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Underground Measurements of Seismic Vibrations at the SSC Site

V.D.Shiltsev*[1], V.V.Parkhomchuk*[1] and H.J.Weaver

ABSTRACT

The results of underground measurements of seismic vibrations at the tunnel depth of the Superconducting Super Collider (SSC) site are presented. Spectral analysis of the data obtained in the frequency band from 0.05 Hz to 1500 Hz is performed. It is found that amplitudes of ambient ground motion are less than requirements for the Collider, but cultural vibrations are unacceptably large and will cause fast growth of transverse emittance of the SSC beams.

1. 0 Introduction

Vibrations of the magnetic elements of the Superconducting Super Collider (SSC) are considered as one of the main sources of transverse emittance growth of the SSC beams. The SSC collider may be the first accelerator where ground motion can seriously jeopardize useful operation of the machine. The issue is that tolerable levels of vibrations for the SSC are at least a few orders of magnitude tighter than those for the largest existing hadron accelerators such as the Tevatron and SPS (CERN), because the transverse emittance of the SSC beam will be about 100 times smaller and the circumference will be about 10 times larger at the SSC than for those smaller machines. The last argument is valuable because a larger circumference means lower revolution and betatron frequencies, and it is dangerous because of the rapid increase of vibrations at lower frequencies. Also, the number of magnetic elements in the rings, which can disturb the ideal motion of the beams, is very large (thousands).

Vibration effects on collider performance have been studied in several works,[1–4,7] and it was found that depending on the frequency of the noise, one can distinguish two mechanisms of beam perturbation. At low frequencies (much less than the revolution frequency), the noise produces a distortion of the closed orbit of the beam. High-frequency noises—especially at frequencies near a fractional part of the betatron oscillation frequency (600–1100 Hz) at the SSC—cause direct transverse emittance growth. The following figures will give an idea of the seriousness of the issue:

1. The acceptable level of uncorrelated low-frequency motion of a single SSC quadrupole is about 0.1–0.3 μm;[3,1,2,7]

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2. High-frequency turn-to-turn jitter of every quad with an amplitude of approximately 10^{-4} μm will cause emittance doubling after only 20 h.[3,4,5,6] (Damping time due to synchrotron radiation in the SSC is about 24 h.)

Therefore, it is necessary to measure ground vibrations over an extremely large frequency range from fractions of a hertz (or the lowest possible frequency) to a few kilohertz. Experimental investigation of underground vibrations at the SSC site at frequencies of 1–100 Hz was made by The Earth Technology Corporation of Long Beach, CA, in 1989.[8] Very detailed analysis was done, but the most interesting frequencies in the kilohertz range and the most powerful vibrations at frequencies below 1 Hz were not investigated. The Vibrational Workshop held at the SSC Laboratory in February 1992 also emphasized the lack of information about these important regions.[9] In our previous papers [10,11] we reported results of measurements of ground motion and the SSC dipole vibrations made at the Accelerator Systems String Test (ASST) which is placed on the surface of the ground. High-precision seismic equipment from Budker INP (Novosibirsk, Russia) allowed us to obtain useful data up to frequencies 20 times larger and 20 times lower than those previously investigated - it covered frequency band of 0.05-2000 Hz. The analysis had shown some amplifications of ground vibrations due to resonant properties of magnetic elements and their support.

This paper is devoted to underground seismic measurements at the SSC site in the frequency band of 0.05–1500 Hz. In Section 2.0 we describe equipment, hardware, data processing, and conditions under which measurements were made. Principal results of measurements, the discussion, and comparison with other data are presented in Section 3.0. Further experiments, development, plans, and main conclusions are summarized in Section 4.0.

2. 0 Experimental

All results presented in this paper were obtained in the Exploratory Shaft (ES) placed in the injector site of the SSC during a 10 week period (June 23 - September 1st, 1993). The shaft (see Fig.1 from Ref. 12) is 16.5 ft diameter from the surface down to the 195 ft , then 10 ft in diameter to the full depth (265 ft), and it penetrates Austin chalk and Eagle Ford shale. The shaft drilling was performed at November 1991 and the horizontal adit was drilled in December 1991. The shale is potentially a more difficult medium and personnel of the joint venture of Parsons Brinkerhoff and Morrison Knudsen (PB/MK) studied the rock reaction to excavation. The horizontal adit - 8 ft wide, 14 ft high and 45 ft long, directed South - is 215 ft (about 68 m) below the surface at the interface of two formations. Equipment and personnel were lowered in a steel cage. One SM-3KV type geophone was installed in the end of the adit. The same type of probe was also installed on the surface not far from the shaft (see Fig. 1). These two probes were used to measure ground vibrations in the adit and on the surface and to observe the correlation between the motion of two points situated down and up the shaft (we refer these as 'down' and 'top'). During the period of observations the SSC injector complex was under construction and operation of heavy machinery, excavation works, industrial car traffic occured in Low Energy Booster and Linac sites within about 1 km distance from the ES. The effect of this was especially seen at weekdays (see Section 3.0).

Two SM-3KV probes No.1112 and No.1140 were carried from the Budker INP (Novosibirsk, Russia) in accordance with inter-laboratory agreement 92-W-11138, Attachment 26, and had been previously tested in vibrational studies for linear collider VLEPP[15], Novosibirsk B-Factory VEPP-5 [16] as well as in ASST measurements [10,11].

A commercial velocitymeter SM-3KV was modified to extend the frequency band to 0.05–1500 Hz. The proper pendulum period of the probe is 2 s. A special electrical feedback system modifies the raw signal from the coil of the pendulum, which vibrates in the magnetic field system; thus, the output signal is proportional to the velocity of vibrations without resonance, emphasizing the proper period. At frequencies above 200 Hz the feedback system gain is small and it doesn't improve probe characteristics. The probe allows us to measure vertical as well as horizontal vibrations after some simple mechanical transformations. During the investigations two probes in the vertical variant were used, with both calibrated in the working frequency range. Calibration at frequencies above 100 Hz was done through the special calibrated coil installed in the probes and by using a special vibrating table in Novosibirsk (Ref. 18) and good confirmation of undirect calibration was found. Results of the calibration are presented in Figure 2. The difference in the sensitivities of the two probes is less than 10%. The mass of the probe is about 6 kg, and its size is 15 cm x 15 cm x 25 cm. Signal-to-noise ratio for SM-3KV probe with the smallest observed ground vibration signals is shown in Figure 3. One can see that the signal-to-noise ratio is less than 2 above 1000 Hz and below 0.05 Hz. Under usual and noisy conditions these ratio becomes many times more (see Section 3.0 below).

In investigations of sound waves descried below we used calibrated piezocelectric hammer made by Dytran Corporation. Electrical signal from the hammer is proportional to the force of strike - it has sensitivity of 1 mV/lb. The hammer has a mass about 2.5 kg (5 lbs wt).

All electrical signals from probes were digitized and developed by a CAMAC-based experimental set-up named ASSA, which includes:

- CAMAC crate
- CAMAC crate controller
- Two 10-bit, 4-channel CAMAC ADC ZIIS-4 type
- CAMAC differential amplifiers for all kinds of probes (this allows us to change the total gain from 0.1 to 10^5 and low-pass frequency filters from 1 Hz to 10 000 Hz)
- Two 256-K, 24-bit word CAMAC memories
- CAMAC timer
- Interface CAMAC (IBM PC)
- IBM 386 personal computer.

The ASSA set-up is fully autonomous and needs only a 110-V outlet.

Signals from all probes were digitized simultaneously by ADCs with a sampling frequency (changeable by timer from 0.1 Hz to 32 kHz) and then were sent to memory for storage. The maximum memory available for one channel is 64-K 24-bit words. It corresponds to 17.8 h of permanent measurement time with a sampling rate of 1 Hz or about 1 min with 1 kHz. For long measurements we used low-pass filters at 2 Hz or 20 Hz; for fast analyses 2000-Hz and 10 000-Hz filters were applied.

The software used allows us to analyze data in both the time and the frequency domain, to transform raw signal data to vibration amplitudes (*i.e.*, transform volts to micrometers), to change all variable parameters of hardware (sampling frequency, gains, filters), to calculate power spectral densities of all signals and spectra of correlation between all pair of channels, and to present results graphically and produce hard copy on a printer.

For calculations of spectra we used the optimized 512-point Raider-Brenner algorithm based on a 16-point Winograd algorithm for discrete Fourier transformation. (See Reference 13 for an example.) On an IBM PC/386, the algorithm works twice as fast as the usual Fast Fourier Transformation (FFT) technique of Cooley and Tukey. This algorithm is very useful because in order to reduce statistical errors we can average over a greater number of spectra (usually 63). Two types of data filtration were used when necessary: Hanning filter (see Reference 14 for an example), and Antimed filter (see Ref. 11 for detailed description), which provides more true data under some conditions.

The power spectral density (PSD) *S(f)* which we calculated have the following relation to rms value of signal $X_{rms}(f_1,f_2)$ in frequency band from f_1 to f_2 :

$$X_{rms}(f_1,f_2)=\int_{f_1}^{f_2} S(f)df \qquad (1)$$

The spectrum of correlation *K(f)* of two signals *X(t)* and *Y(t)* (or, mutual correlation spectrum) that we use in this paper is defined as:

$$K(f)=\frac{<X(f)Y^{*}(f)>}{\left[<|X(f)|^{2}><|Y(f)|^{2}>\right]^{1/2}} \qquad (2)$$

Here the brackets <....> mean averaging over the 63 measurements, and *X(f)* is the Fourier transformation of *X(t)*.

The main aims of our investigations were to determine quantitative characteristics of the SSC site ground vibration at the tunnel depth and compare it with surface data.

3.0 Results

As we mentioned above, daytime amplitudes of ground motion were usually larger than at night and weekends due to construction work at Injector site. Fig. 4 demonstrates raw time records of signals from 'top' and 'down' probes afternoon (Fig.4 a), b)) and at night (Fig.4 c),d)). One should mention that the scale of Y-axis for night data is 40 times less than on the corresponding daily plots. During the day heavy machinery produced about 1200 mV signal at 'top' and about 600 mV at 'down' probes with frequency about 30 Hz. That correspond to about 0.08 micron and 0.04 micron amplitudes (see calibration in Fig. 2). At night vibrations at frequencies of tens Hz and higher are about hundred times less and one can clearly see low-frequency ground motion. This motion, with amplitude of about 0.1 micron and period 5-7 sec, is due to micro seismic waves produced by the closest ocean (Gulf of Mexico). Both 'top' and 'down' seismic probes show practically the same low-frequency signals, while high-frequency noise is about 4 times larger on the surface.

