Fermi National Accelerator Laboratory

FERMILAB-TM-1959

Vibrational Analysis of Tevatron Quadrupoles

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January 1996

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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1. INTRODUCTION

There is motion of the beam in the Tevatron on various time scales from years (slow motion of the tunnel) to tenths of milliseconds (betatron tune motion). This paper will discuss a very restricted frequency range from a few Hertz to a few tens of Hertz. The assumption behind the analysis presented here is that the beam motion is due to transverse motion of Tevatron quadrupoles.

The introduction of the low beta insertions in the Tevatron has necessitated the installation of remote monitoring sensors on the quadrupoles since the quadrupoles are strong and are located in regions where the beta functions are large [1] as shown in figure 1. In general the magnet and support structures are mirror symmetric around the interaction points.

Fig.1 Lattice Beta functions in the D0 interaction region.

Motion of the beam due to a certain magnitude quadrupole motion is proportional to the product of the square root of the beta function and the strength of the quad. Table 1 shows the maximum amplitude in millimeters that would be measured on a Beam Position Monitor in the arcs for a one millimeter displacement of a low beta quadrupole at D0 [2].

	C4Q2	C4Q3	C4Q4	D1Q4	D1Q3	D1Q2
Vertical	15	38	12	10	21	23
Horizontal	12	11	5	6	19	7

Table 1.
Maximum displacement in the arcs for a 1 mm quad displacement

The importance of this monitoring effort was brought to the fore during the rolled quad episode during the last collider run when we did not have this remote monitoring capability. Water levels and inclinometers have been installed on some of the quadrupoles in the interaction regions (figure 2) and have been used, for example, to indicate an ice ball forming on a quadrupole inside the CDF detector [3] and physical displacement of a quadrupole during the installation of shielding [4]. These are important examples however we shall restrict our discussion to motion on shorter time scales.

Fig. 2 Layout of remote monitoring equipment in the D0 interaction region.

Fourier analysis of the inclinometer signals indicated a plethora of frequencies as shown in figure 3.

Fig. 3 Fourier spectrum of the D1Q3 inclinometer (roll)

This discovery of the spikes in the frequency spectrum started this analysis which attempts to correlate the spatial pattern of several differing frequencies of beam motion as measured by the Tevatron Beam Position Monitors (BPMs) with observed motion of the Tevatron quadrupoles (mainly low beta quadrupoles).

2. MAGNET VIBRATION SPECTRA

We enlisted the help of several experts from Argonne National Laboratory [5] to make a systematic study of the vibrational spectra of the ground, the tunnel floor, and quadrupoles (mainly low beta quadrupoles). Figure 4 gives an overview of the site detailing where the motion studies took place.

Fig.4 Location of the vibration analysis studies

A non low beta quadrupole spectrum is shown in figure 5 for various reasons, one of which is that it is so instructive. The location was at A3 which is physically close to the Central Helium Liquefier plant (CHL) which has two types of compressors which have fundamental frequencies of 4.6 and 8.5 Hz. We observe sharp lines in the ground and in the magnet at the fundamental and up to the fifth (third) harmonic for the Helium (Nitrogen) compressor. The ground motion is greater than the magnet up to the 19 Hz region where we observe a well known [6] stand resonance. A particular reason for mentioning the 4.6 Hz signal is that we use this signal as our "standard candle", i.e. this is our frequency calibration check at the different geographical locations.

Fig. 5   Frequency spectra of the A35 Tevatron Quad and the ground nearby

Many sets of data were taken as shown in figure 4 and we will present three sets that are illustrative and that happen to agree with the analysis presented below. Figure 6 shows the vertical frequency spectra measured on one of the Q3 quadrupoles in D0. The interesting portion of this spectrum is in the 20 to 25 Hz region and we shall discuss the relationship of this spectrum to the observed BPM spectrum in the following section.

Fig. 6 Vertical frequency spectrum of the D1Q3 quadrupole in the D0 interaction region

Figure 7 shows the vertical frequency of the two Q3 style quadrupoles in the B0 interaction region. Of interest here is the slight offset in frequency of the two peaks near 18.5 Hz, we shall see this phenomena in the next figure and our interpretation is that the peaks are due to a support structure resonance and the mechanical assemblage, although theoretically mirror symmetric, is slightly different on either side of the collision point. The support structures are different at B0 and D0, and we shall discuss the structure at D0 in more detail below, however the slight differences are apparent at both B0 and D0.

Fig. 7 Vertical frequency spectra of the Q3 quadrupoles in the B0 interaction region

To bring out the difference between ground motion and "stand" resonant effect an analogous plot to the one shown in figure 5 is given in figure 8 which shows the A4Q3 vertical spectra along with the concrete floor at the position of the magnet and we can see several of the ground motion spikes in the concrete and the magnet along with the broader peak at 18.2 Hz in the magnet spectra. So in the low beta quad vibration spectrum we can also see ground motion spikes and "stand" resonances. We expect the ground motion spikes to be the same for all magnets in a region but the possibility exist for slight differences in the mirror symmetric magnets on either side of the interaction regions.

Fig. 8 Comparison of the frequency spectra of Q3 magnet and the nearby floor

An example of a horizontal spectrum is shown in figure 9 which has the same data plotted linearly and semilogarithmically, in the semilog plot we can see the 4.6 Hz, but the linear plot is much cleaner in pointing out the broad strong 13.5 Hz peak and the small differences from one side of the interaction region to the other.

Fig. 9 Horizontal frequency spectra of the Q3 magnets at D0
a. semilog plot b. linear plot

3. BPM SPECTRA

A set of BPM spectra was taken in 1/6 of the Tevatron centered about the D0 interaction region. Twenty one spectra were taken in both the horizontal and vertical planes. Representative spectra in the horizontal and vertical plane are shown in figures 10 and 11. In the vertical case the distinctive pattern between 20 and 25 Hz is one of the most striking features of the vertical spectra and the similarity to the shape in figure 6 will be used to choose which quad to use in our modeling.

Fig. 10 Frequency spectrum of the horizontal Tevatron BPM at station C38

Fig. 11 Frequency sprectrum of the vertical Tevatron BPM at station D11

The signal above background was tabulated for the different frequencies and is given in tables 2 and 3, where the units are in millivolts and 1 millivolt corresponds to an rms motion of 83 microns. Also the displacements that would correspond to a 1 mm displacement of a low beta quadrupole are shown for several quads.

Table 2
Vertical BPM signal above background for BPMs around D0

Table 3
Horizontal BPM signal above background for BPMs around D0

4. ANSYS CALCULATION

After measuring the frequency spectrum on the quadrupoles and noticing that not all the frequencies corresponded to floor vibrations due to external sources (CHL) or internal sources (water flow, air conditioning, ...), we asked for an ANSYS study [5] of the D0 girder and magnet assemblage. There were approximations made in the modeling and as noted above in the discussion about figure 9 there are slight experimental differences between symmetric magnets on either side of the interaction point, nonetheless the study pointed out that there were low lying resonances to be expected. First we will show two calculations that would indicate measurable frequencies when the magnets were measured but would not imply a large excitation to the beam. Figure 12 implies a similar horizontal motion to a Q3 and a Q4 quadrupole but these are opposite polarity quadrupoles and the effect on the beam is less than one would expect from measuring the power spectral density on the Q3 and the Q4. Next we show in figure 13 a case where again a measurement on a quad could be misleading since there is almost no net motion of the magnetic center of the quad.

Fig. 12 ANSYS simulation of one mode of the D0 girder and magnet system

Fig. 13 ANSYS simulation of one mode of the D0 girder and magnet system

Figure 14 gives an example where the contributions of a Q3 and a Q4 would add, and figure 9 shows that we had a signal on the C4 side at this frequency, but unfortunately the C4Q4 did not have a signal. The essential conclusion from the study is not the exact frequencies since fairly rough approximations were made but rather the fact that we should expect a number of low lying resonant frequencies.

