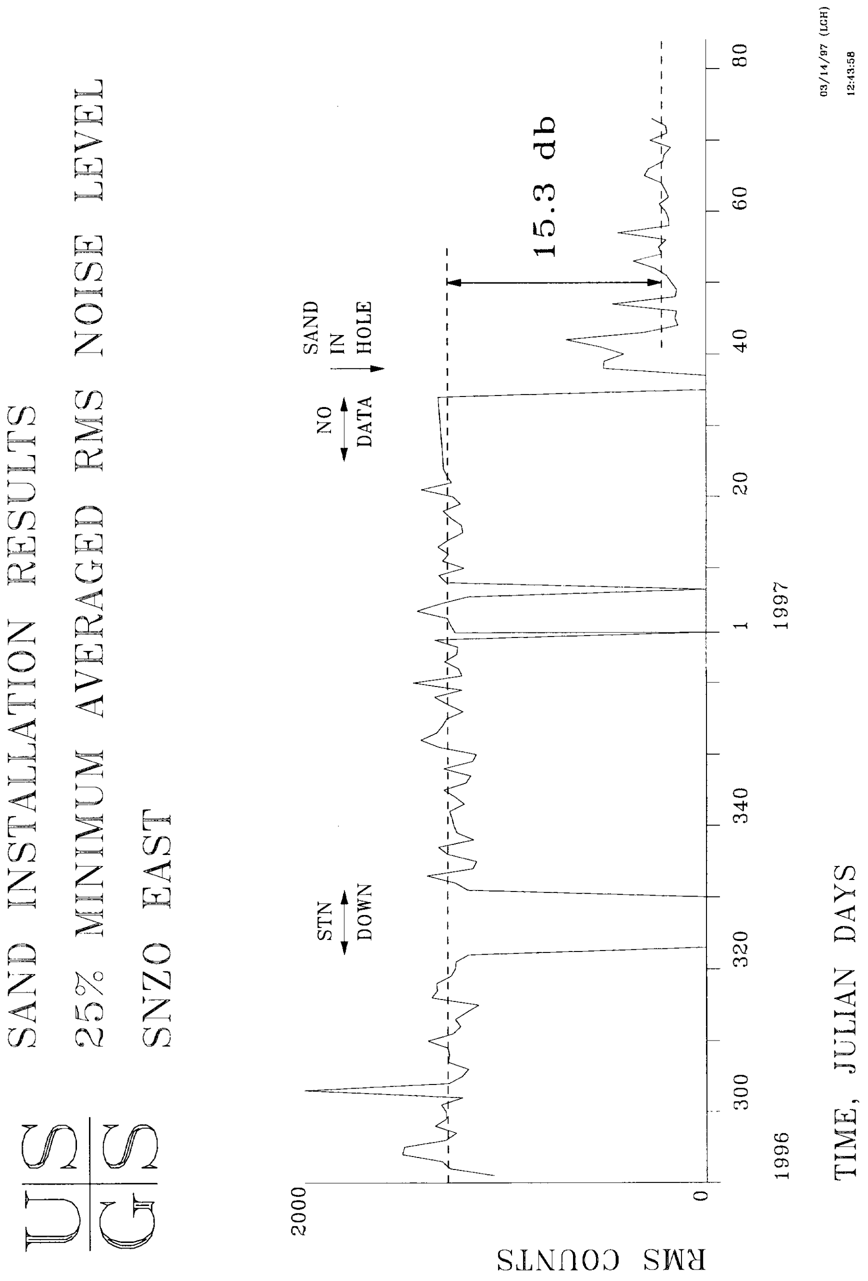

Figure 36. The 25% minimum averaged RMS east noise level at SNZO before and after the sensor was installed in sand.