The probability that amplitude of the ground vibrations is more than a given value of X (micron) during any 5-sec time interval (this is natural scale of micro seismic wave period) is presented in Fig. 5. Data obtained during 1 July - 13 July are developed for this picture. Here solid line and marked points correspond to 'down' and 'top' data. Dash line represents the fit :

$$dW(x > X) = \frac{0.004}{X(\mu m)^{-1.5}} \qquad (3)$$

One can see, that the probability that ground motion is less than 0.1-0.2 micron is about 100%. Large amplitudes $0.2<x<1$ micron are seen more often on the surface. More significant events correspond to remote and small local earthquakes (the SSC site statistics says that local earthquakes are usually small and very rare, see, for example Ref. 20). About twice a week we observed the ground waves from TXI quarry blasts (2000-5000 lb. of explosive material) with amplitude up to 1.5 micron and period about 1-2 s. The quarry is situated about 10 miles North-West of the ES , not far from Midlothian, TX. An example of such blast waves is shown in Fig. 6. The ground vibrations in the shaft and on the surface are the same during about 8 s of the event.

Fig. 7 presents about monthly statistics of events with large amplitudes (30 July -til 24 August). There is shown that the mean time T between events with amplitudes more than X grows approximately linearly with X (see fit in Fig.7) :

$$T(days)=2.3*X(micron) \qquad (4).$$

This is reflection of well known "Gutenberg-Richter law" on frequency of earthquakes (see, for example Ref. 21). Most of events with amplitudes 1-5 micron produce the same signals in the shaft and on the surface. Nevertheless during M6.0 Queen Charlotte Island earthquake at 2:40 a.m. (Texas time) 3rd of August, 1993 we observed that 'down' probe signal had an amplitude about 15 micron while only 10 micron motion was on the surface. The duration of that earthquake in Texas was about 40 min. and waves had a period 5-10 s.

Measurements of propagation of waves from surface to down shaft were made with use of calibrated hammer. Simultaneously measured signals from the hammer and the two probes are shown in Fig. 8 a), b) and c) correspondingly. Experimentator hit the ground by hammer about 5 m away from 'top' probe which shows extremely high level of signal (about 10-20 times more than down shaft where amplitude about 0.002 micron was detected). After calculations of time delay between SM-3KV probes signals (22 ms) we found that sound velocity (P-wave) is about 3000 m/s. The velocity of sound in upper soil was found about 1.5-2.0 km/s. Fig. 9 demonstrates how peak amplitude of 'top' probe signal decreased while distance L between that probe and the point of hammer strike increased up to 90 m. Dashed line in Fig. 9 is plotted accordingly to geometrical factor *1/L* for spherical wave which propagates without dissipation of energy.

Fig. 10 presents power spectral density of ground vibrations on the surface and in the shaft under "typical noisy" and "typical quiet" conditions (about noon and midnight of August 7, 1993). Each PSD consists of three spectra with different ADC's sampling frequencies (20 Hz, 200 Hz and 2000 Hz) and with corresponding low-pass analog filters. In Fig. 10 a) one can see, that day-time technical noises do not influence on vibrations at the shaft only below 0.5 Hz where curves 1 and 2 join each other. Small peak around 0.2 Hz is due to micro seismic waves described above. At frequencies 1 Hz and higher the power of vibrations increases $10^3 - 10^5$ times due to technical activity. Without taking into account peaks, the PSD may be roughly approximated by formula :

$$S(f) = \frac{A}{f^{-3}} \qquad (5)$$

where constant $A = 0.7\,\mu m^2/Hz$ under the noisy conditions and $A = 2*10^{-4}\,\mu m^2/Hz$ in the quiet case. Vibrations of ground surface are about 4 times more powerful and even at low frequencies (below 1 Hz) the technical activity significantly increases vibrations.

Fig. 11 a), b), c) show how rms values of ground vibrations in frequency bands 0.08 Hz-0.2 Hz, 10 Hz-20 Hz and 500-1000 Hz correspondingly varied in time during two weeks in July 1993 (see Eq. (1) for reference on rms value). Accordingly to Fig. 11 a) amplitudes of micro seismic waves are the same for the two probes, slightly varies in time and have the value about 0.1-0.2 micron (during our spring measurements in the ASST that amplitude varied from 0.1 micron to about 1 micron, see Ref. 10,11). Sharp peaks in Fig. 11 a) are connected with local and remote earthquakes and events.

In contrast, high frequency vibrations (see, Fig.11 b) and c)) strongly depends on time and clearly show quiet time at weekends, drop of vibrations at lunch time (every weekday) and even reflect the fact that there are more activity at the beginning of the week than at Fridays. As we said in the Introduction, the level of ground motion vibrations at frequencies of several hundreds Hz (upto 1 kHz) acceptable for the SSC collider is about 0.0001 micron. Fig. 11 c) shows that this level is overcame 3-10 times at weekdays, especially on the surface of the ground. It will cause fast growth of transverse emittance of the SSC beams. On-line simulations of emittance growth (described in Ref. 6) predicted increment of the emittance about 50 times over the designed value. There were also demonstrated that the feedback system can strongly damp this effect.

Fig.12 presents real part , imaginary part and modulus of correlation spectrum *K(f)* between vibrations on the surface and in the adit under quiet conditions (see a), b) and c) correspondingly). Modulus of correlation spectra (or *coherence spectra*) in noisy conditions is shown in Fig. 11 d). One can see, that inspite of some increasing of correlation at frequencies above 10 Hz at noisy case, a good correlation (higher than 0.7) exists only for waves with frequencies 0.1-0.5 Hz and 1-5 Hz. Decreasing of correlation below 0.1 Hz may be due to several effects : noises of seismic probes electronics, different response of the tunnel and the surface on fluctuations of atmospheric pressure, and due to significant uncorrelated slow ground motion (see, for example, Ref. 7). It is hard to give correct explanation of the effect with equipment we used. We plan to make another measurements with special low frequency seismoprobes to investigate slow ground motion.

4. 0 Discussion of Results and Conclusions

Comparison of the spectra of ground motion measured in the SSC Exploratory Shaft with other worldwide data is presented in Fig. 13 a). PSD of ground vibrations at the tunnel depth of the SSC, the UNK tunnel (Protvino, Ref. 15), CERN (TT2A tunnel, Ref. 22) and at the KEK (Tsukuba Mt. shaft, Ref. 23). All spectra were obtained under quiet conditions and have rather similar values. Fig. 13 b) shows comparison of our data (curves 1 and 2) with previous measurements at the depth of 19 m in the SSC site (see Ref.8). Dash line in Fig. 13 b) represents level of acceptability for ground motion (taken from Ref. 10,11) : at low frequencies it determines as condition for beam-beam separation in the interaction point of the SSC less than 10% of beam size in the assumption of uncorrelated motion of magnetic elements. We have to mention that at micro seismic peak frequencies 0.1-0.3 Hz those motions are well correlated, but the issue of uncorrelated displacements with frequencies less than 0.1 Hz are still not carefully investigated experimentally. At high frequencies of about 500-1500 Hz the dashed line shows level of qudrupoles jitter which will cause doubling of transverse emittance of the beams during 20 hours of operation of the SSC. One can see that biggest observed vibrations are far above this level.

While slow vibrations with big amplitudes are interesting from the point of view of distortion of the closed orbit, we have in future plan to continue measurement of spectral and correlation properties of ground vibration with new low-frequency seismoprobes SDE type [18] . (Those seismometers work in the band 0.001 Hz-1 Hz.) This will give necessary information for design of dynamical adjustment scheme which provide head-on beam-beam collisions ("Jostlein scheme"[19], for example).

We found, and on-line simulations[6] of transverse emittance growth confirmed it, that technical activity (as it was during our underground measurements) will cause unacceptably large increment of the beams' emittances. In Ref. 10 and 11 we found that mechanical resonances of magnetic elements and their supports can increase several times this effect. Moreover, considered in Ref. 5 the phenomena of fluctuation of the dipole field due to variation of vacuum chamber shape caused by the turbulence of the liquid Helium flow may add concern on emittance preservation issue (this effect surely needs careful experimental investigation and we have it in plans also). As it was mentioned in Ref. 6 there are only three way to avoid this effect : to reduce vibrations; to increase fractional part of the tune and to install transverse feedback system. The last choice contains more freedom for the SSC than two another.

On our mind it is necessary to include in the design of the SSC a subsystem for monitoring of seismic vibrations. Such a system may consist of 10-12 small seismic stations, similar to which we used in these measurements, which will set around the Collider tunnel and may be one central station with extended equipment for ultra slow ground motion.

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FIGURE CAPTURES

Fig.1 : View of the SSC Exploratory Shaft and underground experiments.
Fig.2 : Calibration curve of SM-3KV probes (No.1112 and No.1140).
Fig.3 : Signal-to-noise ratio under very quiet conditions.
Fig.4 : a) Raw record of 'top' probe signal at 13:00, Fri., July 30.
 b) Raw record of 'down' probe signal at 13:00, Fri., July 30.
 c) Raw record of 'top' probe signal at 02:20, Mon., July 26.
 a) Raw record of 'down' probe signal at 02:20, Mon., July 26.
Fig.5 : Function of probability to find a ground motion with amplitude more than X during 5 s time interval vs. X (solid line -for 'down' probe, points - for 'top' probe, dashed line - fit, see Eq. (3) in text).
Fig.6 : Waves from quarry blast 10 miles away (dashed line- 'down' probe, solid line - 'top' probe).

Fig. 7 : August 1993 statistics of large amplitude events : mean time between events vs. its amplitudes (dashed line - fit , see Eq.(4) in text).

Fig. 8 : Raw data record of effect of hammer strike on the surface :

a) signal from calibrated hammer.
b) signal from probe on the surface.
c) signal from probe in the adit (68 m depth).

Fig. 9 : Peak amplitude of 'top' probe vs. distance to the hammer strike point.

Fig.10: a) Power spectral density of ground vibrations at 68 m depth (1 - in a weekday conditions, 2 - at night).

b) Power spectral density of ground vibrations on the surface (1 - in a weekday conditions, 2 - at night).

Fig. 11: a) Rms value of ground vibrations in frequency band 0.08-0.2 Hz in July 1993 (top graph - on the surface, bottom - in the shaft).

b) Rms value of ground vibrations in frequency band 10-20 Hz in July 1993 (top graph - on the surface, bottom - in the shaft).

c) Rms value of ground vibrations in frequency band 500-1000 Hz in July 1993 (top graph - on the surface, bottom - in the shaft).

Fig. 12: a) Real part of correlation *K(f)* between 'top' and 'down' ground vibrations.

b) Imaginary part of correlation *K(f)* between 'top' and 'down' ground vibrations.

c) Coherence (modulus of correlation *K(f)*) between 'top' and 'down' ground vibrations.

d) Coherence (modulus of correlation *K(f)*) between 'top' and 'down' ground vibrations under noisy conditions.

Fig. 13: a) Comparison of power spectral density of ground vibrations in the SSC exploratory shaft under quiet conditions with other data (see comments in text).

b) Comparison of power spectral density of ground vibrations in the SSC exploratory shaft under noisy(1) and quiet(2) conditions with previous measurements (Ref.8) in the SSC site at depth 19.5 m (3) and level of acceptability for ground vibrations from Ref. 10,11 (see comments in text).