Fig. 14 ANSYS simulation of one mode of the D0 girder and magnet system

5. ANALYSIS

It is the main thesis of this paper that a correlation can be made between the spatial pattern (more precisely the betatron phase pattern) of BPM signals at different frequencies and the observed vibration spectrum of quadrupoles (mainly low beta). We have not attempted an absolute prediction of BPM magnitudes since we did not take the quad vibration data at the same time as the BPM data and it was observed that the vibration magnitude could change drastically in the course of a day, although the order of magnitude is occasionally reasonable. The other point to be made is that due to the magnitude of the beta functions there is almost no betatron phase difference between the elements of the triplet (remember that the betatron phase goes like the integral of the inverse of the beta function). Also there is almost exactly a 180 degree phase advance in going through the interaction point, so one can not even pick out the side of the interaction region let alone a particular quad from the spatial pattern of the magnitude (we have no sign information) of the BPM frequency response. As mentioned above in the section on the ANSYS analysis, the fact that one measures a vibrational component on a magnet is no guarantee that there will be an effect on the beam. Having made these caveats, we are going to nevertheless compare the spatial pattern of the frequency components of the BPM spectra to the pattern of the magnitudes that one would expect from the vibration of a single quad at one of the measured vibrational frequencies. Figures 15 shows the distribution of the 18.5 Hz component of the vertical BPM signal along with the magnitude of the signal expected from the motion of one of the B0

Q3 quadrupoles (refer to figure 7). Figure 16 shows the 21.5 Hz vertical case (refer to figure 6). Our horizontal example is given in figure 17 (refer to figure 9).

Fig. 15 BPM spectrum as a function of normalized betatron phase compared to the relative pattern expected from the motion of the downstream Q3 quadrupole at B0

Fig. 16 BPM spectrum as a function of normalized betatron phase compared to the relative pattern expected from the motion of the downstream Q3 quadrupole at D0

Fig. 17 Horizontal BPM spectrum as a function of normalized betatron phase compared to the relative pattern expected from the motion of the downstream Q3 quadrupole at D0

These plots present clear evidence for beam motion arising from motion of the quadrupoles in the low beta regions of the accelerators. The cause of the motion is due to external vibrations (CHL for example), internal vibrations associated with the air handling equipment (and other causes), and low order "stand" resonances. The frequency spectrum of the losses during collider operation (C:LOSTP) is dominated by a low frequency component at .3 Hz which corresponds to the Main Ring cycle, however there have been periods of time in which higher frequencies in the ten to twenty Hertz region have been observed, figure 18.

Fig. 18 Proton loss spectrum at B0 with a low frequency cut off at 2 Hz

ACKNOWLEDGEMENTS

The author would like to thank the following people for help in obtaining the data presented here, John Seraphin, Rich Janes, Hengjie Ma, and Todd Johnson.

REFERENCES

[1] Norman Gelfand, private communication

[2] Jim Holt, private communication

[3] Tevatron log book, ED42, page 234

[4] C. Moore, T. Johnson, J. Holt, "Observation of C4Q4 Motion", Fermilab internal note EXP-189