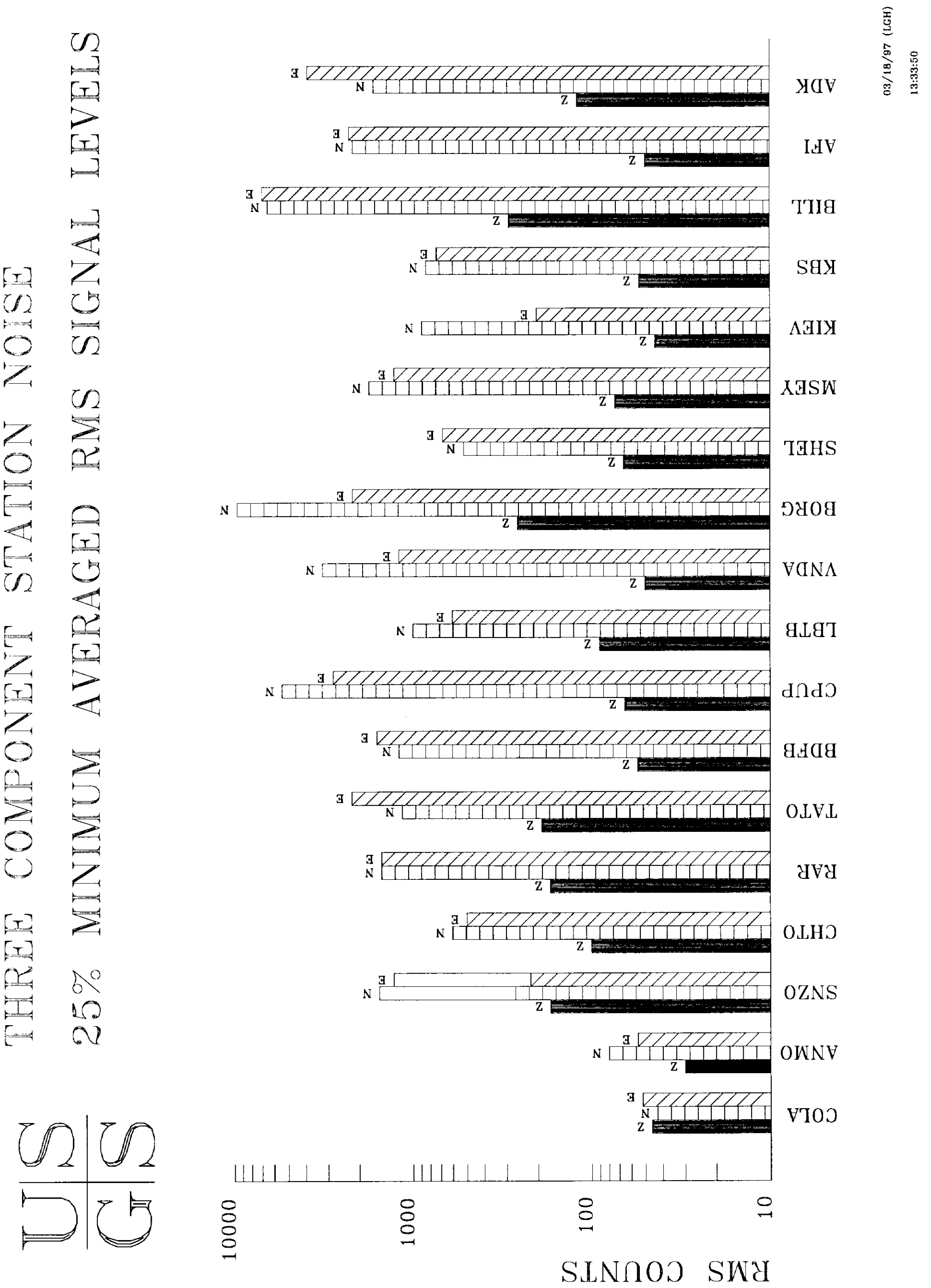

Figure 37. Selected 25% averaged RMS noise levels from the three currently existing sand installations (COLA, ANMO, and SNZO), from several noisy borehole sites (stations CHTO through MSEY), and from five conventional surface installations (KIEV through ADK). The Horizontal noise levels at SNZO before the sand installation are shown as empty bars under N and E. The Horizontal noise levels at SNZO after sand are shown as the shaded portion of the same bars.