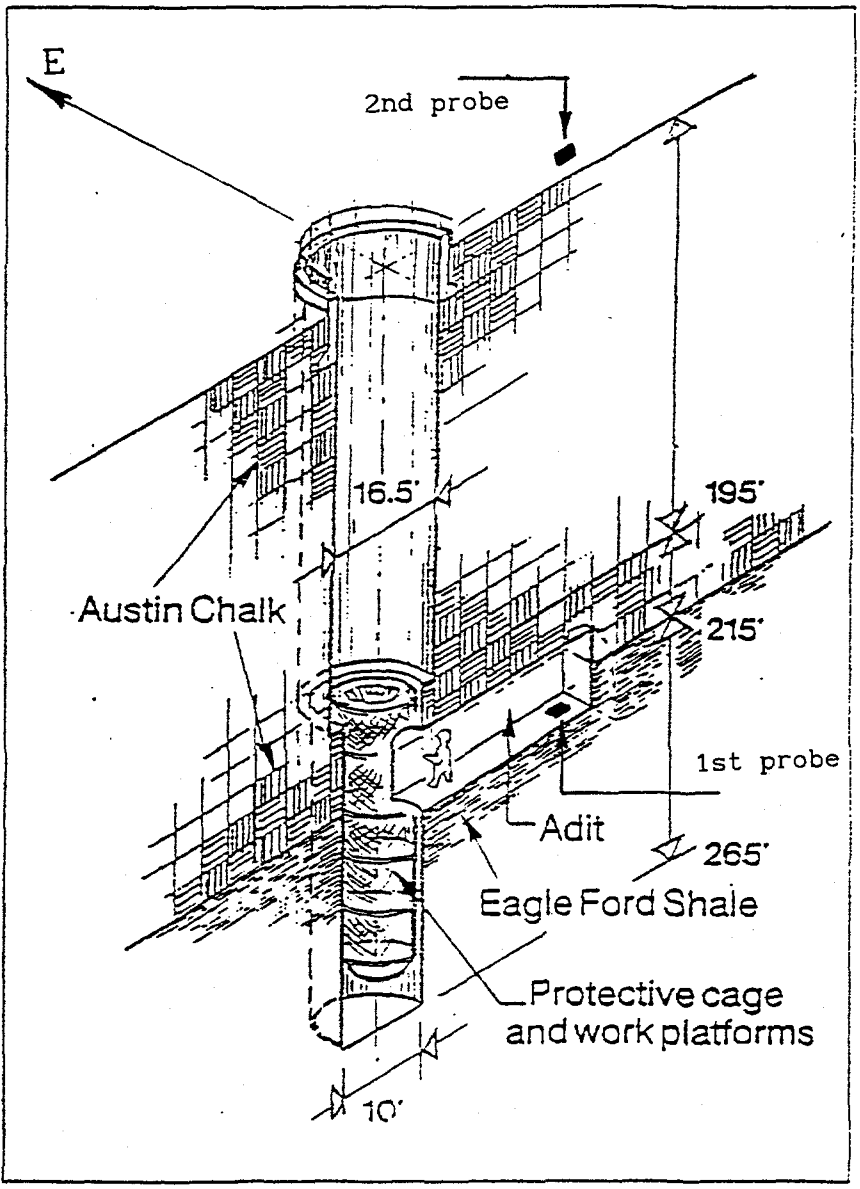
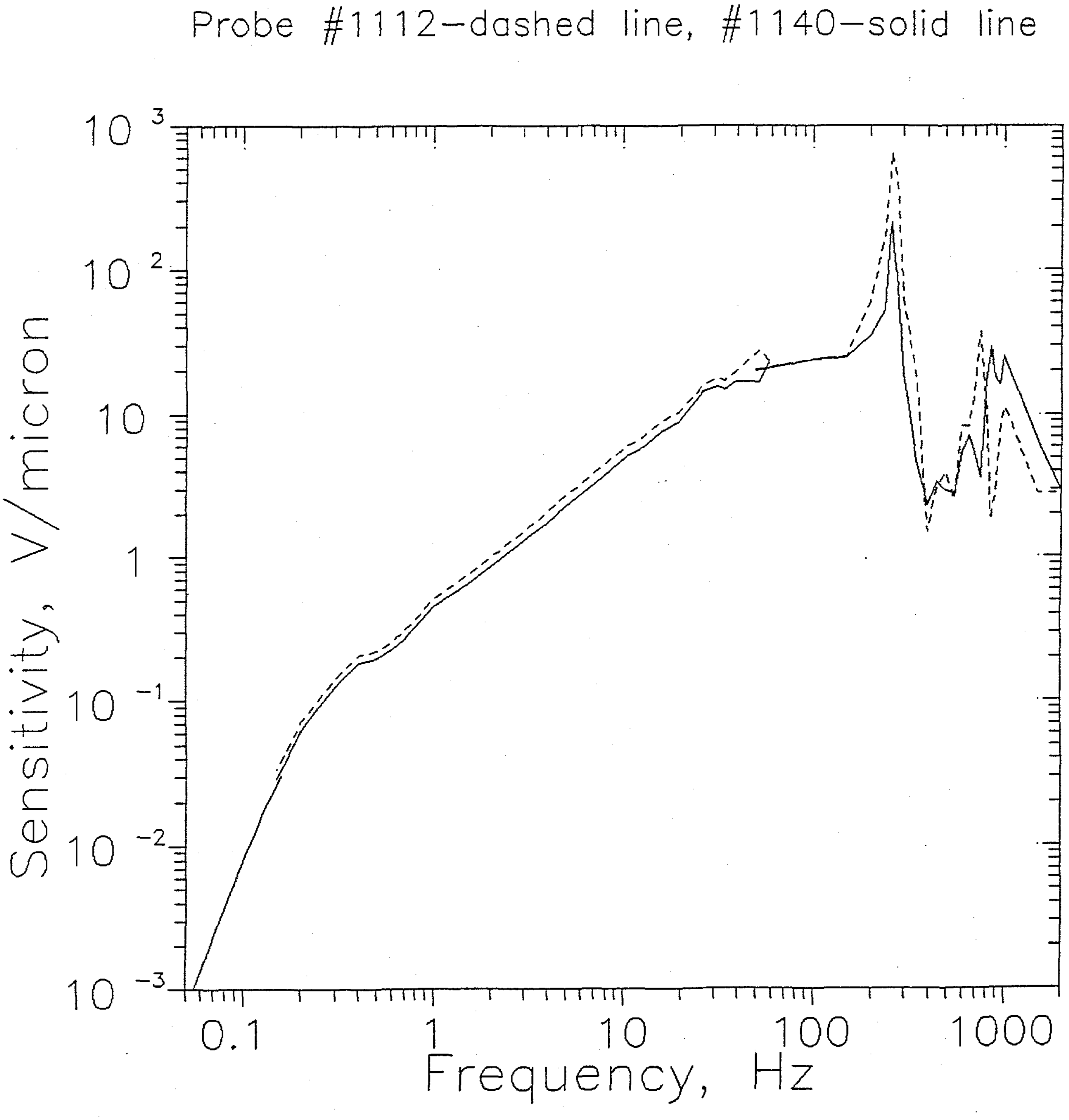
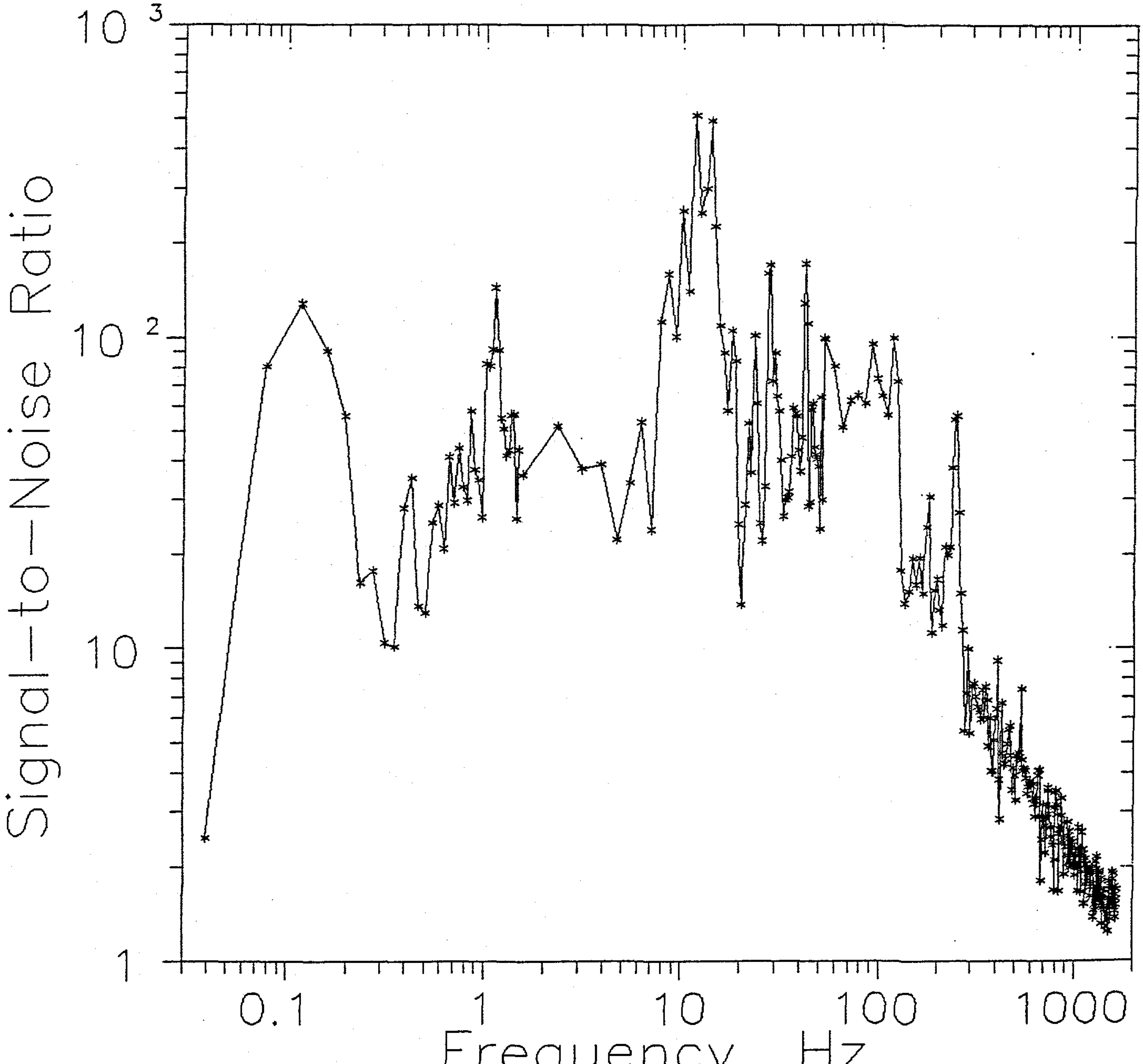

