Ambient Noise Analysis and Finite Difference
Modelling of VLF Borehole Seismic Data

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ABSTRACT

This report describes a preliminary analysis of borehole seismic data to determine VLF/Sub-bottom Seismic Noise in the Atlantic and the preliminary results of finite difference modelling for a Cape Fear environment.

Noise levels were not a simple function of depth and there are indications that noise levels may depend on local geology about a given receiver position and/or on clamping. Coherency of the noise was generally poor (<0.8) and was independent of depth. There is no evidence for distinct polarizations or directionality of the noise. The lowest determined value for ambient noise power on the vertical component was $10^{-4} \text{ nm}^2/\text{Hz}$ in the frequency range from 5-50 Hz. The better clamped horizontal component had comparable power values. In conclusion, although the drill ship was on the site and drill pipe was in the hole, analysis of the data for a large number of windows can provide meaningful upper bounds on the ambient noise levels in the upper crust.

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I. AMBIENT NOISE ANALYSIS IN THE WESTERN NORTH ATLANTIC

A. DSDP Site 418

Borehole seismic data was acquired at DSDP Site 418 on ODP Leg 102 in March-April 1985 (Leg 102 Shipboard Scientific Party, 1986; Auroux and Stephen, 1986; Senske and Stephen, submitted; Swift and Stephen, submitted). Figure 1 shows the location of the site in the western North Atlantic. Over 3100 airgun and explosive shots and over 90 hours of ambient noise were recorded for a geophone clamped at 5 depths into basement. Table 1 summarizes the time intervals over which digital data were acquired real time. For each of 3139 shots at least 3 seconds of ambient noise was acquired prior to the first compressional wave arrival. Table 2 summarizes the intervals over which analog data were acquired. The ambient noise data described in this report are based on the digital data.

All the data were acquired while the drill ship was on site and with pipe in the hole. Both the ship and the pipe would contribute to background noise. We will show that noise power levels varied by 60 db during the experiment, but the quietest intervals are comparable to background noise levels obtained in the South Pacific during the Ngendie experiment.

For a preliminary analysis we chose to study five three-second windows at each hour during the shooting program. Appendix 1 describes our calibration and analysis procedures. In Figure 2 we show the average power level between 5 and 50 Hz for each channel (vertical, horizontal 1 and horizontal 2). A number of observations are immediately apparent. Noise power levels vary by 60 db. The quietest depth was the second deepest (330 m). The noisiest depth was 41 m which was directly below the pipe.

In Figure 3 we plot the ratios of the three components for each interval used in Figure 2. If the ratios were constant or showed trends, it could imply directionality or polarization of the noise. Again there is considerable variability. The most dramatic feature is that H1 is about ten times lower in power than H2. The mean ratio also appears to vary significantly with depth. That H1 is lower in power than H2 cannot be due to instrumental or recording response since this was checked prior to the experiment. It is also unlikely to be real (due to actual polarization of the noise field) since it is unlikely that the tool would clamp in the same orientation at each of five positions. (Estimation of tool orientation from P-wave arrivals gave the H1 azimuth as 15.5° , 140° , and 84° for the three deep positions 230, 330, 430 into basement, respectively). At this point we feel that the most likely explanation for the low power values on H1 is inadequate coupling. The clamping arm for the borehole seismometer was oriented 15° away from the H2 axis so it is arguable that it was better coupled than H1.

Coherence between components was only fair (less than 0.8) and did not show significant trends with depth (Figure 4).

Figure 1. DSDP Sites 417 and 418 are located in the western North Atlantic on 110 my old crust.

TABLE 1

SOBO NOISE DATA
(DSDP SITE 418, MARCH/APRIL 1985)
(25 02.10'N, 68 03.44'W)
TABLE of DIGITIZED SHOT TIMES and NUMBERS

Files have 3 seconds of ambient noise data prior to the first arrival of shots.

Depth into basement	Source	# Shots	Dates and Times(GMT)	
			Start	Stop
430	Expl.	284	3/31 0436	- 2024
430	Airgun	612	2136	- 4/1 0729
330	Airgun	272	0954	- 1425
330	Expl.	157	1530	- 2336
330	Airgun	501	4/2 0015	- 1003
230	Expl.	297	1009	- 4/3 0221
230	Airgun	662	0243	- 1345
81	Airgun	187	1415	- 1721
81	Expl.	118	1857	- 4/4 0122
41	Expl.	049	0219	- 4/4 0518
		<u>3139</u>	<u>96 hours 42 minutes</u>	
			total window length	

2 hours 37minutes of digitized noise data

TABLE 2

SOBO NOISE DATA
(DSDP SITE 418, MARCH/APRIL 1985)
(25 02.10'N, 68 03.44'W)
TABLE for ANALOG TAPE TIMES

The tapes have continuous recording of background noise levels during the times listed below.