[5] J. Jendrzejczyk, R. K. Smith

[6] H. Pfeffer, private communication

[7] Bruce Hoffman, private communication

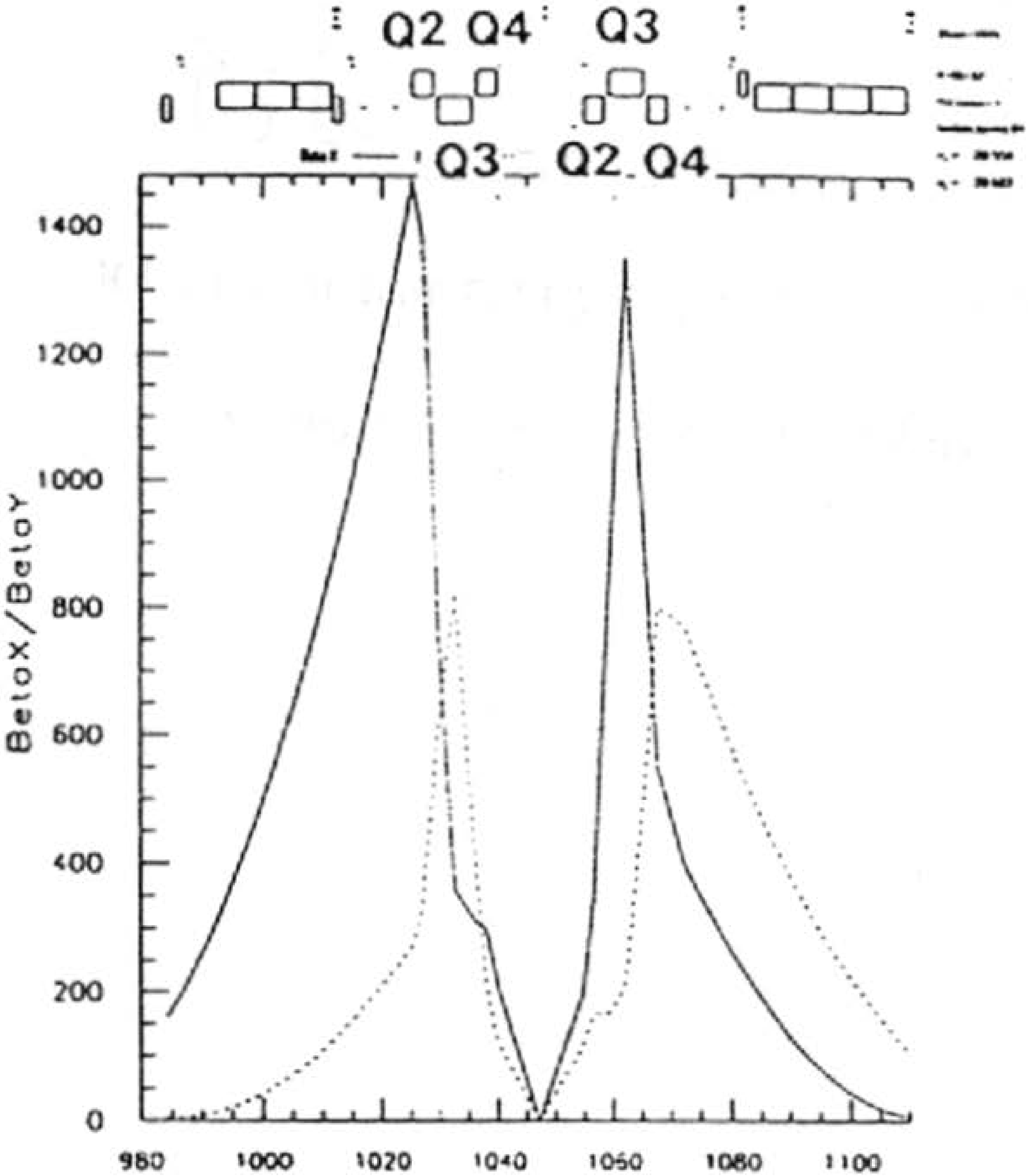
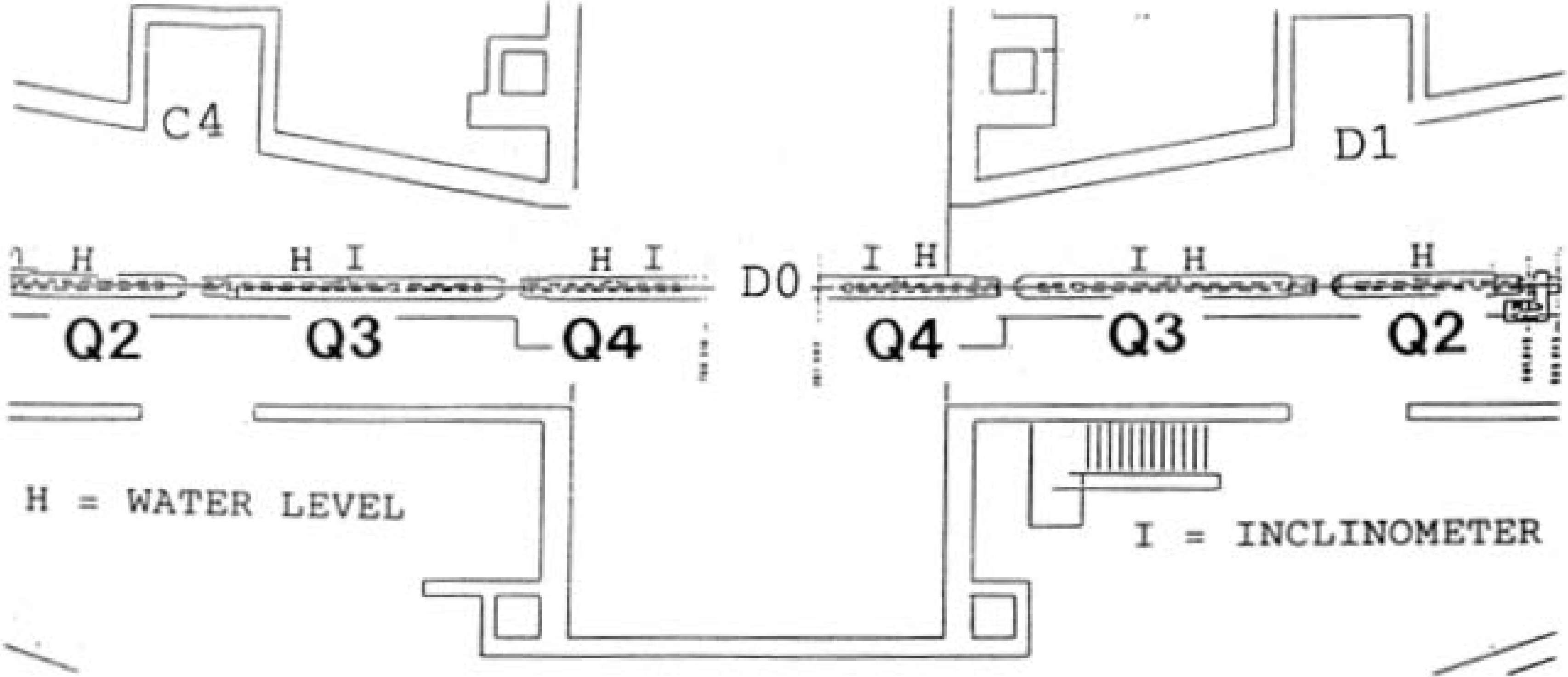
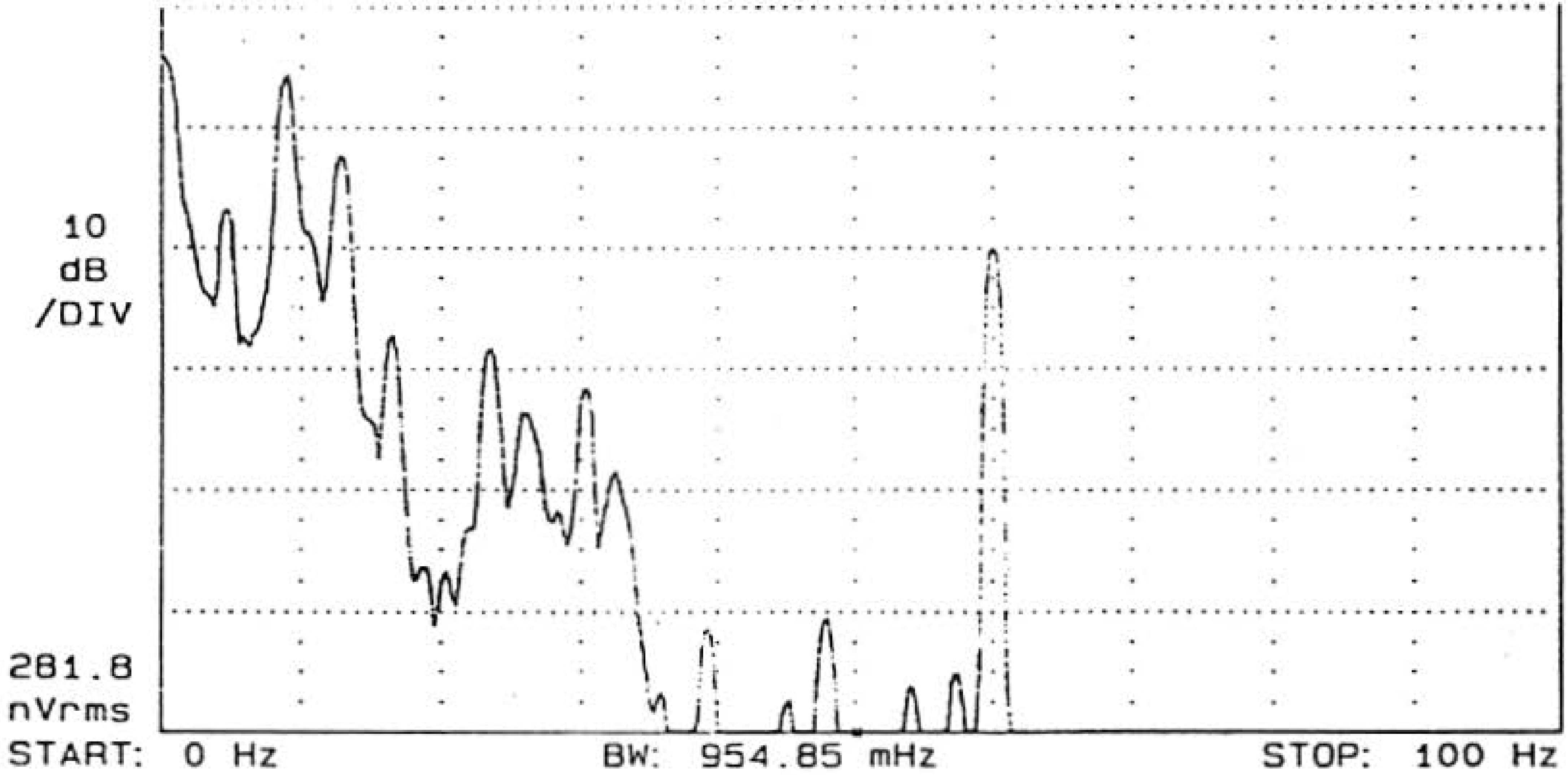


Fig.1 Lattice Beta functions in the D0 interaction region.