E
2nd probe
16.5'
195'
215'
Austin Chalk
1st probe
Adit
265'
Eagle Ford Shale
Protective cage
and work platforms
10'

Fig 2



Probe #1112-dashed line, #1140-solid line

Fig 3

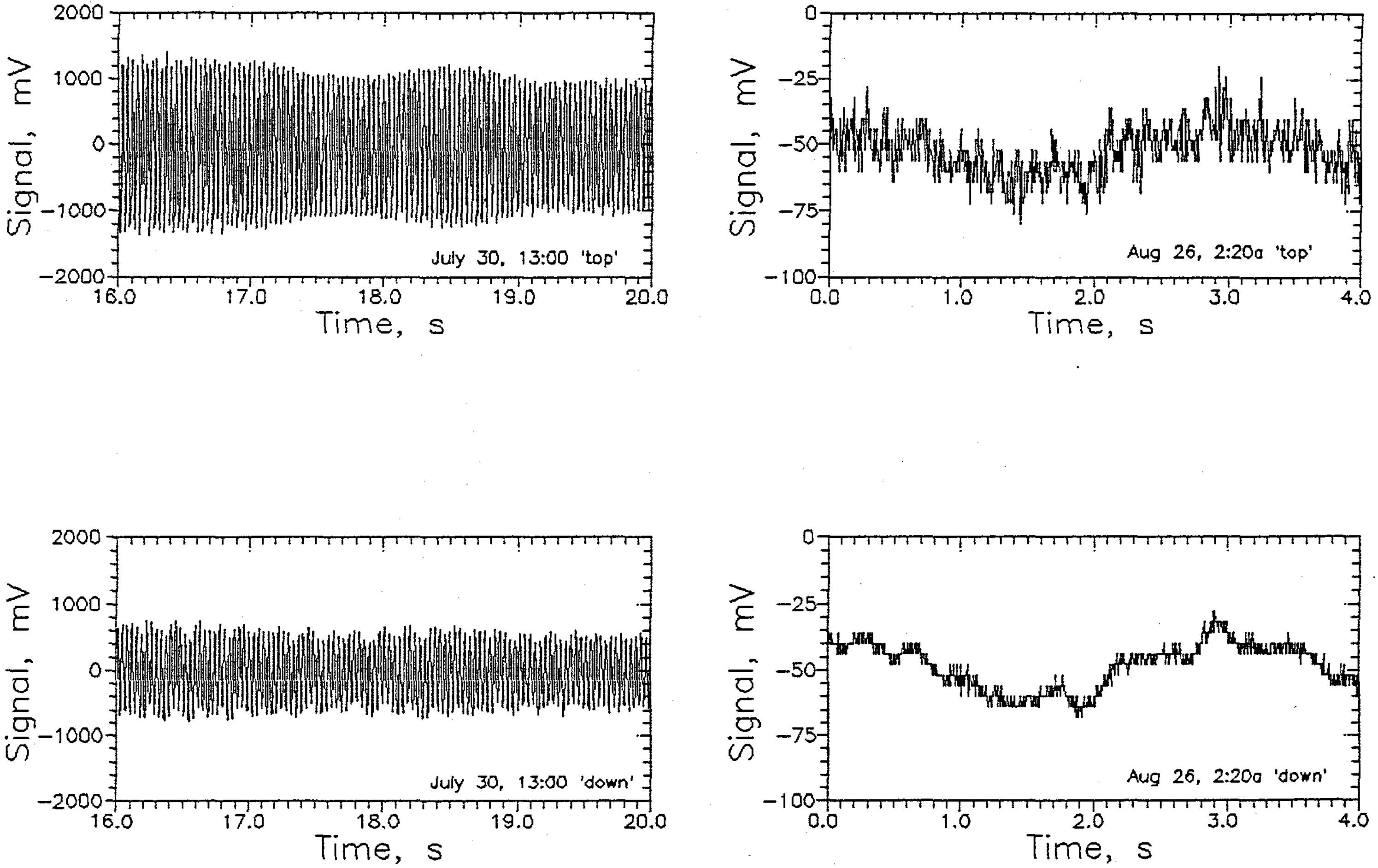


10 3
10 2
10
1
0.1
1
10
100
1000
Signal-to-Noise Ratio
Frequency, Hz

Fig 4

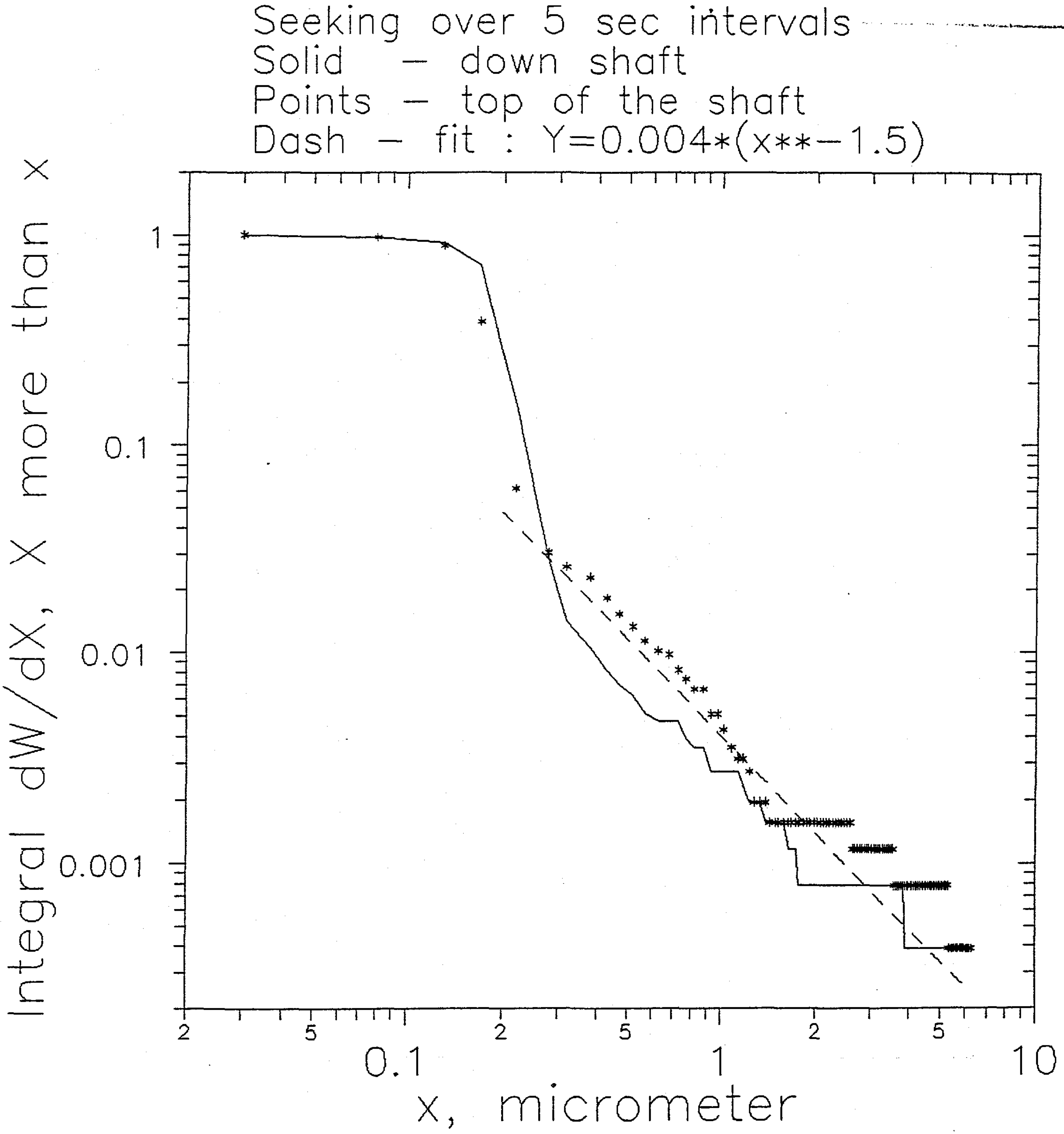
a) c)

b) d)



Signal, mV
2000
1000
0
−1000
−2000
16.0
17.0
18.0
19.0
20.0
Time, s
July 30, 13:00 'top'
Signal, mV
0
−25
−50
−75
−100
0.0
1.0
2.0
3.0
4.0
Time, s
Aug 26, 2:20a 'top'
Signal, mV
2000
1000
0
−1000
−2000
16.0
17.0
18.0
19.0
20.0
Time, s
July 30, 13:00 'down'
Signal, mV
0
−25
−50
−75
−100
0.0
1.0
2.0
3.0
4.0
Time, s
Aug 26, 2:20a 'down'

Fig 5



Seeking over 5 sec intervals
Solid - down shaft
Points - top of the shaft
Dash - fit : Y=0.004*(x**-1.5)
Integral dW/dX, X more than x
1
0.1
0.01
0.001
2
5
0.1
2
5
1
2
5
10
x, micrometer