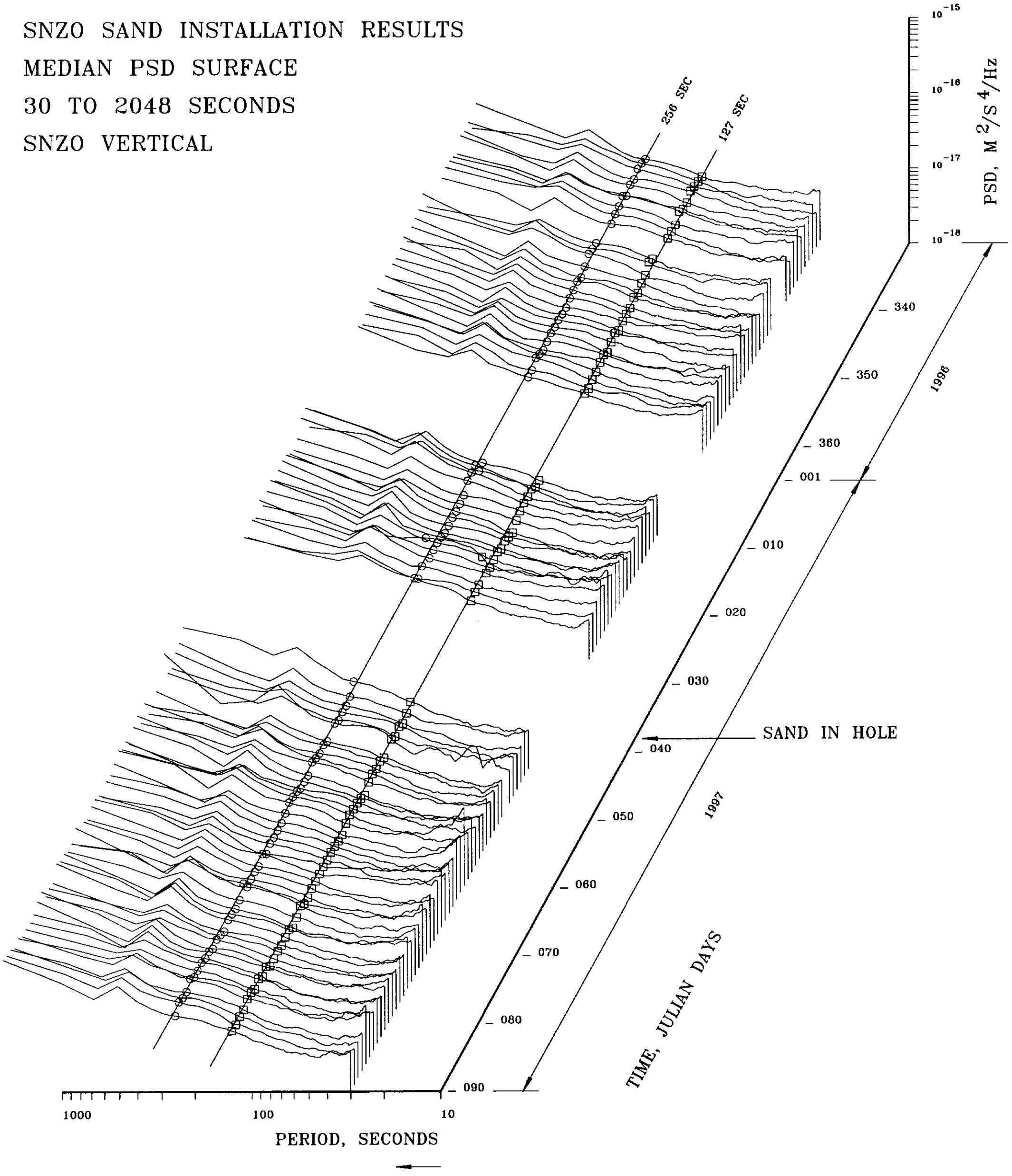

Figure 38. Median power spectral density surface for the vertical component before and after sand in the borehole at SNZO. The circles are the PSD levels at 256 seconds on each day and the squares are the PSD levels at 127 seconds.

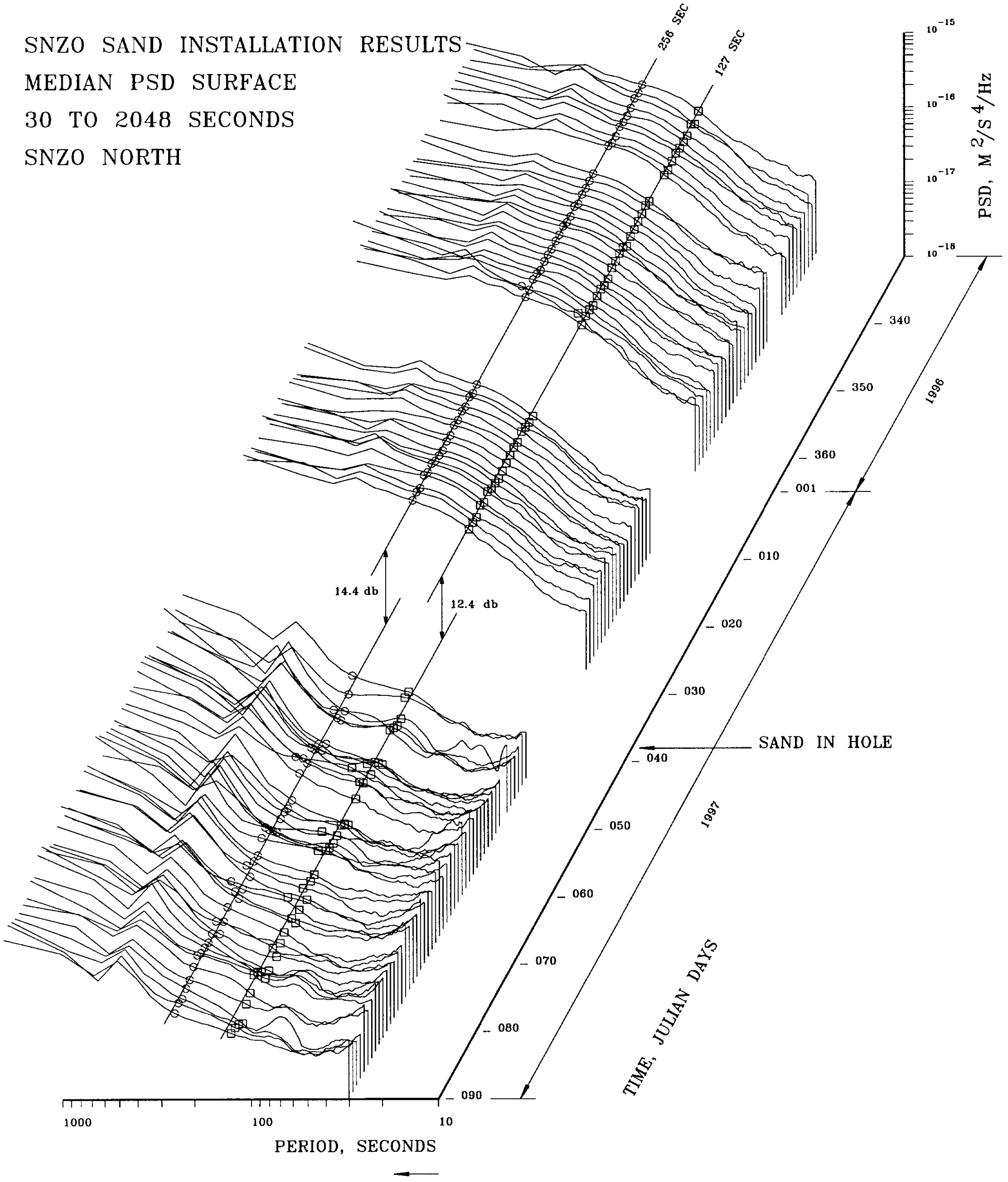

Figure 39. Median power spectral density surface for the north component before and after sand in the borehole at SNZO. The circles are the PSD levels at 256 seconds on each day and the squares are the PSD levels at 127 seconds.