C4
D1
H
H I
H I
D0
I H
I H
H
Q2
Q3
Q4
Q4
Q3
Q2
H = WATER LEVEL
I = INCLINOMETER


10
dB
/DIV
281.8
nVrms
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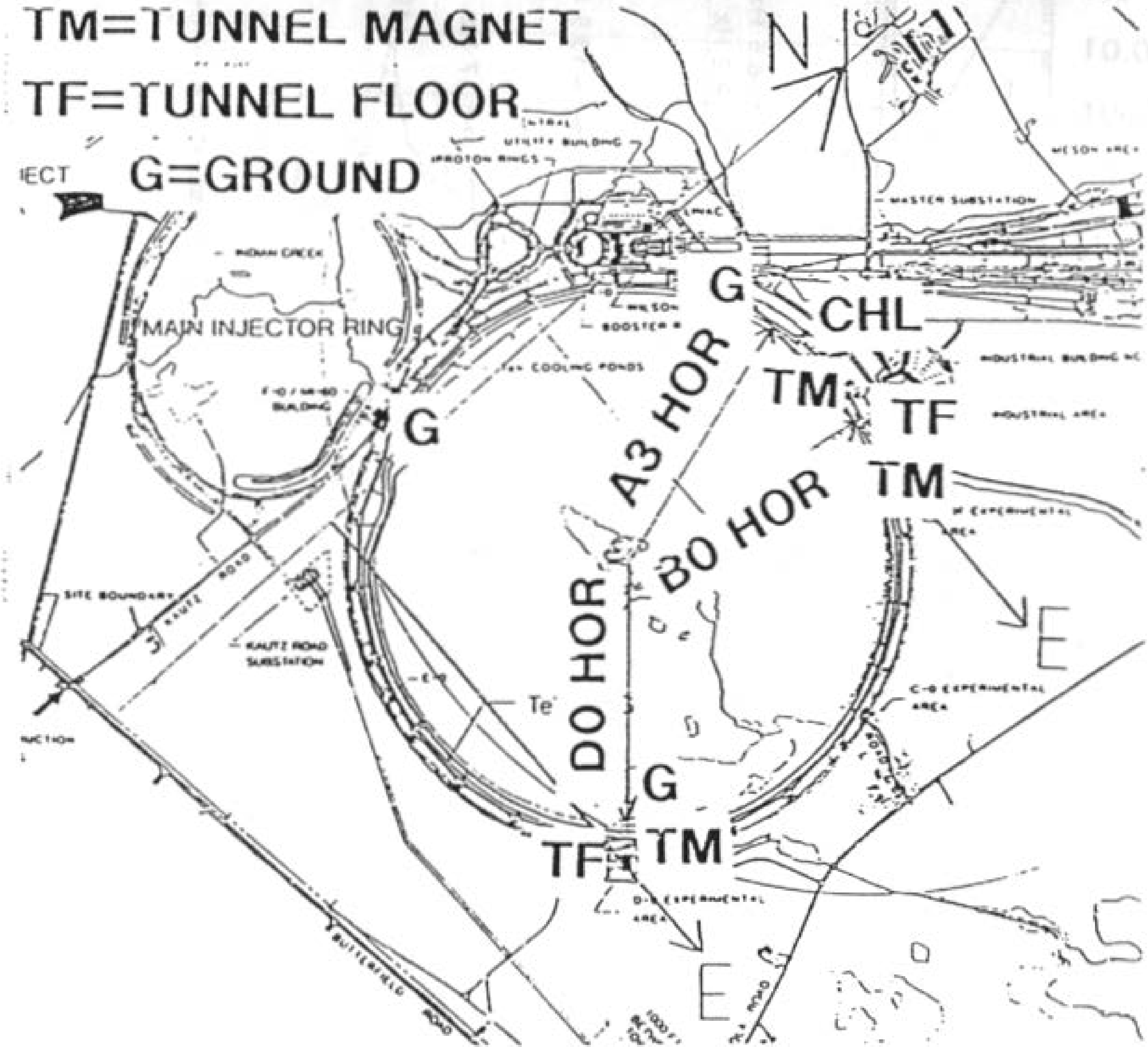