Fig 6

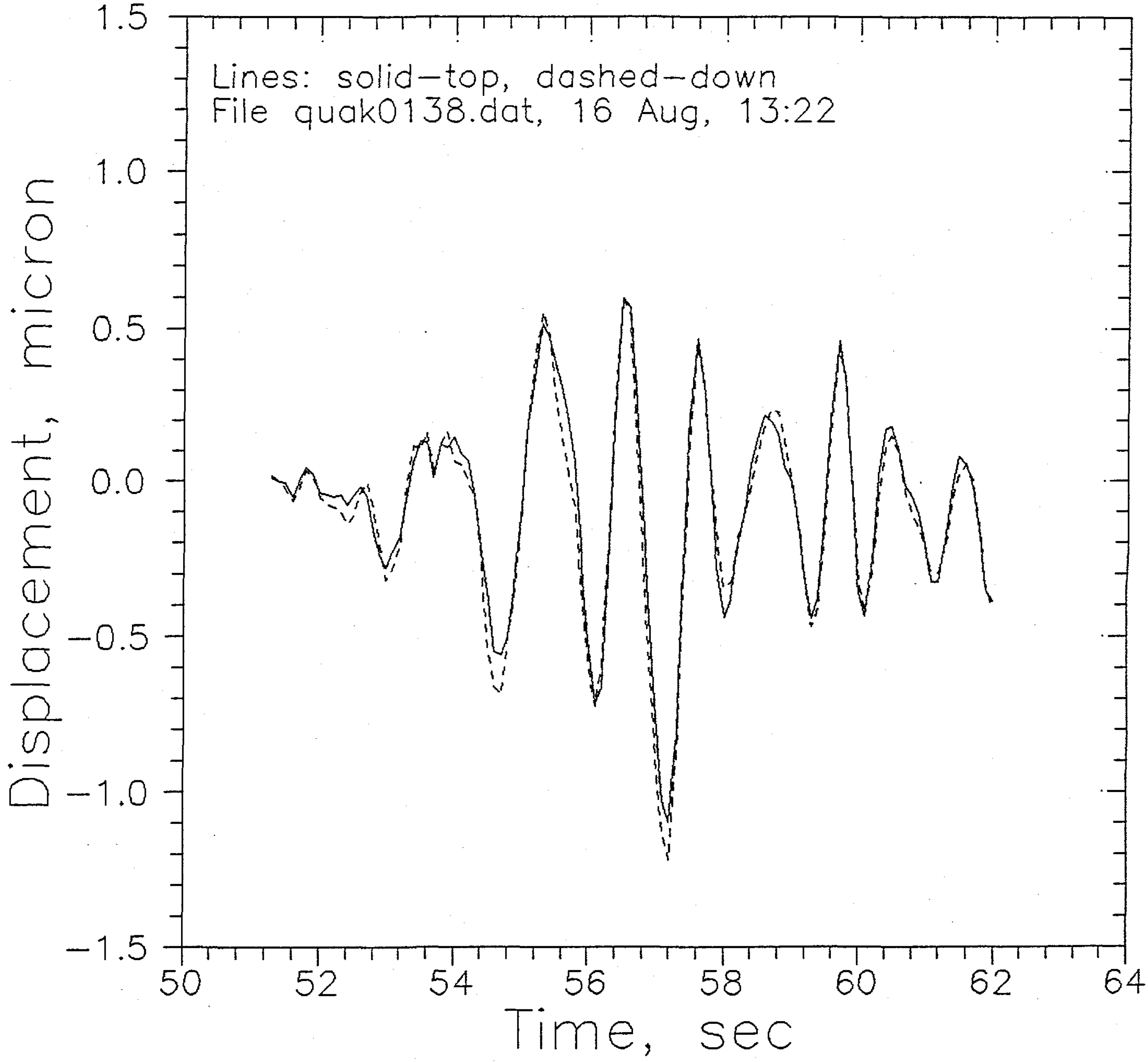
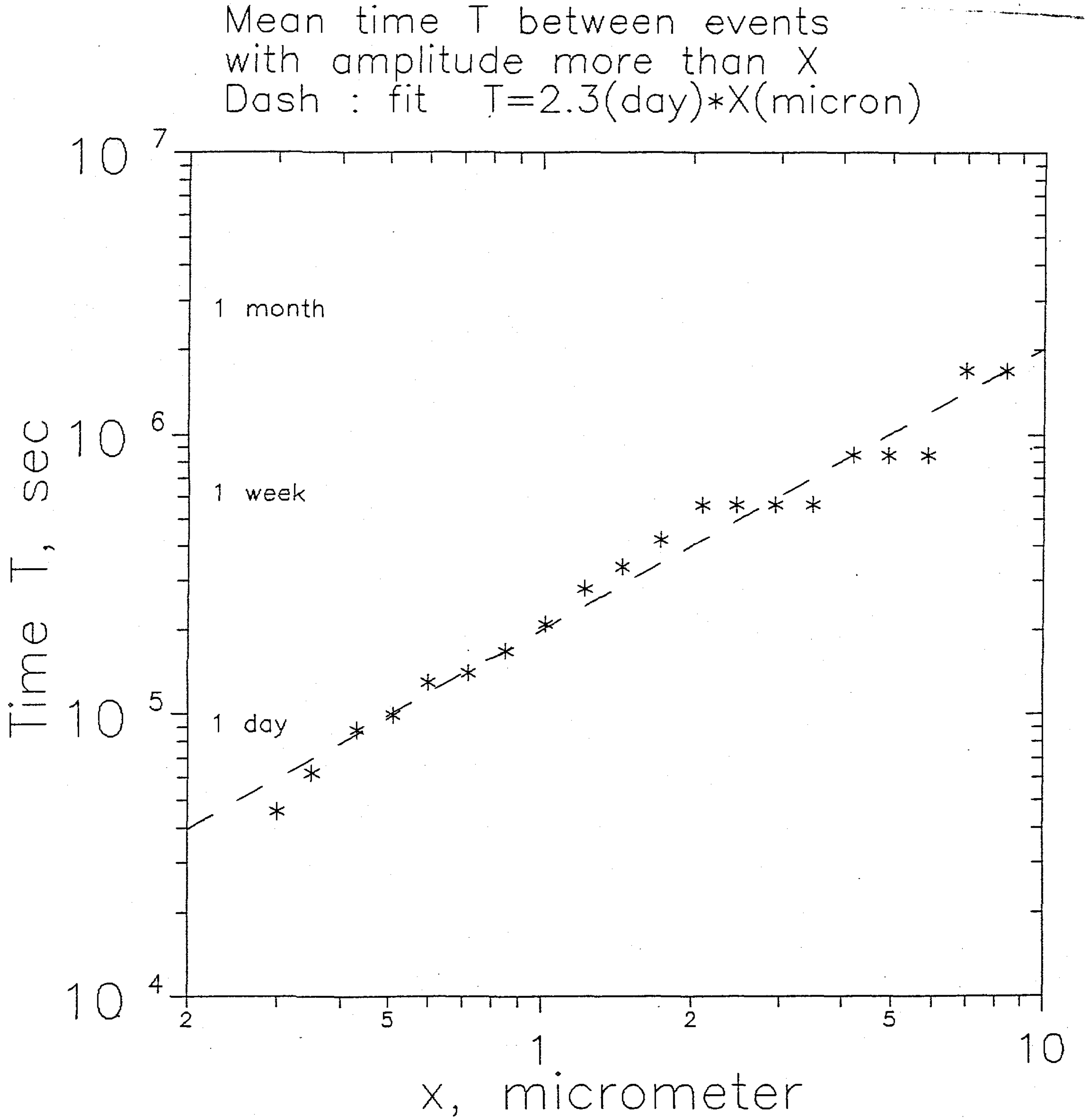

Lines: solid-top, dashed-down
File quak0138.dat, 16 Aug, 13:22
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Displacement, micron
50
52
54
56
58
60
62
64
Time, sec

Fig 7



Mean time T between events
with amplitude more than X
Dash : fit T=2.3(day)*X(micron)

Fig 8

a)
b)
c)

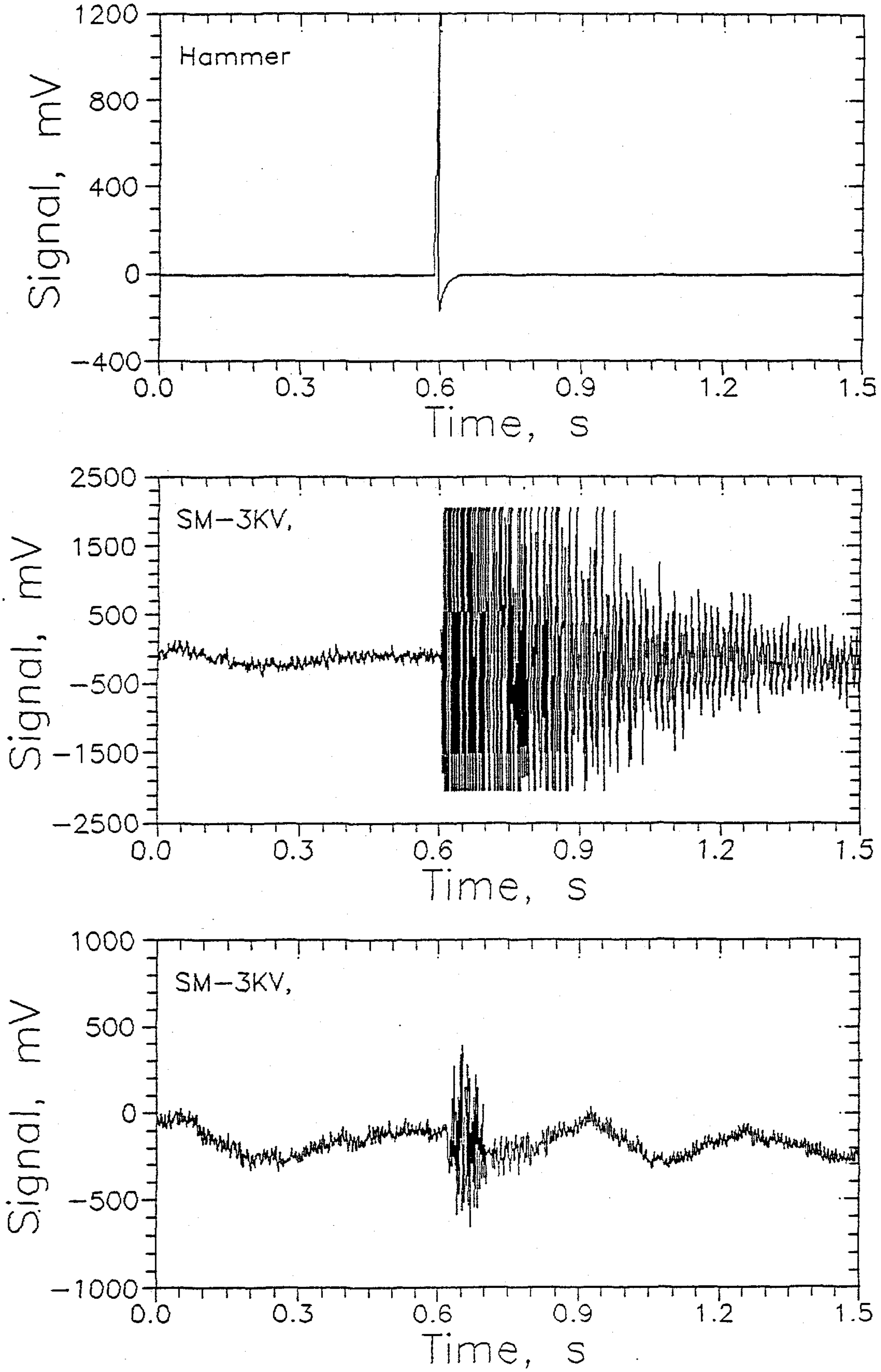

Hammer
Signal, mV
1200
800
400
0
−400
0.0
0.3
0.6
0.9
1.2
1.5
Time, s
SM−3KV,
Signal, mV
2500
1500
500
−500
−1500
−2500
0.0
0.3
0.6
0.9
1.2
1.5
Time, s
SM−3KV,
Signal, mV
1000
500
0
−500
−1000
0.0
0.3
0.6
0.9
1.2
1.5
Time, s