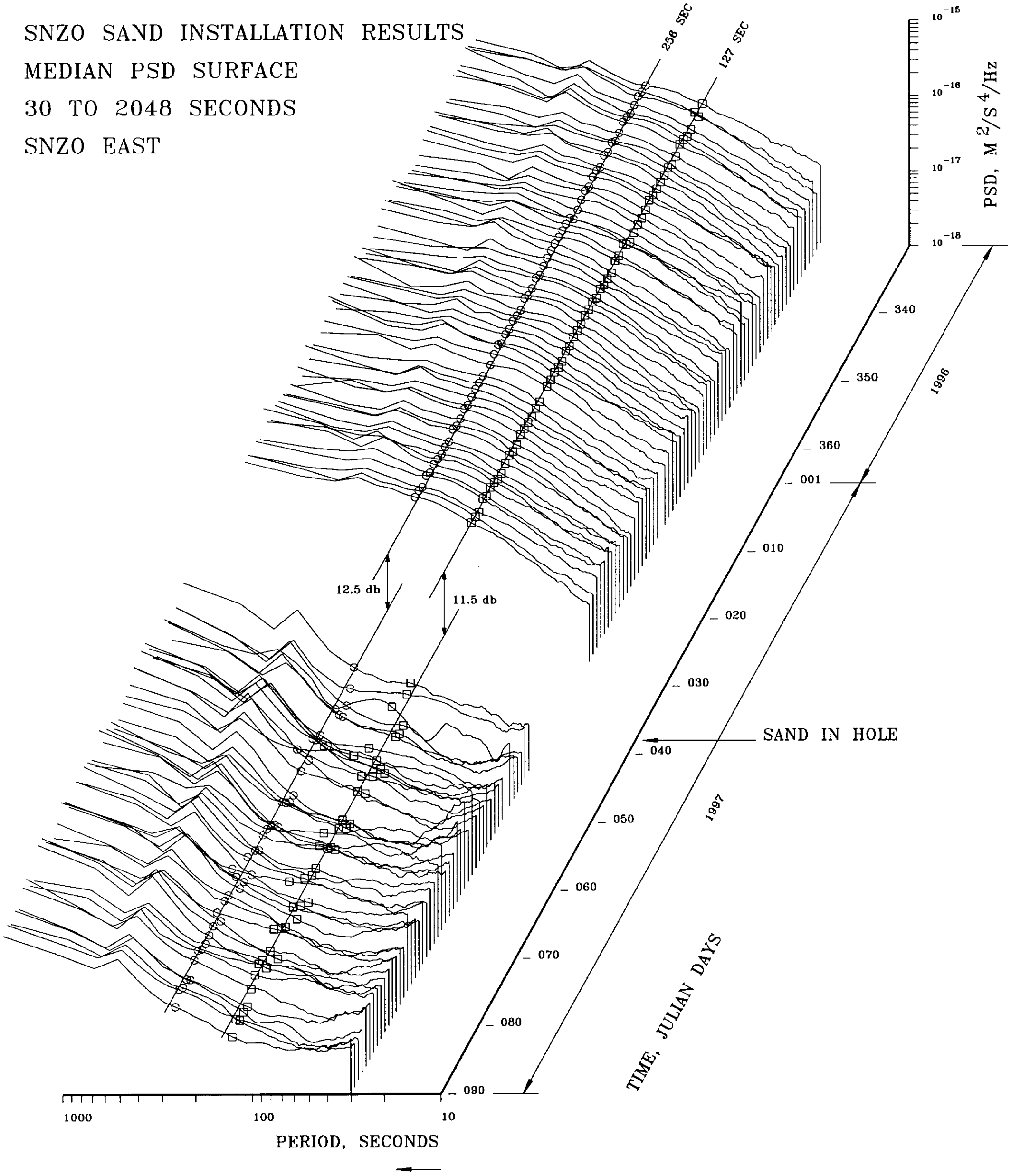

Figure 40. Median power spectral density surface for the east component before and after sand in the borehole at SNZO. The circles are the PSD levels at 256 seconds on each day and the squares are the PSD levels at 127 seconds.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40-70	70-100	100-200	200-400	400-700	700-2048
219-221	3.51	4.24	8.27	23.96	84.72	1331
221-223	3.07	5.09	11.36	18.46	68.45	842
223-225	2.54	3.12	8.44	17.00	77.76	1124
Averages	3.04	4.15	9.36	19.81	76.98	1099
Sand poured into serial number 26 borehole on day 225						
226-228	2.47	2.89	7.51	15.33	60.95	951
228-231	1.52	2.58	4.97	12.47	65.42	662
231-233	1.53	2.04	3.71	11.01	67.89	1228
233-236	1.60	2.00	4.79	11.19	63.94	1149
236-238	2.31	3.05	5.70	13.92	59.72	726.
238-241	1.96	2.75	5.61	17.28	59.68	731.
241-243	2.16	3.08	5.06	13.14	42.38	247
243-246	1.90	2.35	3.75	14.74	77.53	384
246-248	2.29	3.45	6.06	15.32	70.27	968
248-250	3.14	3.48	7.29	30.96	77.32	837
250-253	1.65	2.66	4.86	13.74	84.72	984
253-255	1.54	1.84	3.52	10.84	54.97	578
256-258	1.95	2.77	4.66	13.88	80.93	854
258-260	2.21	2.56	5.12	11.99	65.51	645
Averages	2.02	2.68	5.19	14.70	66.52	782
Delta db	-1.78	-1.90	-2.56	-1.29	-0.63	-1.48
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	1.44	2.02	3.13	9.20	53.19	750
Sand poured into serial number 26 borehole on day 267						
267-270	1.74	2.32	3.39	8.26	67.46	1451
270-272	1.43	2.20	3.77	9.29	63.77	737
272-275	1.89	2.46	3.81	9.71	49.74	619

Table 6. Tabulation of the vertical band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	11.33	42.83	79.23	159	336	3310
221-223	12.61	36.26	70.25	111	577	3973
223-225	10.65	31.31	61.94	116	382	3745
Averages	11.53	36.80	70.47	129	432	3676
Sand poured into serial number 26 borehole on day 225						
226-228	2.58	5.88	11.98	32.37	120	738
228-231	1.85	3.51	6.90	14.53	109	1068
231-233	1.52	3.19	7.39	16.99	130	2723
233-236	1.61	2.98	6.80	13.50	111	940