Tape #	Dates and Times(GMT)	
	Start	Stop

1	3/31 0435	- 1049
2	1356	- 2024
3	2040	- 4/1 0310
4	0342	- 1234
5	1302	- 1948
6	2000	- 4/2 0242
7	0251	- 0822
8	0835	- 1721
9	1730	- 4/3 0230
10	0243	- 1058
11	1113	-
12		- 4/4 0140
13	0142	- 4/4 0610
<hr/>		
92 hours		

NOISE (5-50 Hz): VERTICAL CHANNEL

Figure 2a. Average displacement power density over the frequency band from 5 to 50 Hz was computed for five windows each hour during the experiment (plotted here by shot number). Although there are clearly some noisy traces, quiet periods have comparable background noise levels to other borehole sites such as the Ngendie site in the South Pacific. We feel that H1 is consistently quieter than H2 because of a coupling problem.

NOISE (5-50 HZ): H1 CHANNEL

NOISE (5-50 Hz): H2 CHANNEL

NOISE (5-50 Hz): VERTICAL/H1

Figure 3a. Ratios of the average power levels (Fig. 2) between channels. Isotropic, unpolarized noise should hover around 10^0 . The H1 component appears anomalously low. Since power density on H1 remains low regardless of clamping depth, we suggest that H1 may not be as well clamped as H2.

NOISE (5-50 HZ): VERTICAL/H2

Figure 3b

NOISE (5-50 Hz): H1/H2

Figure 3c

AVERAGE COHERENCE: HORIZONTAL 1 VS. HORIZONTAL 2

Figure 4 a. The average coherency between channels is generally low (<0.8) and has no detectable depth dependence.

AVERAGE COHERENCE: VERTICAL VS. HORIZONTAL 2

Figure 4b

AVERAGE COHERENCE: VERTICAL VS. HORIZONTAL 1

Actual spectra for the quietest shots from Figure 2 are shown in Figure 5 for each geophone depth. H1 has consistently lower power. At this value of smoothing, blade lines from the drill ship were not evident.

Figure 6 compares the vertical component spectra for the quietest shots with noise results from the Ngendie experiment (Shearer and Orcutt, submitted). The quietest depth was 330 m and its power level was within a factor of ten of the Ngendie data between 5 and 20 Hz. Noise levels seem to depend on local geology and clamping as well as depth.

Figure 7 shows the quietest spectrum at DSDP Site 418A, the background noise spectra in ocean boreholes at two other sites, and a spectrum from a remote continental site. The Site 418A spectrum was calculated on a 3 sec time series from the vertical component prior to shot 1680 with the geophone at 330 m subbasement (Figure 5d). The Ngendie spectrum was measured at 54 m subbasement beneath 5600 m of water and 70 m of sediment in DSDP Site 595B located on 140 my old ocean crust 1500 km west southwest of Tahiti (Shearer and Orcutt, submitted, Adair, 1986). Shearer and Orcutt attribute the spectral peak at 10 Hz to blade thrusters of the D/V GLOMAR CHALLENGER, that remained on site during the measurement. The HIG spectrum was measured at 20 m subbasement beneath 5500 m of water and 358 m of sediment in DSDP Site 581C located on 110 my old crust 400 km east of Hokkaido, Japan (Dunneber et al, 1985). The spectrum shown is from the quietest horizontal geophone recorded 9 months after emplacement of the seismometer package (Dunneber et al, 1985, their figure 3). Lajitas, Texas, is a remote test site for measuring the sensitivity of seismometers (Herron, 1982). The spectrum shown was measured with state-of-the-art equipment between 1979-1982. Herrin (1982) suggests that at frequencies above 20 Hz instrument-generated noise may have been greater than ambient background noise.