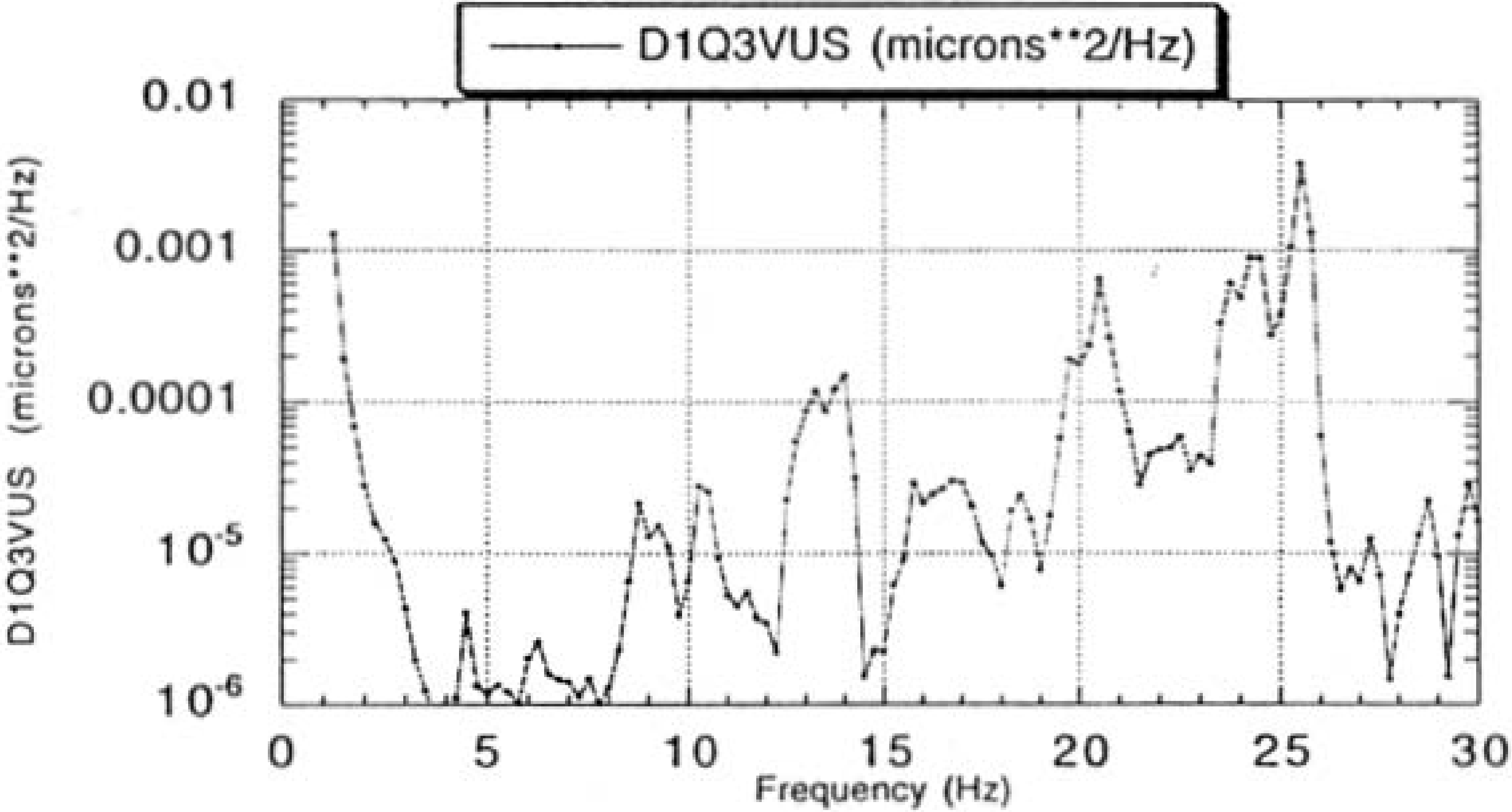
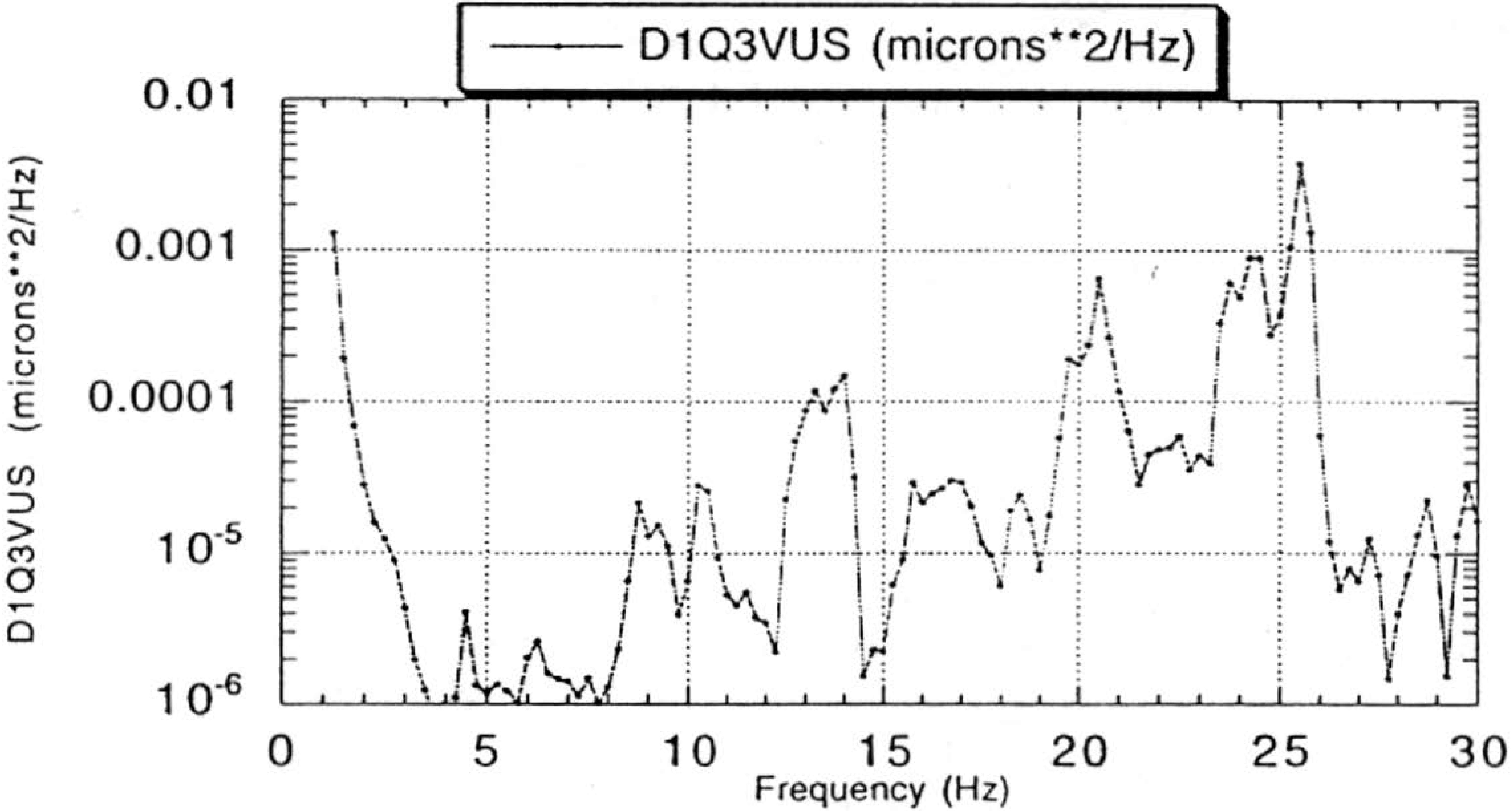
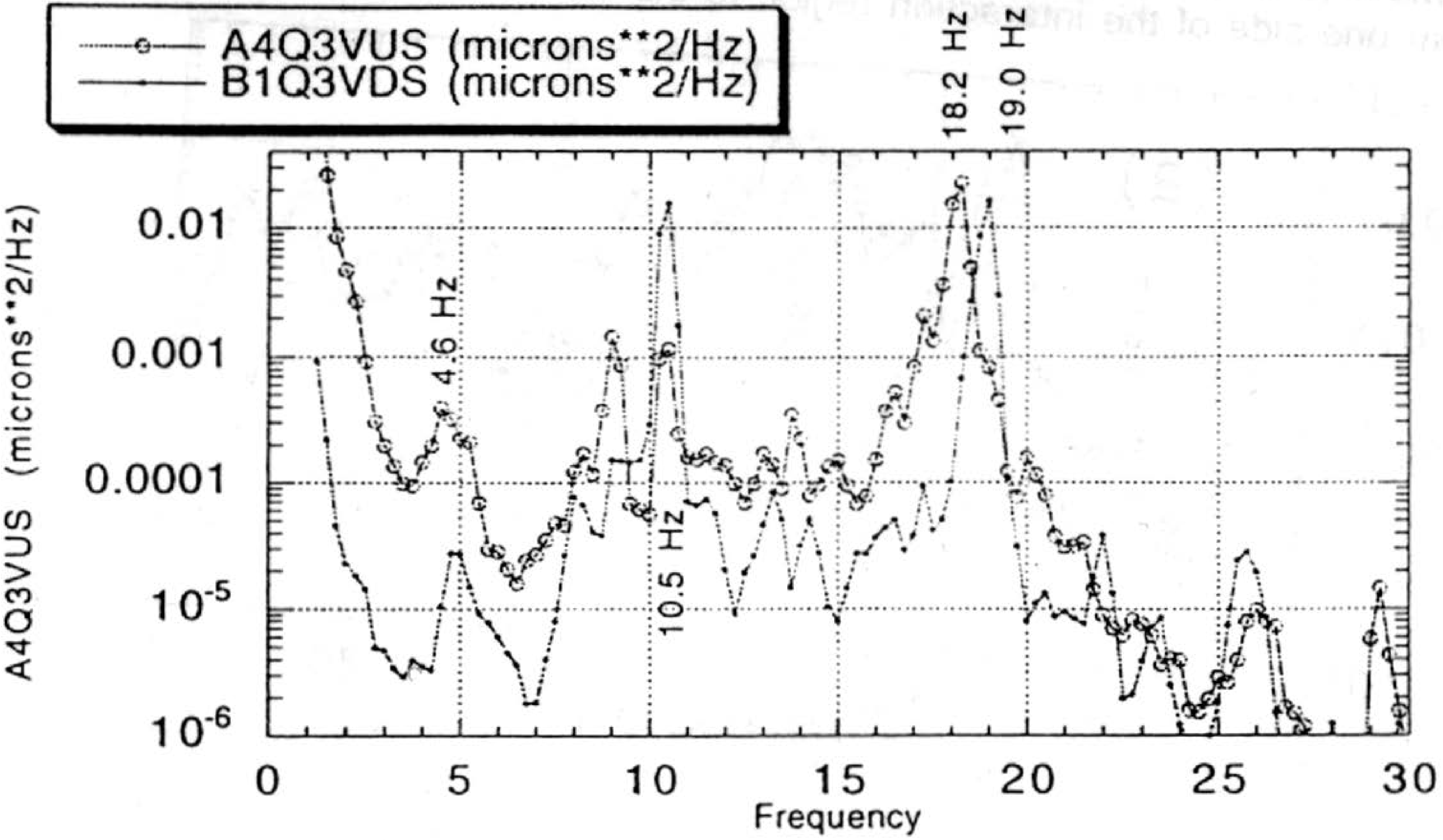
BW: 954.85 mHz
STOP: 100 Hz