Fig 9

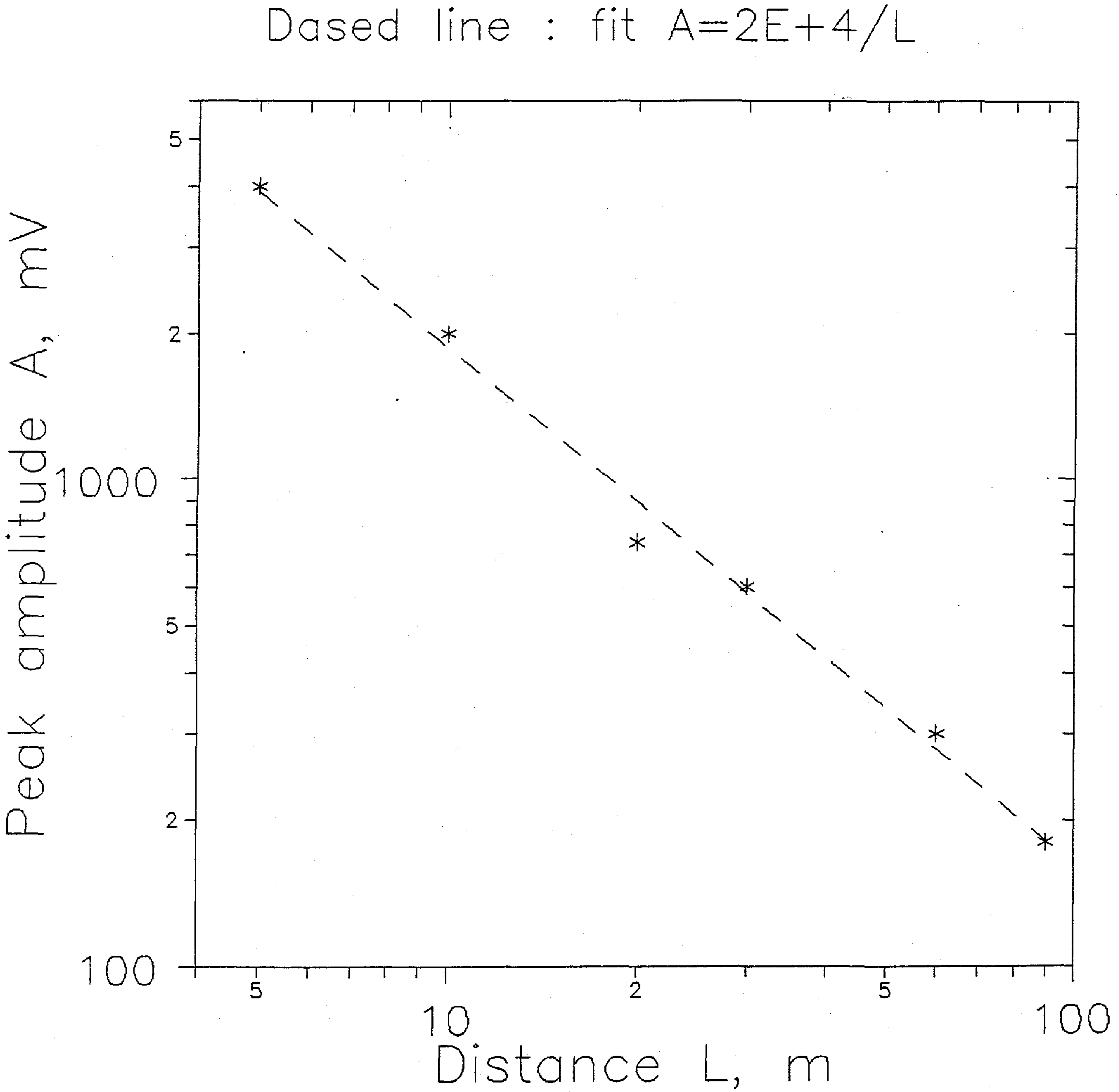
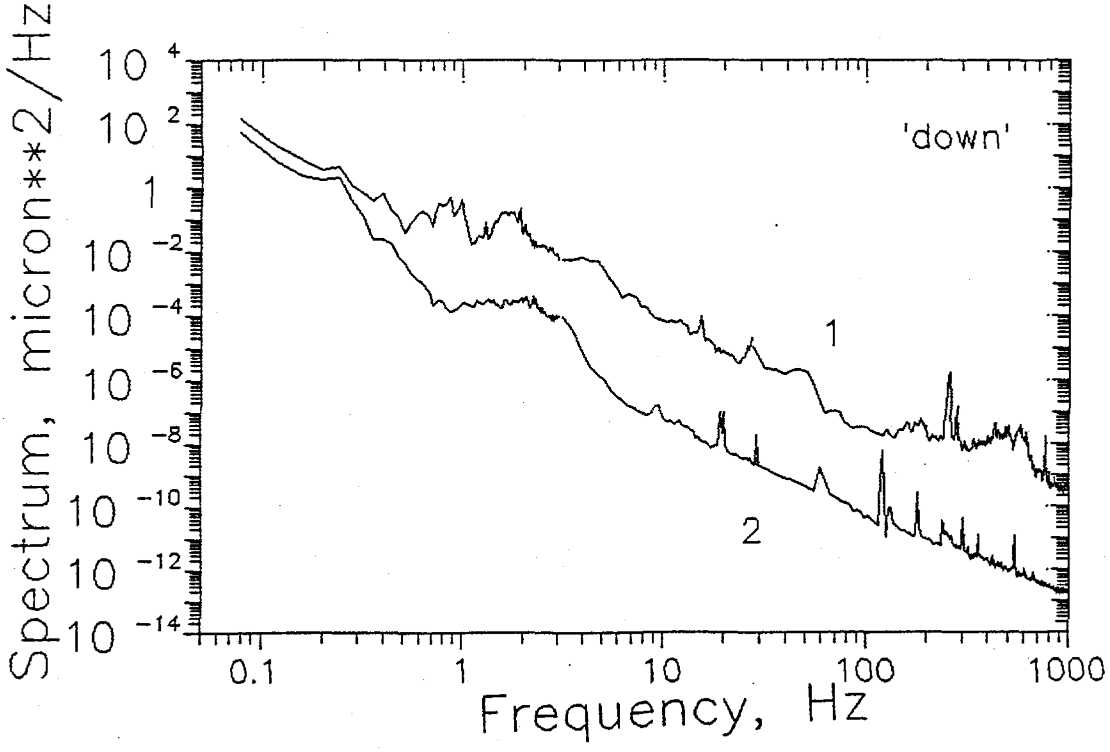
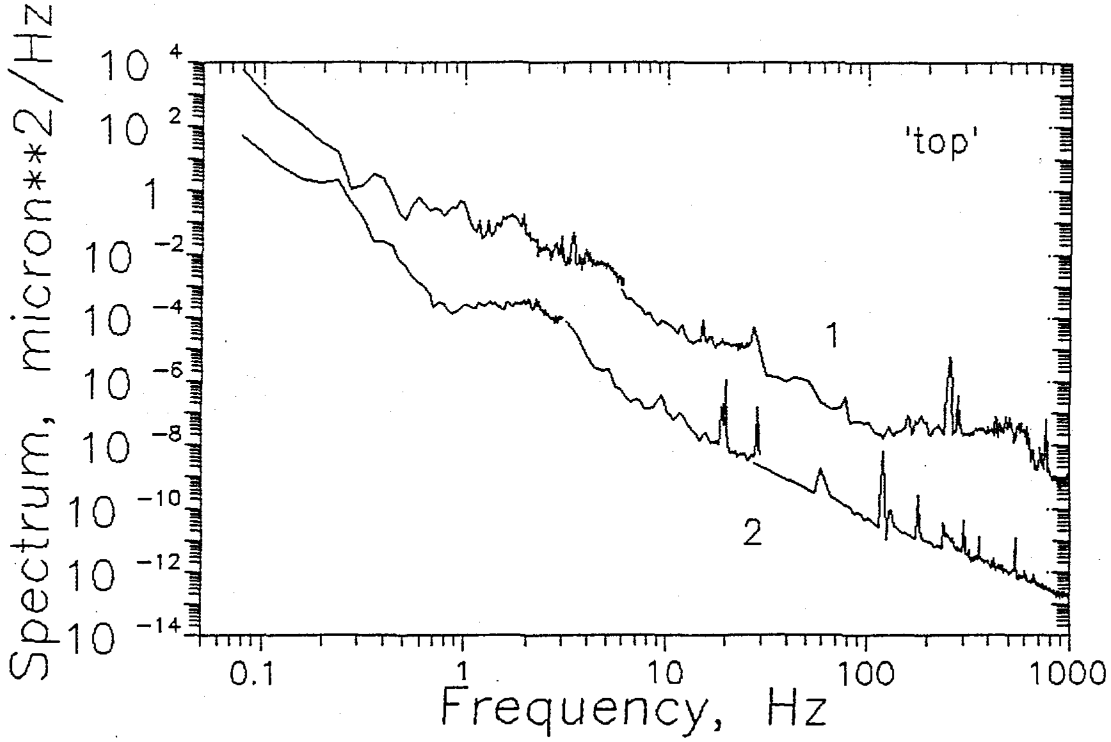

Dased line : fit A=2E+4/L
Peak amplitude A, mV
5
2
1000
5
2
100
5
10
2
5
100
Distance L, m

Fig 10 a)



'down'
1
2
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0.1
1
10
100
1000
Frequency, Hz
Spectrum, micron**2/Hz

Fig 10 b)



Spectrum, micron**2/Hz
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
'top'
1
2
0.1
1
10
100
1000
Frequency, Hz

Fig 11 a)