Figure 7 is the first comparison of background noise spectra from different ocean borehole sites. At frequencies of 5-35 Hz, the noise levels at Site 418 (western North Atlantic) are about 8 dB higher than at Site 595B (southwest Pacific) which are 5-8 dB higher than at Site 581C (northwest Pacific). A noise comparison on the basis of site location alone is premature because the equipment and processing used at the three different sites have not been intercalibrated. It is interesting to note that at frequencies of 4-12 Hz that the noise levels at the continental test site are only 2-12 dB quieter than the ocean borehole sites. Above 12 Hz the continental site is at least 15 dB quieter than the quietest ocean borehole site (581C).

In conclusion, although the drill ship was on the site and drill pipe was in the hole, analysis of the data for a large number of windows can provide meaningful upper bounds on the ambient noise level at Site 418. The noise was not a simple function of depth and there are indications that it may depend on local geology about a given receiver position and/or on clamping. Coherency of the noise was generally poor (<0.8) and was independent of depth. There is no evidence for distinct polarizations or directionality of the noise. The lowest determined value for ambient noise power on the vertical channel at

Displacement Power Density ($\text{nm}^{**2}/\text{Hz}$)

NOISE SPECTRA

Figure 5a. Displacement power density noise spectra are shown here for the quietest shot at each depth from Figure 2. For each shot the vertical and the two horizontal components are shown. Spectra were computed over a 3-second record (1500 points) with a 512 point moving average window.

Figure 5b

Figure 5c

Displacement Power Density (nm^2/Hz)

NOISE SPECTRA

Figure 5d

Figure 5e

SPECTRA OF QUIETEST SHOTS

Figure 6. The vertical component spectra from each plot in Figure 5 are plotted along with the spectrum of the Ngendie experiment (Shearer and Orcutt, submitted). Noise levels for the quietest window at a depth of 330 m are comparable to the Ngendie data.

OCEAN BOREHOLE NOISE SPECTRA

Figure 7. Comparison of noise spectra from three ocean borehole sites: Site 418A (330 m subbasement) western North Atlantic (this report); Site 581C (20 m subbasement) western North Pacific (Dunnebler et al., 1985); Site 595B (54 m subbasement) in west South Pacific (Shearer and Orcutt, submitted); and Lajitas, TX (Herron, 1982).

Site 418 was 10^{-4} nm²/Hz in the frequency band from 5-50 Hz. The best clamped horizontal component had comparable power values. The above values will be refined and other data sets investigated in future work.

B. DSDP Site 417

Borehole seismic data was acquired at DSDP Site 417 on Leg 52 in March 1977 (Stephen, 1978, 1979, 1981; Stephen et al., 1980; Salisbury et al., 1979). The bulk of our effort on this contract concentrated on noise analysis for DSDP Site 418. However, initial results of background noise analysis for the Site 417 data set (228 m into basement) give a noise level of 4.8×10^{-7} m/s in a frequency band from 5 to 25 Hz (Stephen, 1979). This is comparable to noise levels on sea bottom seismometers in the North Sea (Smith and Christie, 1977). The noise levels on our Site 417 data set were indistinguishable from recording system noise on that experiment, so the above value should be considered an upper bound on actual in situ noise.

More analysis of the Site 417 data, along the same lines as for the 418 data, will be the subject of future work.

II. FINITE DIFFERENCE MODELLING OF VLF PULSE PROPAGATION

The modelling of VLF propagation in a Cape Fear environment was also preliminary. The method of finite differences can be used to study wave propagation in strongly range dependent environments or in media with random distributions of elastic parameters.

Figure 8 compares the response for propagation in a shallow homogeneous channel with the response for a continental margin model. There are three significant observations: i) There is an indication of a horizontal reflection from the shelf break. ii) The ground wave arrival is larger for the continental margin model because of focusing at the shelf break. iii) The water wave arrivals or 'normal modes' in shallow water convert to direct water waves as they propagate along the wedge. We are in the process of analyzing these results further.

Figure 9 shows an example of wave propagation in a flat, but statistically heterogeneous media. The mean velocity-depth function varies linearly with depth and the standard deviation decreases linearly with depth. Scattering from the heterogeneities causes a 'secondary' Stoneley wave which is a likely candidate for the mode of propagation of noise in the sea floor.

III. CONCLUSIONS

Over the brief period of this introductory contract we have quantified noise levels and properties within the upper oceanic crust and initiated application of modelling techniques to study noise propagation mechanisms.