236-238	2.23	3.92	7.99	18.31	106	983
238-241	1.77	3.13	7.39	17.93	151	1830
241-243	2.62	4.10	9.38	25.42	83.89	715
243-246	2.56	3.94	7.11	17.30	90.00	631
246-248	2.36	3.74	6.75	12.69	81.71	853
248-250	3.04	4.04	10.02	23.86	116	759
250-253	2.02	3.45	8.10	19.32	113	1190
252-255	1.64	2.52	5.61	18.33	80.79	738
255-258	1.79	2.85	5.35	9.33	176	1540
258-260	2.41	3.33	8.05	23.35	144	1246
Averages	2.14	3.61	7.77	18.80	115	1140
Delta db	-7.31	-10.08	-9.67	-8.35	-5.74	-5.09
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	4.14	11.19	22.56	67.04	195	1258
Sand poured into serial number 26 borehole on day 267						
267-270	4.33	6.28	16.77	87.46	781	6450
270-272	4.37	8.55	22.96	118	500	6211
272-275	4.57	6.57	13.25	40.58	125	1406

Table 7. Tabulation of the north band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	36.58	105	296	767	2387	8326
221-223	44.20	92.98	280	705	3238	8923
223-225	36.39	85.04	264	618	1618	12790
Averages	39.06	93.34	280	697	2414	10013
Sand poured into serial number 26 borehole on day 225						
226-228	2.67	5.44	10.79	27.15	117	873
228-231	2.20	4.15	6.30	15.49	107	1512
231-233	1.95	3.29	7.36	19.23	132	1808
233-236	1.88	3.60	5.12	20.14	154	1421
236-238	2.53	4.87	10.02	24.02	104.	1263.
238-241	2.04	3.51	7.70	19.12	131	1002
241-243	2.91	5.09	8.37	30.98	256	1408
243-246	2.51	3.56	6.50	17.13	101	830
246-248	2.47	4.03	6.20	15.42	88.83	1199
248-250	3.50	3.78	8.68	23.70	114	1786
250-253	2.52	3.80	7.05	22.17	123	897
253-255	1.86	3.09	7.67	34.44	117	1000
255-258	2.03	3.36	6.18	24.48	292	1371
258-260	2.59	4.24	8.99	37.83	259	2196
Averages	2.40	3.99	7.64	23.66	150	1326
Delta db	-12.11	-13.69	-15.64	-14.69	-12.08	-8.78
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	3.96	5.39	20.72	82.62	262	3032
Sand poured into serial number 26 borehole on day 267						
267-270	6.94	10.77	22.24	89.85	577	6652
270-272	5.65	9.23	26.52	168	1367	10280
272-275	4.52	6.36	16.27	39.49	238	2156