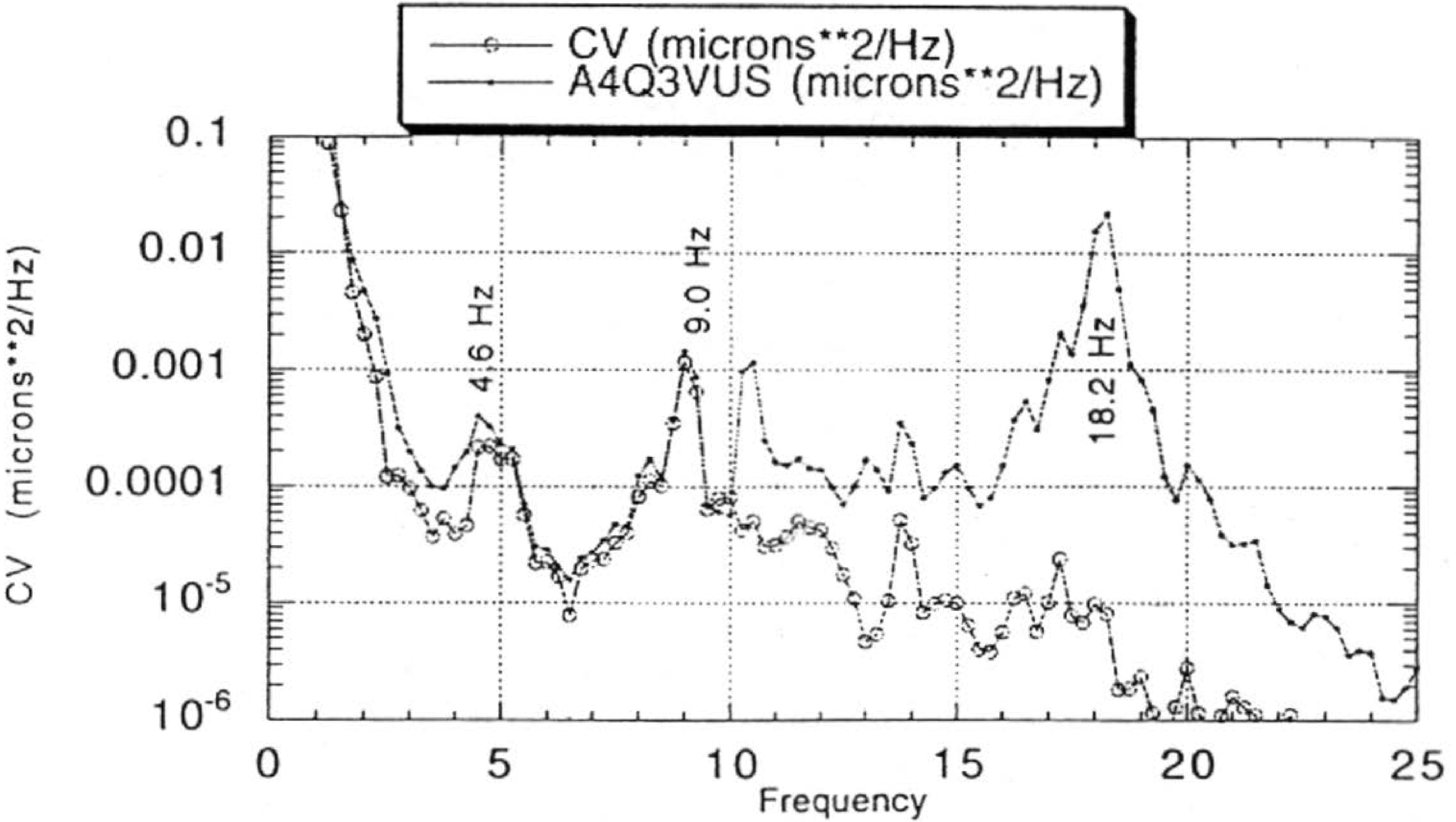

TM=TUNNEL MAGNET
TF=TUNNEL FLOOR
G=GROUND
MAIN INJECTOR RING
G
G
CHL
TM
TF
TM
A3 HOR
B0 HOR
D0 HOR
G
TM
TF
N
E
E
MASTER SUBSTATION
SITE BOUNDARY
KAUTZ ROAD SUBSTATION
C-0 EXPERIMENTAL AREA
D-0 EXPERIMENTAL AREA
Te



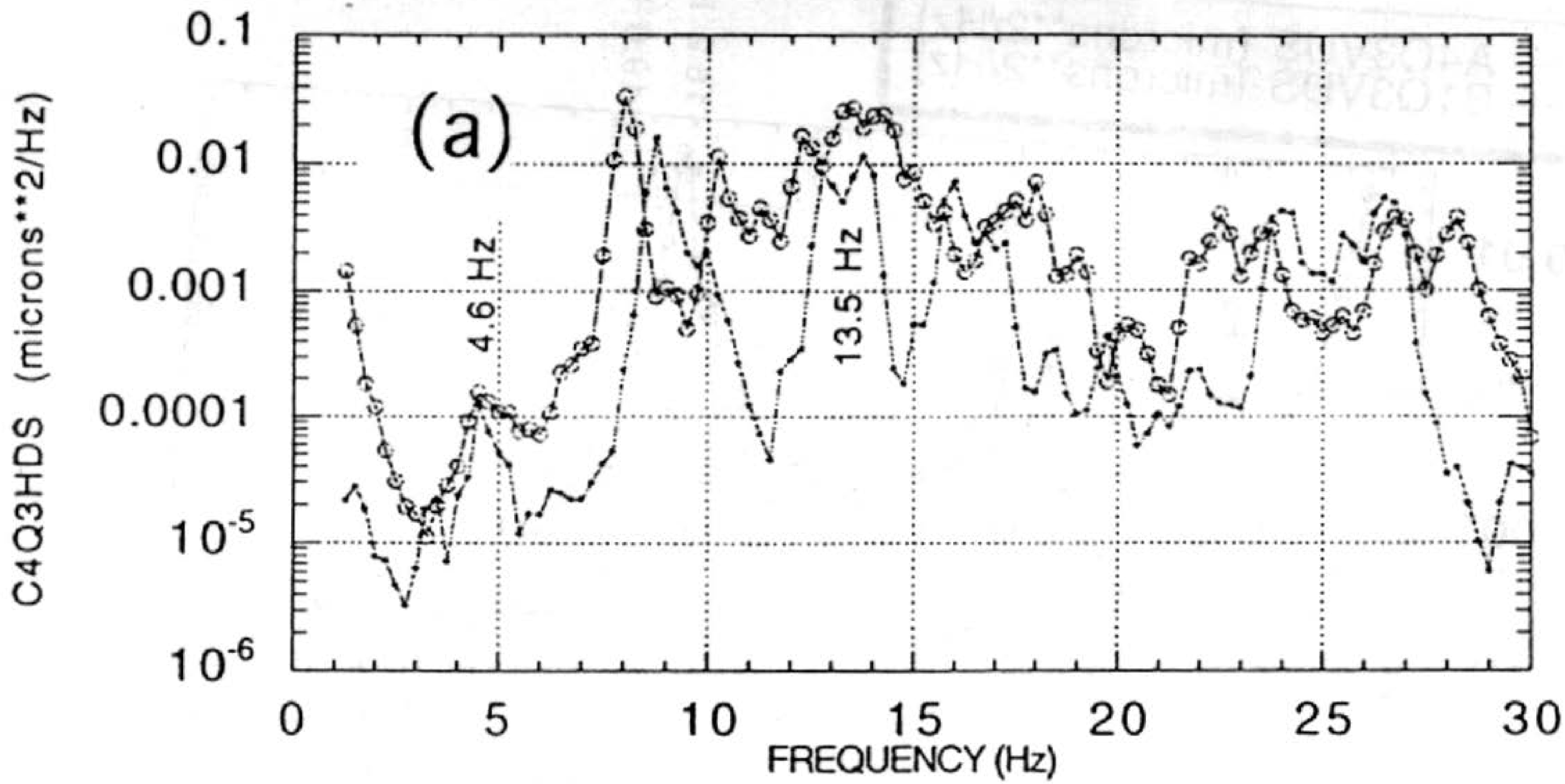
D1Q3VUS (microns**2/Hz)
0.01
0.001
0.0001
10-5
10-6
D1Q3VUS (microns**2/Hz)
0
5
10
15
20
25
30
Frequency (Hz)


D1Q3VUS (microns**2/Hz)
0.01
0.001
0.0001
10^{-5}
10^{-6}
D1Q3VUS (microns**2/Hz)
0
5
10
15
20
25
30
Frequency (Hz)