Receivers at 45 m depth

Figure 8a. The finite difference method has been used to compute wave propagation in wedge-like environments such as continental margins. Figure 8a shows time series at two gains for a laterally homogeneous channel. Figure 8b shows the same results for a wedge model in which the 'shelf break' occurs at 1.25 km. The most amazing feature is that the modal pattern remains the same in the two models out to 2.5 km beyond the break. Apparently the shallow channel constructs a beam which propagates into the wedge independently of the bottom.

Receivers at 45 m depth

Figure 8b

COMPRESSIONAL VELOCITY
MODEL RANDOM

KM/SEC

1.5 3.2 4.8 6.0

Figure 9a. Random velocity variations can also be treated by finite differences. In this example, the mean and standard deviation of the velocity field (Figure 9a) vary linearly with depth below the seafloor to a uniform medium representing Layer 3. The 3.6 second snapshot (Figure 9b) shows diffractions and secondary Stonely waves in both the compressional (divergence) and shear (curl) components which are not observed for media without random fluctuations. Figure courtesy of M. Dougherty.

TIME 3.6 SEC

MODEL RANDOM

Figure 9b (Figure courtesy of M. Dougherty.)

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V. APPENDIX

A. Calibration

This is a summary of calibrations done on the OSE system that was used to record background noise within oceanic crust at Site 418A on ODP Leg 102 (Figure A-1). More detailed descriptions of the OSE system appear in Stephen (1978, 1979).

The borehole geophone package is a modified GEO SPACE WLS-1100 wall locking seismometer with an electrically driven, spring-loaded arm. The seismometer contains two pairs of horizontal, orthogonally-oriented geophones and one pair of vertical geophones. The tool clamping arm is oriented at 15° to the second (using the nomenclature in this report) horizontal geophone pair. We used GEO SPACE HS-1 geophones with a natural frequency of 4.5 Hz, coil resistance of 215 ohms, and shunt resistance of 360 ohms. The geophones produce a direct current voltage whose amplitude varies with displacement velocity and whose sign indicates direction of motion. The geophone pairs are wired in series to sum the voltage output. We used the frequency calibration provided by GEO SPACE (Figure A-2) to determine the voltage response of the geophone to its velocity. Since the response is essentially flat in the frequency range 5 to 100 Hz, we used 0.65 volts per in/sec to convert voltage to displacement velocity for all three channels.

The stock GEO SPACE preamplifier was replaced with an adjustable three component amplifier built at WHOI. The amplifier gain was set at 48 dB during shooting of the first radial line (shots 20-32) and then at 60 dB during the remainder of the experiment. This nominal gain value was removed from the digitally recorded data by the software which converted the data from SEG Y to ROSE format (Figure A-1). Prior to the cruise, R. Fileo tested the preamplifier (Table A-1). At a setting of 60 dB, each of the three pairs of geophones slightly over-amplified a 1 mV signal by a factor of 1.2. So, we corrected all three channels by a factor of 0.833.

Prior to operations at Site 418A, attenuation was measured through one of the 6 conductor, double armored logging cables aboard the D/V RESOLUTION. However, another cable of similar type and length was used during the experiment. For our calibration we assumed that the attenuation response of the cables was identical. The test circuit started at the downhole measurements lab and ran through the logging cable, winch, and deck cable leading to the underway geophysics lab. Within the geophysics lab the signal passed through the attenuator, emitter follower, and junction box to a oscilloscope and analog tape recorder (Figure A-1). Attenuation was zero at 10 Hz but increased at higher frequencies (Table A-2). At all frequencies, the response was uniform among the three channels. Since the frequencies of interest to NORDA extended up to 50 Hz, all three channels of data were corrected by a factor of 0.96.

The analog signal conditioning in the underway geophysics lab was through an attenuator (reduces voltage added by the preamplifier to drive the logging cable), emitter follower (corrects electrical distortion introduced by

Figure A-1. Block diagram of equipment used to measure VLF noise on ODP Leg 102 aboard the D/V RESOLUTION.

Figure A-2. Amplitude response of the Geo Space HS-1 geophone.
(Diagram courtesy of Geo Space, Houston.)

Table A-1. Gain calibration of the WHOI downhole seismometer preamplifier prior to ODP leg 102.

Setting	Input	Output H1	Output H2	Output V
0 dB	0.100 V	0.200 V	0.200 V	---
12	0.100	0.540	0.530	0.530 V
24	0.100	1.6	1.6	1.6
36	0.100	6.5	6.5	6.5
48	0.010	2.7	2.6	2.7
60	0.001	1.2	1.2	1.2
72	0.001	4.1	4.0	4.0

Room Temperature

December 1984

Frequency 50 Hz

R. Fileo

Table A-2. Calibration test during Leg 102 on the SEDCO cable, winch, deck cable, lab attenuator, and emitter follower.