Table 8. Tabulation of the east band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	2.38	3.38	6.04	16.11	42.72	941
221-223	2.09	3.78	9.10	15.36	45.88	802
223-225	1.11	2.09	5.78	12.18	48.02	621
Averages	1.86	3.08	6.97	14.55	45.54	788
Sand poured into serial number 26 borehole on day 225						
226-228	1.08	1.61	4.66	12.55	32.64	1206
228-231	0.91	1.41	3.29	9.65	49.65	526
231-233	0.81	1.19	2.49	8.66	31.90	717
233-236	0.77	1.24	3.35	9.20	34.93	610
236-238	1.25	1.63	3.98	11.14	41.33	421
238-241	0.84	1.43	3.40	14.29	46.05	381
241-243	0.83	1.30	2.89	9.40	25.77	940
243-246	0.73	1.18	2.25	12.36	57.05	263
246-248	1.10	1.60	3.59	12.52	49.51	992
248-250	1.26	2.08	4.60	21.17	53.72	737
250-253	0.88	1.50	3.08	9.95	56.81	1141
253-255	0.74	1.00	1.81	8.73	34.91	325
255-258	0.72	1.14	2.23	9.68	45.96	1265
258-260	0.85	1.31	3.21	8.75	34.13	342
Averages	0.92	1.40	3.20	11.29	42.45	705
Delta db	-3.07	-3.42	-3.38	-1.10	-0.30	-0.49
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	0.35	0.58	1.70	6.59	33.37	1288
Sand poured into serial number 26 borehole on day 267						
267-270	0.52	0.82	1.52	5.36	33.87	1451
270-272	0.44	0.86	1.60	5.97	39.60	907
272-275	0.56	0.96	2.09	7.90	31.28	683

Table 9. Tabulation of the vertical band-averaged noise levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	12.87	37.36	60.28	135	202	1756
221-223	11.57	32.87	57.43	82.72	308	1900
223-225	9.36	28.07	49.61	88.23	192	2509
Averages	11.27	32.77	55.77	102	234	2055
Sand poured into serial number 26 borehole on day 225						
226-228	0.38	0.56	2.40	4.33	12.25	508
228-231	0.28	0.44	1.96	5.71	14.05	578
231-233	0.18	0.17	2.04	2.76	15.94	988
233-236	0.34	0.57	2.22	5.92	11.35	173
236-238	0.23	1.11	1.73	4.65	19.00	393
238-241	0.15	0.60	1.68	4.42	28.94	1132
241-243	0.23	0.97	3.73	11.63	22.19	517
243-246	0.42	0.53	1.06	7.99	17.48	157
246-248	0.33	1.09	2.74	3.60	31.59	369
248-250	0.36	0.51	3.44	7.57	16.68	423
250-253	0.32	0.69	3.04	5.87	24.34	1333
253-255	0.33	1.05	1.74	3.67	61.89	478
255-258	0.13	0.62	3.49	2.46	66.81	1066
258-260	0.25	0.60	1.12	8.96	55.12	512
Averages	0.28	0.68	2.31	5.68	28.40	616
Delta db	-16.04	-16.83	-13.82	-12.54	-9.16	-5.23
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	2.53	9.49	15.05	54.28	92.11	673
Sand poured into serial number 26 borehole on day 267						
267-270	2.32	3.43	9.67	53.91	323	6275
270-272	2.18	3.91	13.56	65.60	132	4233
272-275	2.30	3.29	9.19	18.69	29.51	1050

Table 10. Tabulation of the north band-averaged noise levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	37.97	102	244	632	1525	5652
221-223	38.97	92.15	255	586	2437	8283
223-225	29.69	80.46	211	449	921	10940
Averages	35.54	91.54	237	556	1628	8292
Sand poured into serial number 26 borehole on day 225						
226-228	0.51	0.44	4.02	7.28	234	1441
228-231	0.39	0.26	1.64	9.96	34.53	815
231-233	0.48	0.53	2.89	12.50	42.72	1252
233-236	0.34	1.01	1.02	8.27	46.19	336
236-238	0.43	0.49	2.98	6.24	21.27	466
238-241	0.30	0.91	4.16	8.78	53.24	583
241-243	0.52	0.83	1.14	9.44	47.19	1045
243-246	0.38	0.93	1.56	2.31	36.80	559
246-248	0.55	0.78	1.50	2.26	14.39	416
248-250	0.27	0.71	4.63	5.92	41.72	916
250-253	0.48	0.27	1.44	4.78	21.40	539
253-255	0.26	0.18	1.54	13.80	28.65	123
255-258	0.16	0.56	3.75	7.12	124	951
258-260	0.31	0.69	2.11	12.17	33.36	186
Averages	0.38	-/61	2.46	7.92	55.68	688
Delta db	-19.66	-21.74	-19.84	-18.46	-14.66	-10.81
Remove sensor, wrap in rubber sheeting, reinstall in air						
265-267	1.07	3.27	11.83	70.58	200	1630
Sand poured into serial number 26 borehole on day 267						
267-270	2.72	6.28	12.97	59.53	362	9727
270-272	2.13	5.52	10.46	57.83	825	9848
272-275	1.26	2.46	7.98	21.78	135	1611