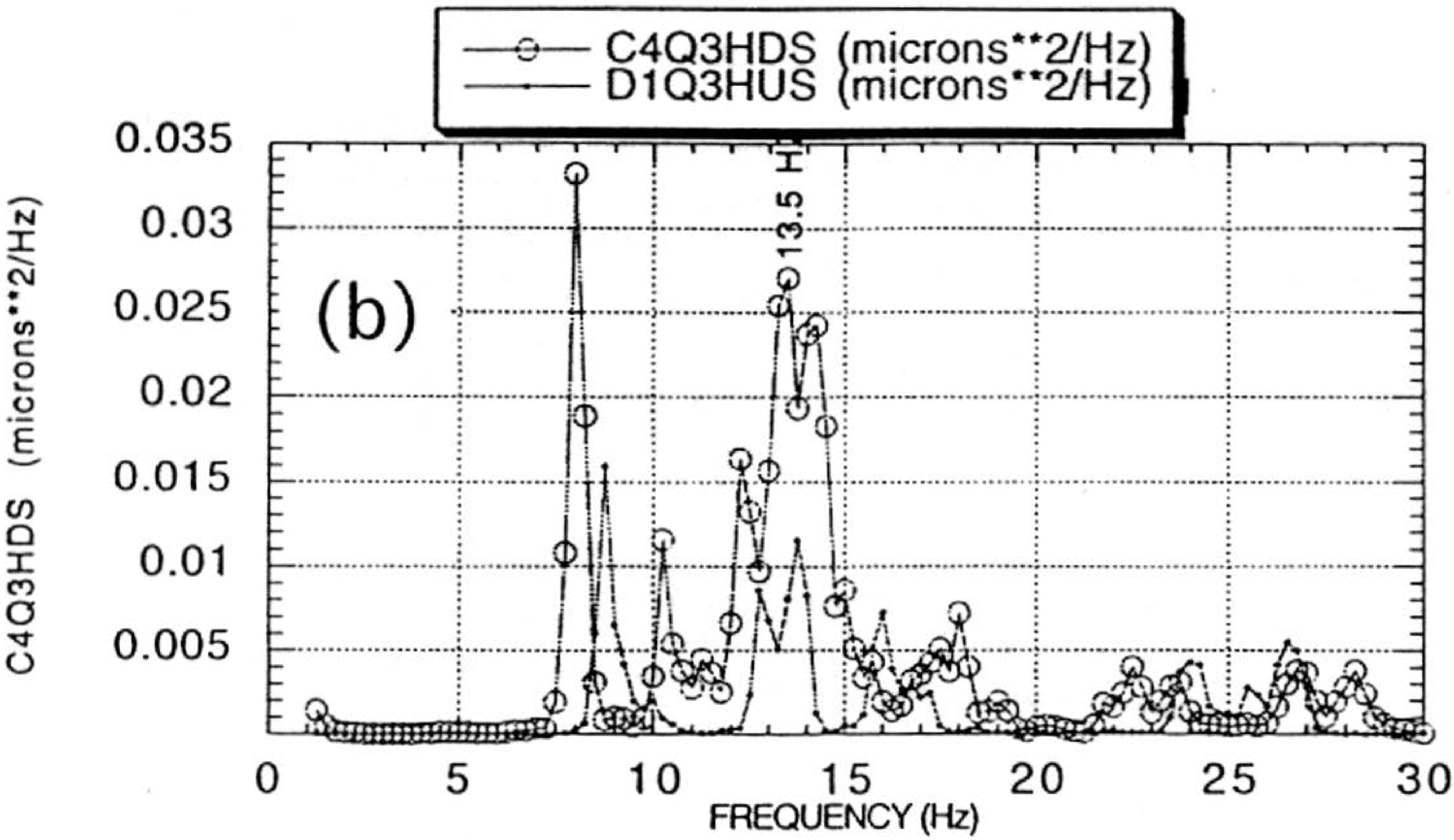

A4Q3VUS (microns**2/Hz)
B1Q3VDS (microns**2/Hz)
18.2 Hz
19.0 Hz
4.6 Hz
10.5 Hz
0.01
0.001
0.0001
10-5
10-6
A4Q3VUS (microns**2/Hz)
0
5
10
15
20
25
30
Frequency



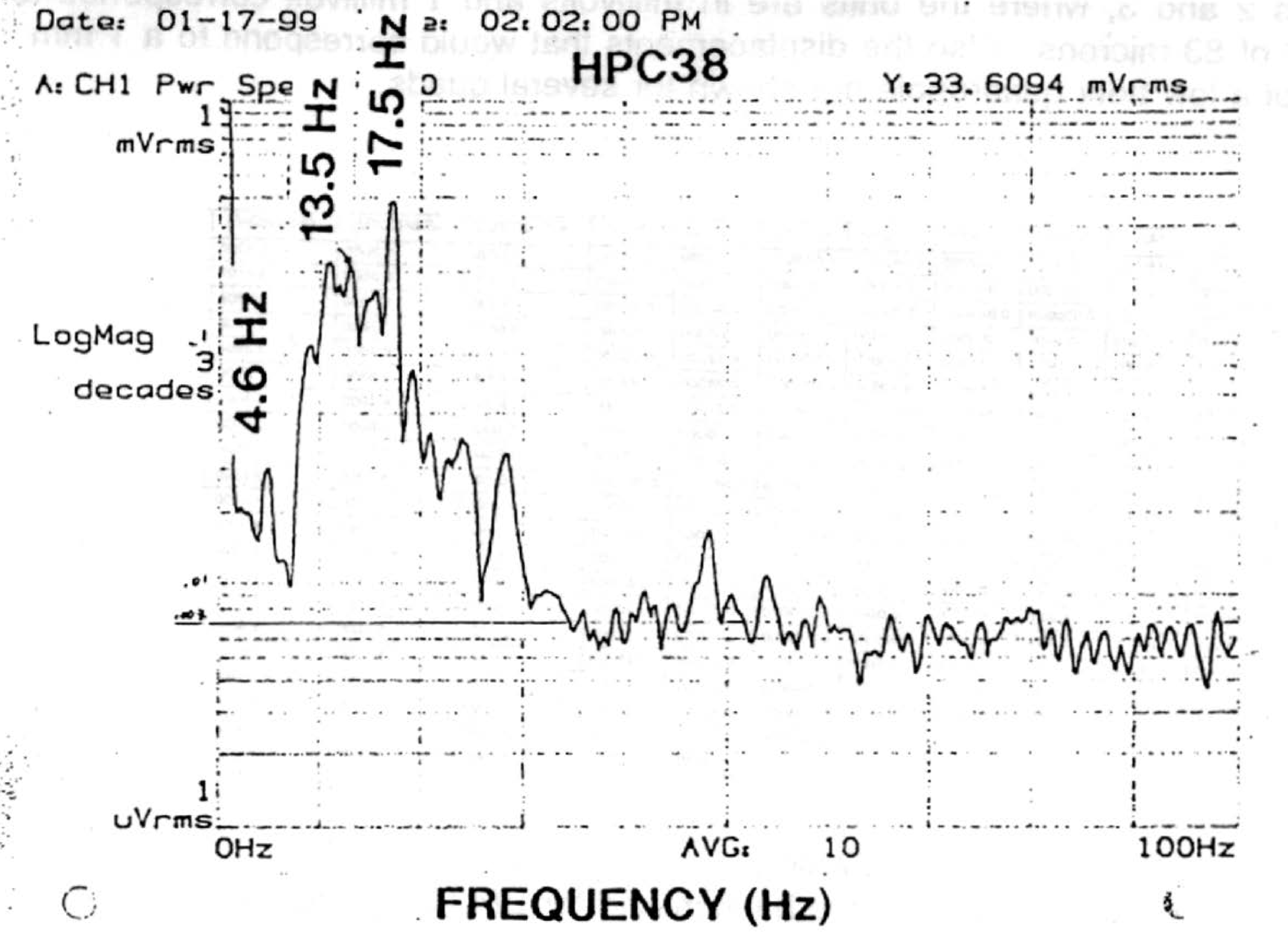
CV (microns**2/Hz)
A4Q3VUS (microns**2/Hz)
0.1
0.01
0.001
0.0001
10-5
10-6
CV (microns**2/Hz)
4.6 Hz
9.0 Hz
18.2 Hz
0
5
10
15
20
25
Frequency



(a)
4.6 Hz
13.5 Hz
C4Q3HDS (microns**2/Hz)
FREQUENCY (Hz)