Frequency	Input	Output V	Output H1	Output H2
5 Hz	5 V	5.8 V	5.8 V	5.8 V
10	5	5.0	5.0	5.0
20	5	4.8	4.8	4.8
40	5	4.8	4.8	4.8
80	5	4.6	4.6	4.6
160	5	4.6	4.6	4.6
320	5	4.5	4.5	4.5
500	5	4.2	4.2	4.2

March 18, 1985

R. Stephen

Ambiant air temperature

attenuator), Wavetek filter (analog bandpass filter), and Ithaco amplifier (gain control) prior to digital conversion by a MASSCOMP based acquisition system. The attenuator was set at 0 dB throughout the cruise. The gain setting on the Ithaco amplifier varied among 0, 6, and 12 dB during the experiment. In a manner similar to that for the tool preamplifier, the nominal amplitude gain of the Ithaco amplifier was later removed by software which converted from SEGY to ROSE format. During the OSE there was no gain or attenuation applied to the signal in the emitter follower, Wavetek filter, or the analog to digital conversion.

L. Gove calibrated the portion of the data stream that included the Wavetek filter, Ithaco amplifier, MASSCOMP computer, and the software gain control. On each of the three channels, he placed an AC voltage with varying frequency and peak-to-peak amplitude (Table A-3). The output was digitized at 500 Hz and recorded in SEGY format on the MASSCOMP computer. We converted these results from SEGY to ROSE format and applied nominal corrections for settings on the Ithaco amplifier and hypothetical gain control applied by the attenuator and the tool preamplifier. We took the absolute value of the oscillating signal and found the maximum number of digital instrument units during each test "shot" (Table A-3). Assuming that the system responds identically to negative and positive voltages and that there is no temporal drift in the system during the test shot, the maximum number of digital units is the calibrated system response to a DC voltage with amplitude equal to one half of the input AC voltage (peak-to-peak).

At specific frequencies, the digital unit output is a slightly non-linear function of the input voltage (Table A-3). However, the shape of the non-linear response is different at different frequencies. The source of the non-linearity is probably small errors in the input voltage or errors arising from the assumption that the maximum digital units recorded is a measure of the peak voltage. In either case, the errors would not have affected results recorded during the OSE, and the system response can be reasonably assumed to be linear. Accepting this assumption, we corrected the maximum number of digital units to an input signal of 2 volts peak-to-peak (Table A-3, columns 10-12) and averaged the corrected output at each of the six frequencies (columns 13-15). Since NORDA is interested in noise at 5-35 Hz, we used the calibration factors for 15 Hz to correct our data.

Test shots 8-10 provide a calibration of the Ithaco amplifier (Table A-3). After correction to an input of 2 volts peak-to-peak and zero gain, the results indicate that the amplifier underperformed by about 6% at a gain setting of 6 dB and by about 9% at 20 dB. We did not take account of this lack of performance in correcting our noise data.

Test shots 1 and 11-13 provide a calibration of the software which corrected for gain applied by the tool preamplifier (Table A-3). The increase in output (after correction to 2 V peak-to-peak, columns 10-12) at 6 dB gain (compare shot 13 to shot 1) is negligible, but at 20 dB gain (compare shot 12 to shot 11) the increase ranges up to 2%. The preamplifier signal was set at

Table A-3. Results of calibration test on electronics equipment in the underway geophysics lab and the MASSCOMP A-D computer. The output values (columns 7-15, digital units) have been reduced by a factor of 10^3 to make the table more compact.