Table 11. Tabulation of the east band-averaged noise levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 26 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	1.15	1.37	2.86	11.78	39.48	380
221-223	1.52	1.77	2.98	5.95	40.70	434
223-225	1.38	1.97	3.77	6.78	38.75	512
226-228	1.72	1.75	2.77	5.58	46.25	564
228-231	0.88	1.30	2.13	5.17	37.71	581
231-233	0.56	0.57	1.21	3.37	18.83	233
233-236	1.04	1.44	2.57	5.71	39.69	451
236-238	1.27	1.54	2.51	5.23	42.66	675
238-241	1.42	1.64	3.39	7.58	36.04	527.
Averages	1.22	1.48	2.69	6.35	37.79	484
Sand poured into serial number 114 borehole on day 241						
241-243	1.67	1.98	3.21	7.80	54.80	742
243-246	1.40	1.46	2.12	4.95	29.17	487
246-248	1.47	1.77	2.64	5.91	43.85	849
248-250	1.61	2.06	2.49	11.97	47.05	874
250-253	1.27	1.32	2.48	5.59	40.23	547
253-255	1.06	1.09	2.43	5.51	32.15	648
255-258	1.22	1.57	2.63	5.59	45.56	828
258-260	1.48	1.77	3.00	7.69	32.41	490
260-262	1.77	1.88	3.83	5.31	36.59	1025
262-265	2.22	2.01	3.05	7.17	44.09	428
265-267	1.38	1.87	2.95	6.44	29.89	253
267-270	1.49	1.85	2.67	7.72	54.42	508
270-272	1.34	1.43	2.91	6.57	45.56	693
272-275	1.61	2.10	3.11	6.95	47.43	437
Averages	1.50	1.73	2.82	6.80	41.66	629
Delta db	0.91	0.66	0.21	0.30	0.42	1.14

Table 12. Tabulation of the vertical band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	2.00	4.41	11.82	52.03	247	2232
221-223	2.47	4.88	8.32	24.15	364	3223
223-225	2.13	5.64	13.64	53.13	256	2255
226-228	3.41	7.02	17.59	74.04	356	2576
228-231	2.54	4.66	11.29	31.55	287	2738
231-233	1.41	2.57	6.78	21.78	312	2317
233-236	1.67	2.85	7.47	23.24	293	2484
236-238	3.33	5.83	14.11	90.50	517	3843
238-241	2.75	4.87	11.40	44.32	414	6710
Averages	2.41	4.75	11.38	46.08	338	3153
Sand poured into serial number 114 borehole on day 241						
241-243	4.24	10.72	21.56	94.52	1072	6396
243-246	6.37	11.46	49.98	252	1391	7185
246-248	5.60	10.94	45.66	150	626	4644
248-250	6.55	11.32	40.96	162	897	5137
250-253	5.69	13.02	45.93	135	771	6826
253-255	5.13	9.76	40.76	178	993	6943
255-258	7.13	13.32	48.76	233	1059	7241
258-260	6.48	10.70	40.48	248	1004	7459
260-262	6.85	13.87	50.81	253	1102	8762
262-265	8.60	13.52	54.29	230	1592	7704
265-267	6.10	10.26	36.70	164	696	4651
267-270	7.04	10.88	42.09	199	814	7601
270-272	5.92	13.59	42.98	185	1246	8219
272-275	5.68	11.72	37.75	140	555	6049
Averages	6.31	11.79	42.77	187	987	6772
Delta db	4.18	3.95	5.75	6.09	4.65	3.32

Table 13. Tabulation of the north band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	3.57	6.78	28.36	86.97	624	3962
221-223	7.69	12.22	23.30	84.36	1156	15630
223-225	6.76	13.18	33.41	157	1036	13310
226-228	4.91	10.10	23.26	82.10	380	2670
228-231	3.35	7.65	16.28	64.81	594	5063
231-233	3.81	10.10	24.46	80.78	557	6969
233-236	3.40	7.61	19.50	105	838	8299
236-238	8.49	13.26	30.62	144	1134	10740
238-241	7.59	14.75	67.07	162	1449	26500
Averages	5.11	10.63	29.58	107	896	10349
Sand poured into serial number 114 borehole on day 241						
241-243	4.01	9.74	24.48	86.35	713	7038
243-246	4.74	8.86	28.36	128	600	3437
246-248	4.99	9.21	33.73	114	583	3835
248-250	6.77	11.98	41.34	188	794	6765
250-253	5.98	11.09	33.78	134	641	3434
253-255	5.35	10.59	39.27	166	563	3506
255-258	6.07	11.98	45.70	229	1005	4980
258-260	7.36	10.74	41.20	161	920	6772
260-262	7.56	14.86	40.39	180	950	4228
262-265	9.35	13.28	35.12	147	537	2622
265-267	6.09	10.08	36.18	129	516	4162
267-270	7.34	12.26	35.49	131	570	2589
270-272	6.79	10.54	43.62	130	584	5244
272-275	6.58	11.88	41.18	115	523	3576
Averages	6.36	11.22	37.13	146	679	4442
Delta db	0.62	0.24	0.99	1.32	-1.21	-3.67