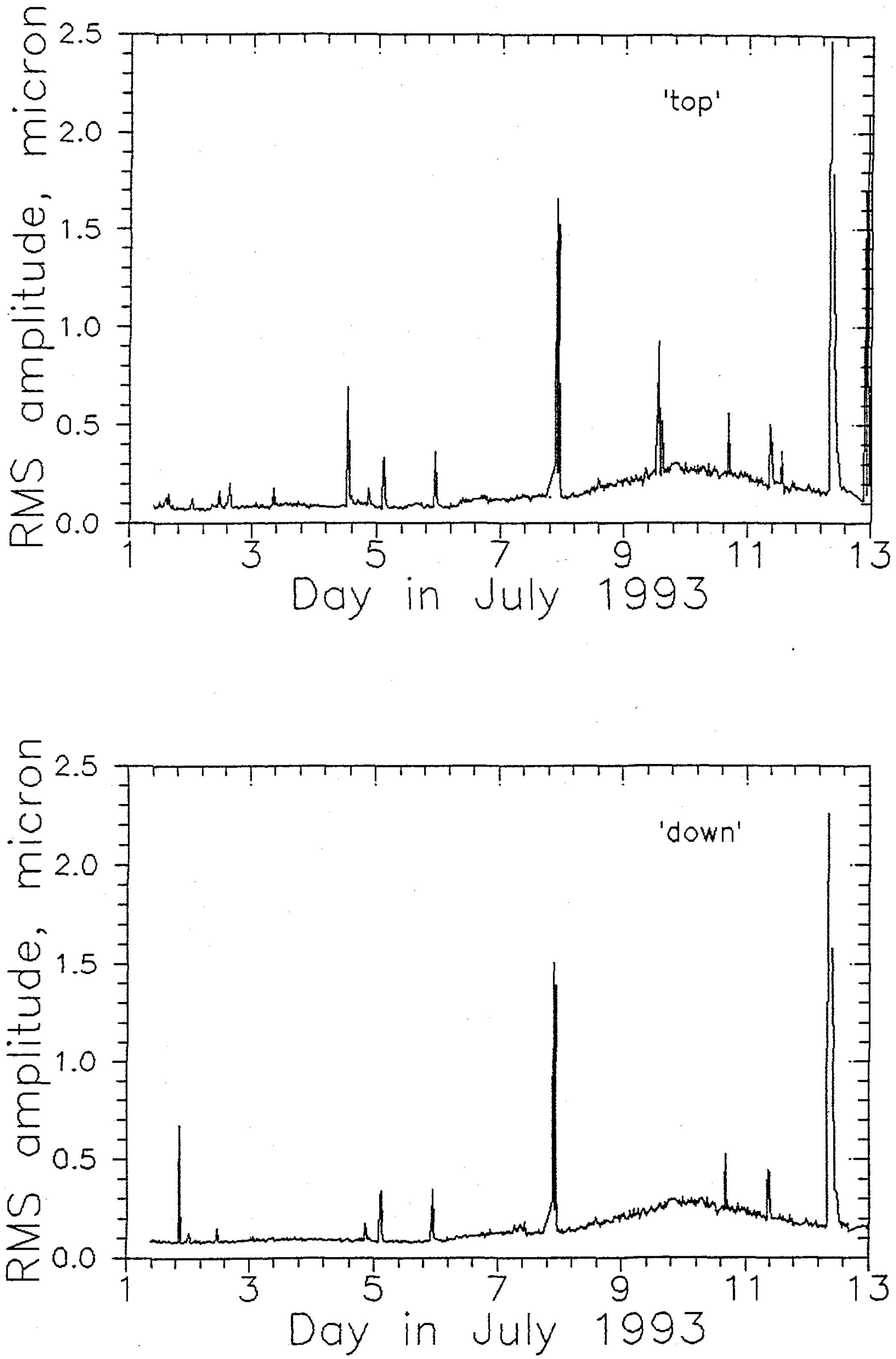

'top'
RMS amplitude, micron
0.0
0.5
1.0
1.5
2.0
2.5
1
3
5
7
9
11
13
Day in July 1993
'down'
RMS amplitude, micron
0.0
0.5
1.0
1.5
2.0
2.5
1
3
5
7
9
11
13
Day in July 1993

Fig 11(b)

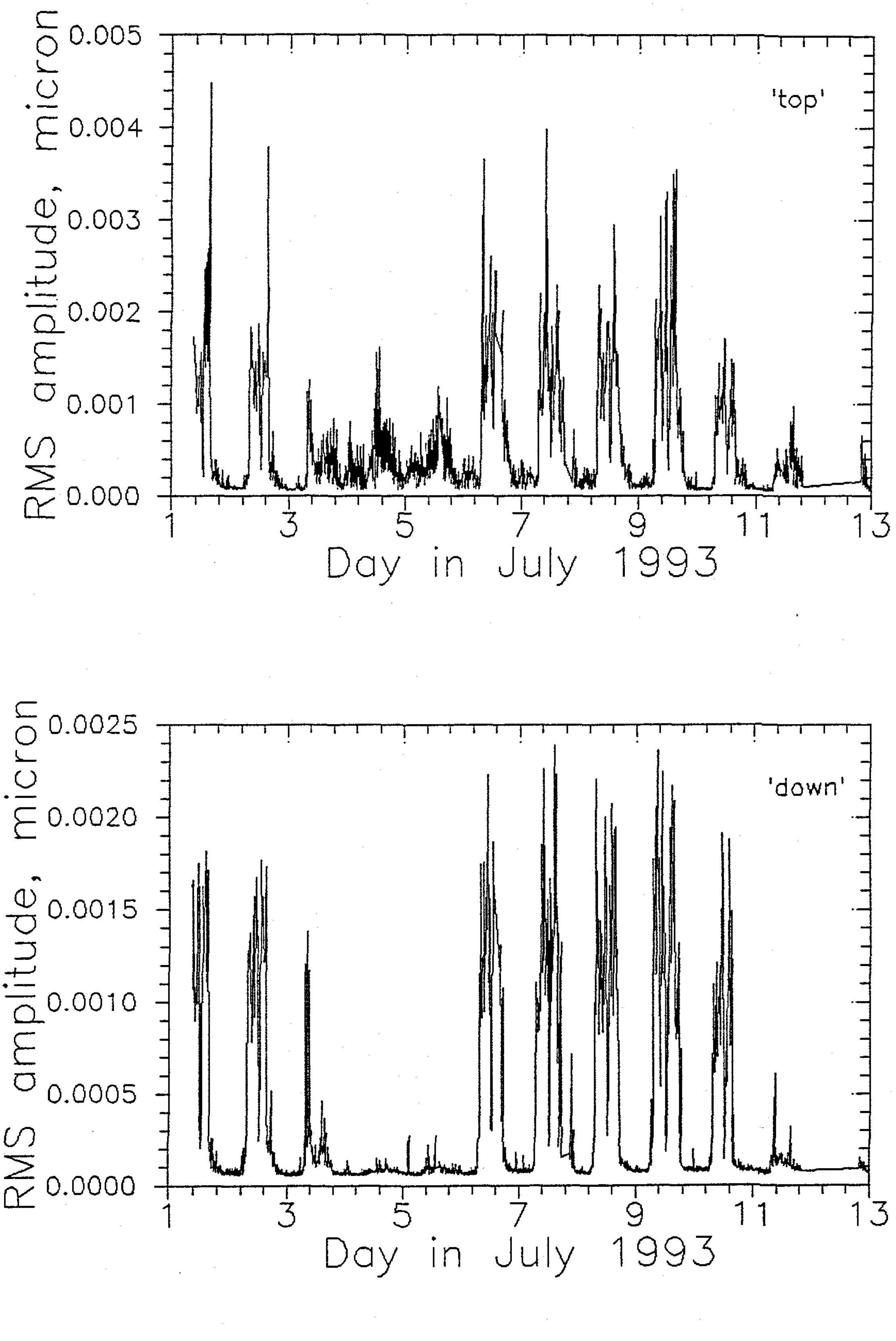
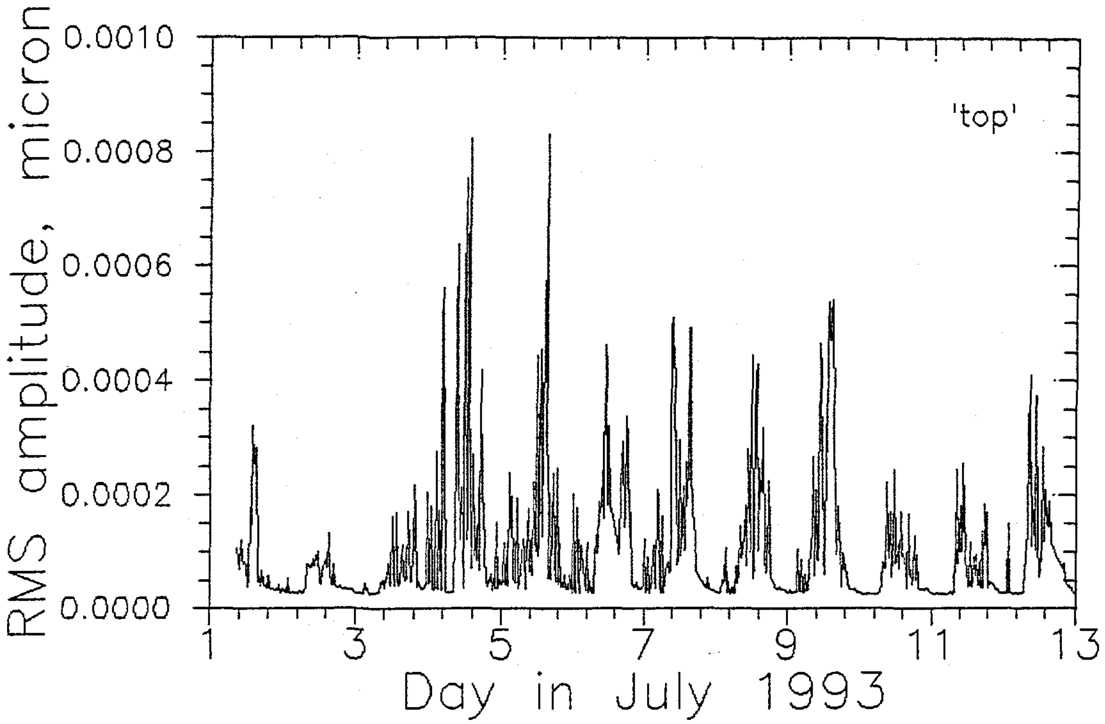

RMS amplitude, micron
0.005
0.004
0.003
0.002
0.001
0.000
'top'
1
3
5
7
9
11
13
Day in July 1993
RMS amplitude, micron
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
'down'
1
3
5
7
9
11
13
Day in July 1993

Fig 11 c)


RMS amplitude, micron
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
'top'
1
3
5
7
9
11
13
Day in July 1993

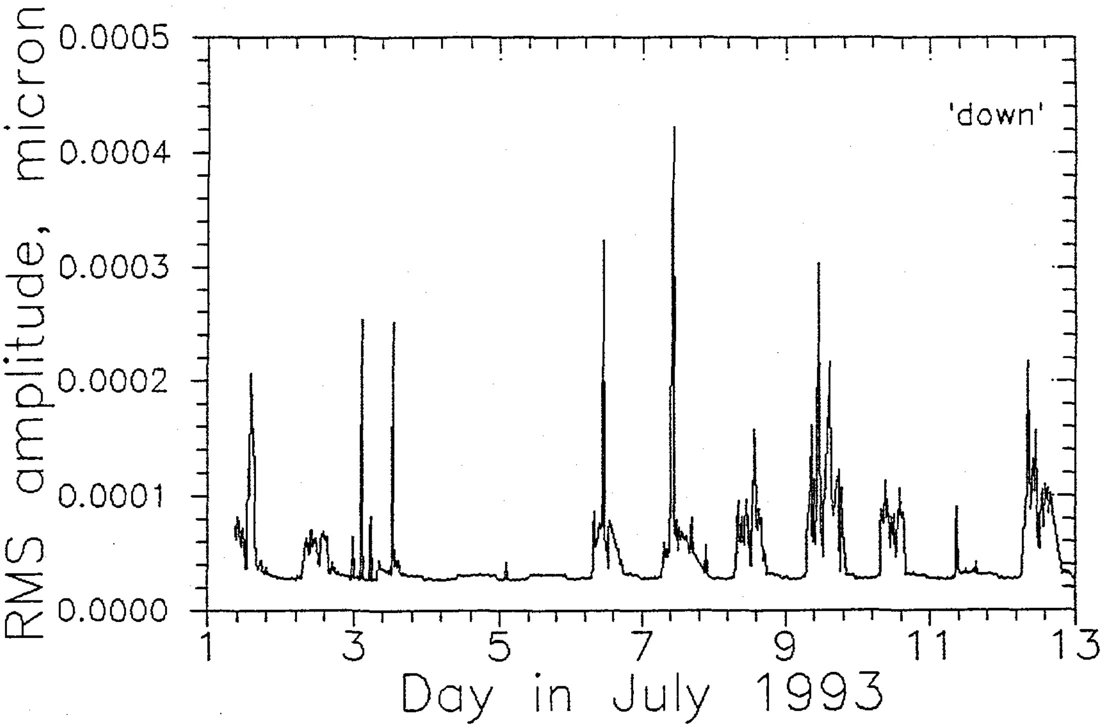

RMS amplitude, micron
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
'down'
1
3
5
7
9
11
13
Day in July 1993