TEST SHOT	INPUT (volts) (P-P) V,H1,H2	FREQUENCY (Hz)	ITHACO GAIN (dB) V,H1,H2	ATTENUATOR GAIN* (dB)	TOOL* GAIN (dB)	OUTPUT (digital units)			(d.u., corrected to 2 V P-P)			CALIBRATION FACTORS (digital units**)		
						Vert	H1	H2	Vert	H1	H2	Vert	H1	H2
1	2	5	0,0,0	0	0	9493	9352	9417	9493	9352	9417	9657	9546	9611
2	4					19814	19604	19739	9907	9802	9870	(188)	(199)	(200)
3	6					29083	28797	28983	9694	9599	9661	(n=4)	(n=4)	(n=4)
4	8					38131	37728	37986	9533	9432	9497			
5	2,-,2					9669	115	9579	9669	115	9579			
6	2,2,-					9655	9517	48	9655	9517	48			
7	-,2,2					60	9516	9577	60	9516	9577			
8	.2		20,6,0			9735	1979	1032	9735	9919	10320			
9	.2		0,20,6			1104	9585	1981	11040	9585	9929			
10	.2		6,0,20			2050	1047	9631	10275	10470	9631			
11	.2		0,0,0			1098	1029	1035	10980	10290	10350			
12	.2				20	108	105	103	10800	10500	10300			
13	2				6	4762	4698	4732	9502	9374	9442			
14	2			+20	0	951	936	940	9510	9360	9400			
15	2			-6		9545	9378	9434						
16	2	75		0		9400	9561	9341	9400	9561	9341	9410	9577	9358
17	4					18810	19163	18723	9405	9582	9362	(14)	(14)	(15)
18	6					28277	28760	28113	9426	9587	9371			
19	6	15				28506	28287	28442	9502	9429	9481	9585	9497	9545
20	4					19389	19223	19308	9695	9612	9654	(99)	(100)	(95)
21	2					9559	9451	9501	9559	9451	9501			
22	2	35				9405	9330	9304	9405	9330	9304	9370	9320	9312
23	4					18502	18454	18444	9251	9227	9222	(106)	(89)	(94)
24	6					28362	28213	28227	9454	9404	9409			
25	6	150				3745	3683	3422	1248	1228	1141	1263	1236	1144
26	4					2546	2503	2306	1273	1252	1153	(13)	(14)	(8)
27	2					1267	1229	1137	1267	1229	1137			
28	2	125				9130	9067	8913	9130	9067	8913	9348	9317	9153
29	4					18659	18622	18290	9330	9311	9145	(227)	(254)	(244)
30	6					28748	28723	28200	9583	9574	9400			

* Attenuation/gain applied by software during format change to account for hypothetical attenuation/gain applied by hardware.

** Standard deviations in parentheses. N is the number of shots averaged.

"P-P" means peak-to-peak.

Room temperature
March 1985
L. Gove

60 dB throughout most of the OSE, so potential errors in our results may exceed 2%. Since we did not test the software at 60 dB, we made no corrections to our results for this potential error.

Shots 1 and 14-15 tested the software which corrected for gain applied by the attenuator (Table A-3). After correction to 2 V peak-to-peak, the distortion in output for a setting of 20 dB is negligible. When the thumb wheel was set at -6 dB (shot 15), the output was not significantly different than that at 0 dB (shot 1), so either the software or the thumbwheel failed. Since the attenuator was set at 0 dB throughout the OSE, no correction factor was necessary for the noise calibration.

B. Time Series Analysis

The geophones in the OSE seismometer produce voltage in proportion to the velocity of ground motion. Using our calibration factors, we obtained at each OSE shot a three second time series in units of inches per second. Calibrated noise studies are usually reported in units of cumulative displacement from arbitrary zero up to the sample time, t_n :

$$D_n = \int_{i=0}^{i=n} V_i dt$$

where D_n = cumulative displacement of the geophone up to time t_n .

V_i = velocity at time t_i .

dt = sample period.

We converted our data from inches to nanometers and integrated from the start of the time series using the trapezoid rule:

$$D_n = [(1/2)V_0 + V_1 + \dots + V_{n-1} + (1/2)V_n]dt.$$

Each displacement time series (here, three seconds of data or 1500 points) was subdivided into three subsets of 512 points (about 1 second) using 85% overlap with contiguous subsets. Values in each subset were adjusted to give a zero mean and then tapered using the pi prolate window of Thompson (1977). The discrete fast Fourier transform of each subset was calculated. The power spectral density function was found by calculating the autocorrelation, and the coherence between two time series (here, different channels of one shot) was found by calculating the cross correlation. In both cases, the results were smoothed by arithmetic averaging of the three subsets. As a result, the spectra have 6 degrees of freedom.

The fast Fourier transform routine was written by R.C. Singleton (Stanford University, 1968), the spectral density code by S. Webb (WHOI, 1985), the main program streaming the data by T. Bolmer (WHOI), the routine reading the ROSE data files by L. Gove (WHOI), and the code doing the calibration and displacement integration by S. Swift (WHOI).

C. References

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