Table 14. Tabulation of the east band-averaged signal levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the signal level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	0.31	0.79	0.69	2.26	23.43	387
221-223	0.40	0.46	0.81	2.70	16.39	454
223-225	0.22	0.30	0.34	2.96	17.55	219
226-228	0.23	0.10	0.54	2.91	19.36	880
228-231	0.28	0.29	0.32	2.29	13.04	216
231-233	0.25	0.30	0.84	1.62	10.31	334
233-236	0.26	0.26	1.00	1.91	15.77	287
236-238	0.21	0.22	0.82	2.98	18.51	427
238-241	0.40	0.53	0.85	2.67	20.65	674
Averages	0.28	0.36	0.69	2.48	17.23	431
Sand poured into serial number 14 borehole on day 241						
241-243	0.26	0.25	0.77	3.20	19.08	307
243-246	0.29	0.25	0.83	1.40	13.21	79.31
246-248	0.31	0.20	0.70	2.31	15.16	769
248-250	0.35	0.57	0.63	4.89	18.99	691
250-253	0.38	0.55	0.91	2.16	7.73	296
253-255	0.41	0.52	0.89	1.86	14.13	594
255-258	0.31	0.40	0.64	3.59	13.59	1096
258-260	0.32	0.53	1.03	4.52	17.23	833
260-265	No noise level estimates - #26 was not operating					
265-267	0.28	0.54	1.46	3.69	16.98	198
267-270	0.35	0.50	1.05	5.16	30.77	1635
270-272	0.33	0.34	0.70	4.05	19.62	650
272-275	0.31	0.50	1.13	4.79	33.06	329
Averages	0.33	0.43	0.89	3.47	18.30	623
Delta db	0.59	0.75	1.13	1.46	0.26	1.60

Table 15. Tabulation of the vertical band-averaged noise levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40 -70	70-100	100-200	200-400	400-700	700-2048
219-221	0.42	1.14	5.22	17.16	117	1520
221-223	1.33	1.51	3.76	9.37	93.47	523
223-225	1.09	3.16	6.51	34.18	93.25	1215
226-228	0.94	1.59	7.55	34.18	215	2517
228-231	0.91	2.25	3.37	16.46	127	1783
231-233	0.89	1.76	3.93	13.21	184	1580
233-236	0.54	0.93	3.53	12.24	170	1646
236-238	1.37	2.37	7.10	43.49	297	2917
238-241	1.35	2.00	5.92	35.47	214	6333
Averages	0.98	1.86	5.21	23.97	168	2226
Sand poured into serial number 114 borehole on day 241						
241-243	2.38	6.17	13.90	61.72	723	4446
243-246	4.05	9.02	38.84	194	1088	6687
246-248	3.36	8.96	37.69	134	512	3736
248-250	3.86	9.70	31.17	145	509	5050
250-253	4.17	11.48	37.66	107	543	5604
253-255	4.05	8.63	33.55	136	757	5320
255-258	4.94	12.58	36.71	189	772	4318
258-260	4.35	9.05	31.22	212	659	6105
260-265	No noise level estimates - #26 was not operating					
265-267	3.76	8.05	28.46	134	534	4802
267-270	4.17	9.07	35.90	167	441	5801
270-272	3.55	7.20	26.22	59.82	760	6632
272-275	4.28	10.94	23.34	76.61	269	1675
Averages	5.09	9.24	31.22	135	631	5015
Delta db	7.15	6.97	7.78	7.50	5.75	3.53

Table 16. Tabulation of the north band-averaged noise levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.

	AVERAGING BAND LIMITS IN SECONDS					
Days	40-70	70-100	100-200	200-400	400-700	700=2048
219-221	1.68	1.48	12.43	31.46	30.01	4460
221-223	2.75	4.18	9.76	31.62	81.64	15560
223-225	3.64	4.74	11.85	92.29	315	9548
226-228	2.71	5.41	15.67	64.42	248	2472
228-231	1.46	3.42	10.24	42.98	339	10460
231-233	3.04	8.18	19.75	68.61	330	7359
233-236	2.19	4.88	14.80	88.35	546	7199
236-238	5.46	9.76	22.37	107	732	10460
238-241	5.73	11.62	46.44	107	583	21590
Averages	3.18	5.96	18.15	70.41	356	9901
Sand poured into serial number 114 borehole on day 241						
241-243	1.65	5.08	13.67	58.23	349	6475
243-246	2.54	5.86	21.75	106	459	3035
246-248	3.06	7.26	27.48	90.52	518	2902
248-250	3.78	9.01	30.02	159	600	5914
250-253	3.72	9.09	26.79	111	492	3762
253-255	4.07	8.68	31.78	134	449	3249
255-258	4.35	10.18	36.51	183	704	3280
258-260	4.27	9.05	32.03	120	581	5041
260-265	No noise level estimates - #26 was not operating					
265-267	3.81	8.80	27.53	81.01	318	2243
267-270	No reliable noise level estimates - #26 too noisy					
270-272	4.04	10.59	29.46	85.20	392	3006
272-275	3.55	7.97	22.69	55.93	217	2231
Averages	3.53	8.32	27.25	107	462	3831
Delta db	0.45	1.45	1.77	1.84	1.13	-4.12

Table 17. Tabulation of the east band-averaged noise PSD levels in units of $10^{-19} m^2/s^4/Hz$ for sensor 114 averaged over the indicated bands for the duration of the experiment. The row "Delta db" contains the change in the noise level (in db) resulting from introducing sand into the borehole for the indicated band.