Fig 12 a) b)
c)

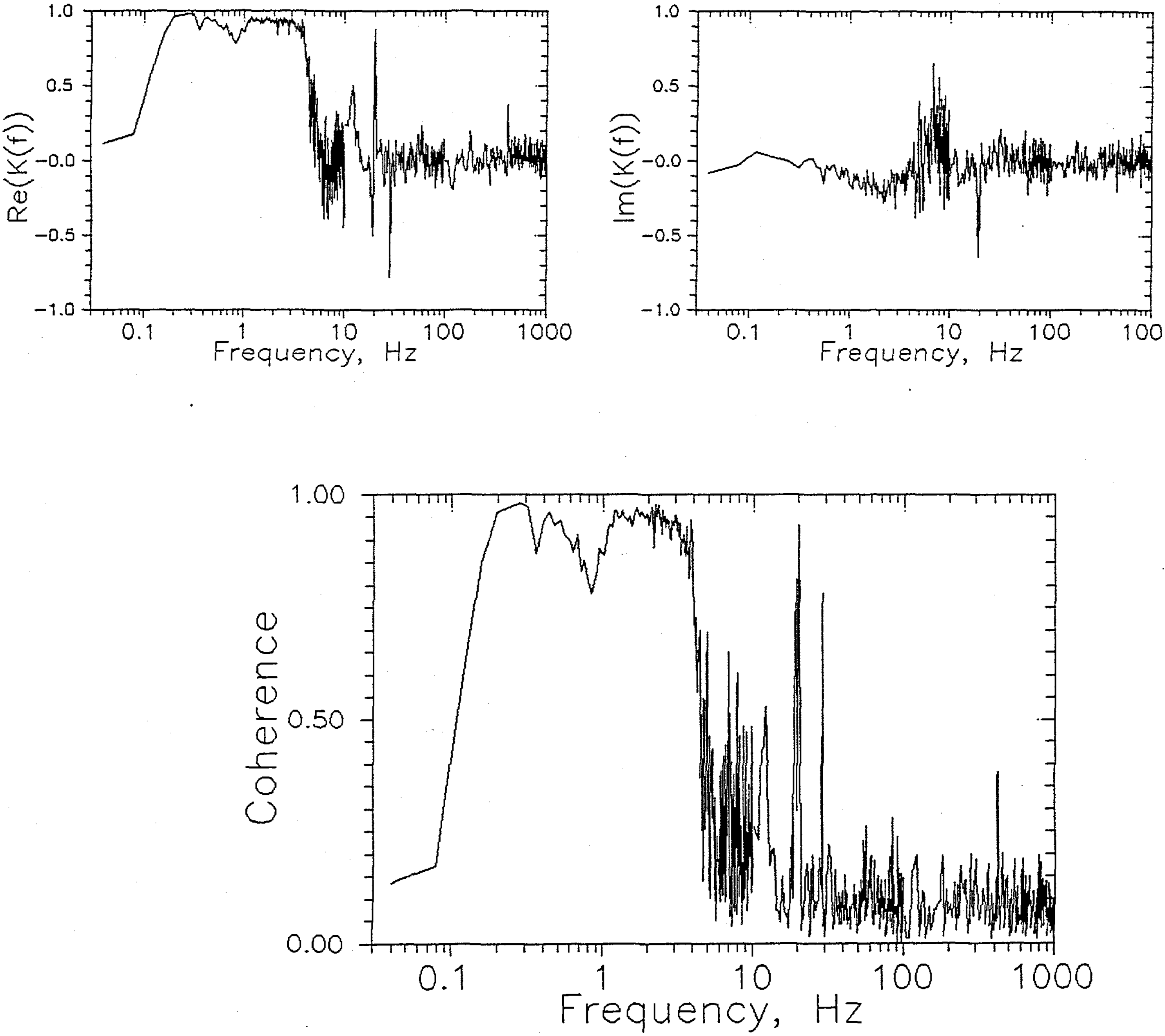

1.0
0.5
-0.0
-0.5
-1.0
Re(K(f))
0.1
1
10
100
1000
Frequency, Hz
1.0
0.5
-0.0
-0.5
-1.0
Im(K(f))
0.1
1
10
100
1000
Frequency, Hz
1.00
0.50
0.00
Coherence
0.1
1
10
100
1000
Frequency, Hz

Fig (12 d)

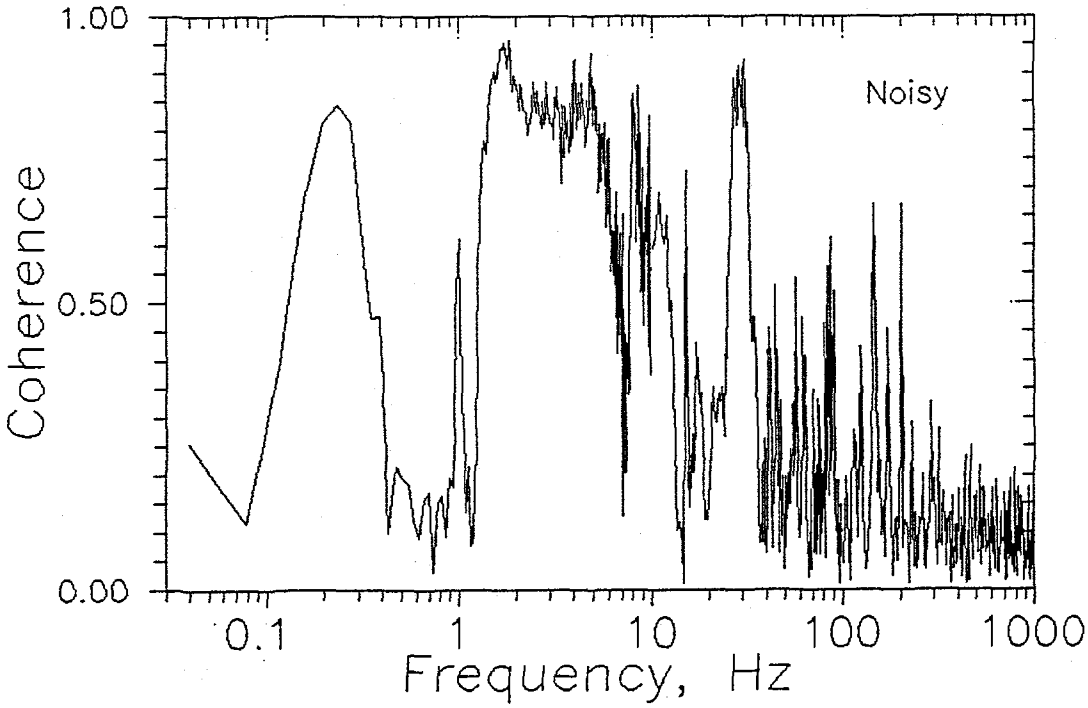
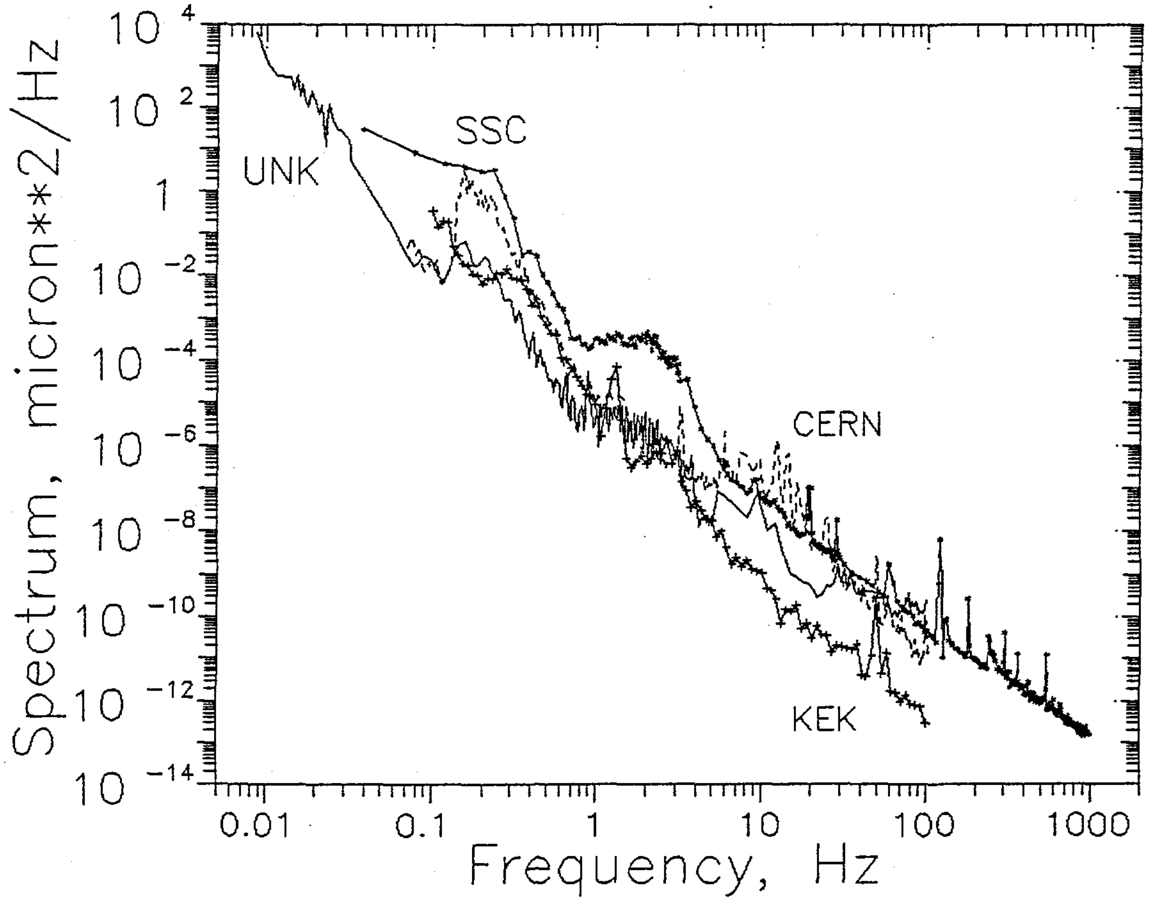


Fig 13 a)



Spectrum, micron**2/Hz
10 4
10 2
1
10 −2
10 −4
10 −6
10 −8
10 −10
10 −12
10 −14
UNK
SSC
CERN
KEK
0.01
0.1
1
10
100
1000
Frequency, Hz

Fig 13 b)

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