C4Q3HDS (microns**2/Hz)
D1Q3HUS (microns**2/Hz)
(b)
13.5 H
C4Q3HDS (microns**2/Hz)
FREQUENCY (Hz)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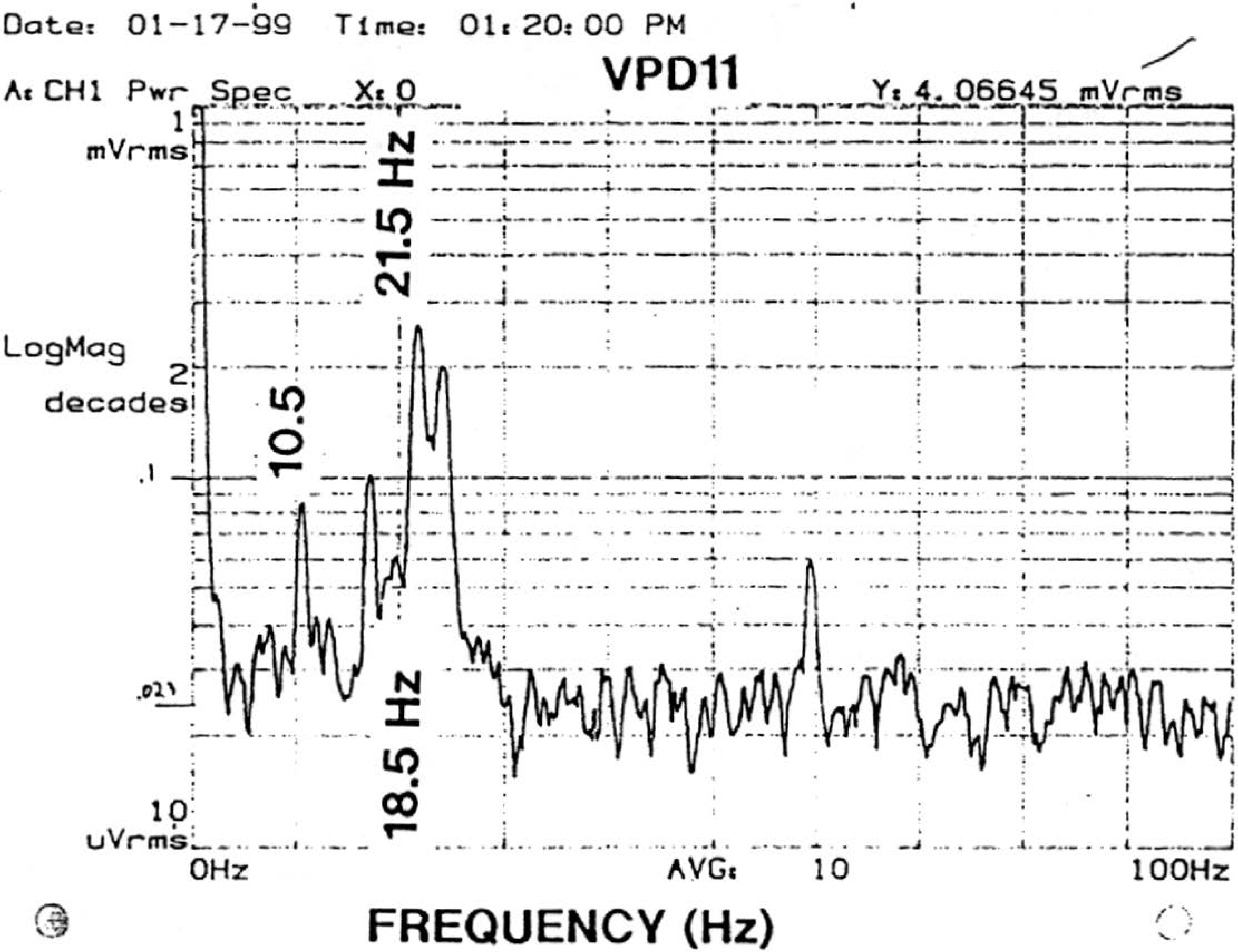
HPC38
A: CH1 Pwr Spe
Y: 33.6094 mVrms
1
mVrms
LogMag
3
decades
1
uVrms
4.6 Hz
13.5 Hz
17.5 Hz
0Hz
AVG:
10
100Hz
FREQUENCY (Hz)



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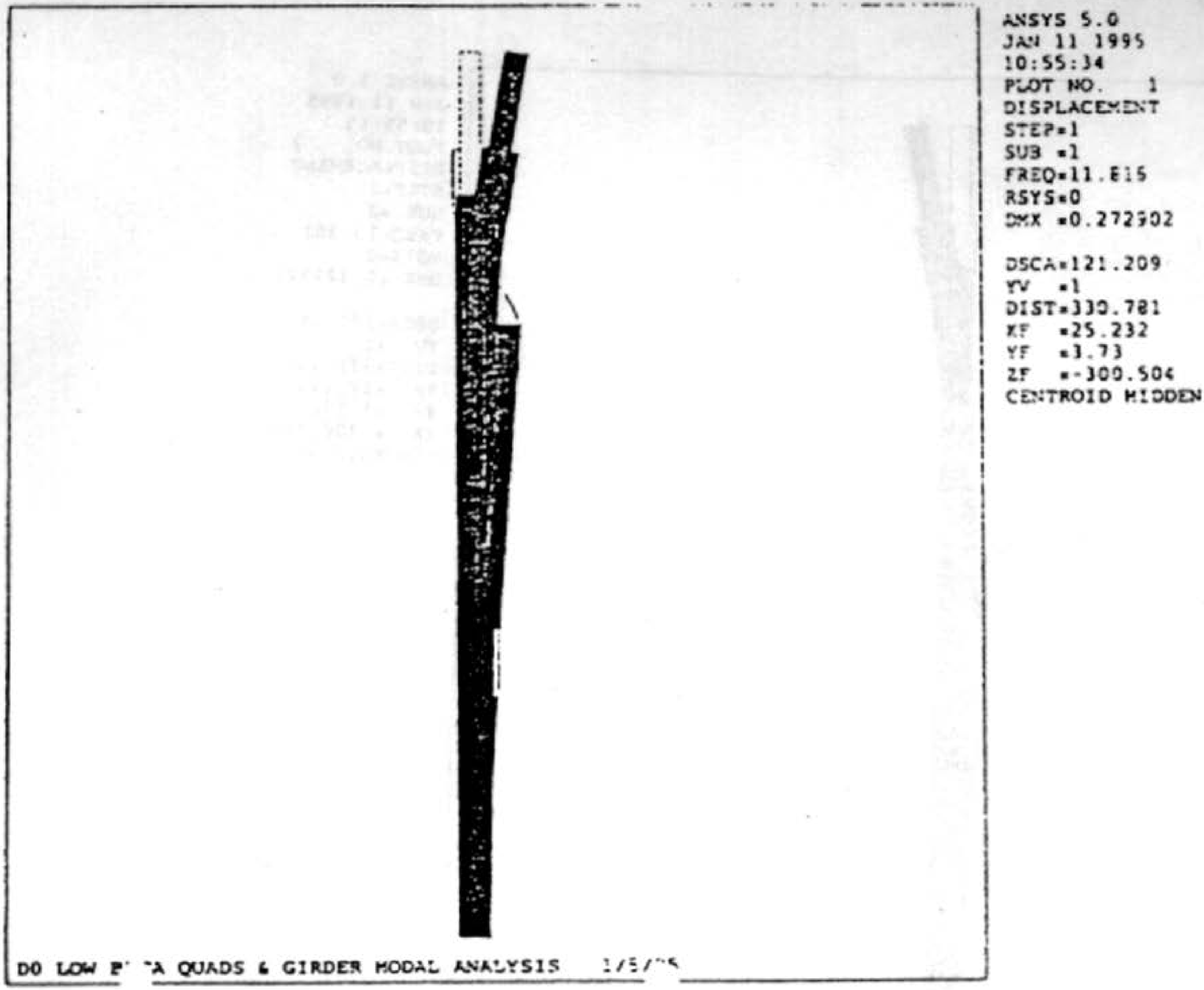
Y: 4.06645 mVrms
1
mVrms
LogMag
2
decades
.1
.021
10
uVrms
21.5 Hz
10.5
18.5 Hz
0Hz
AVG: 10
100Hz
FREQUENCY (Hz)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DSCA=121.209
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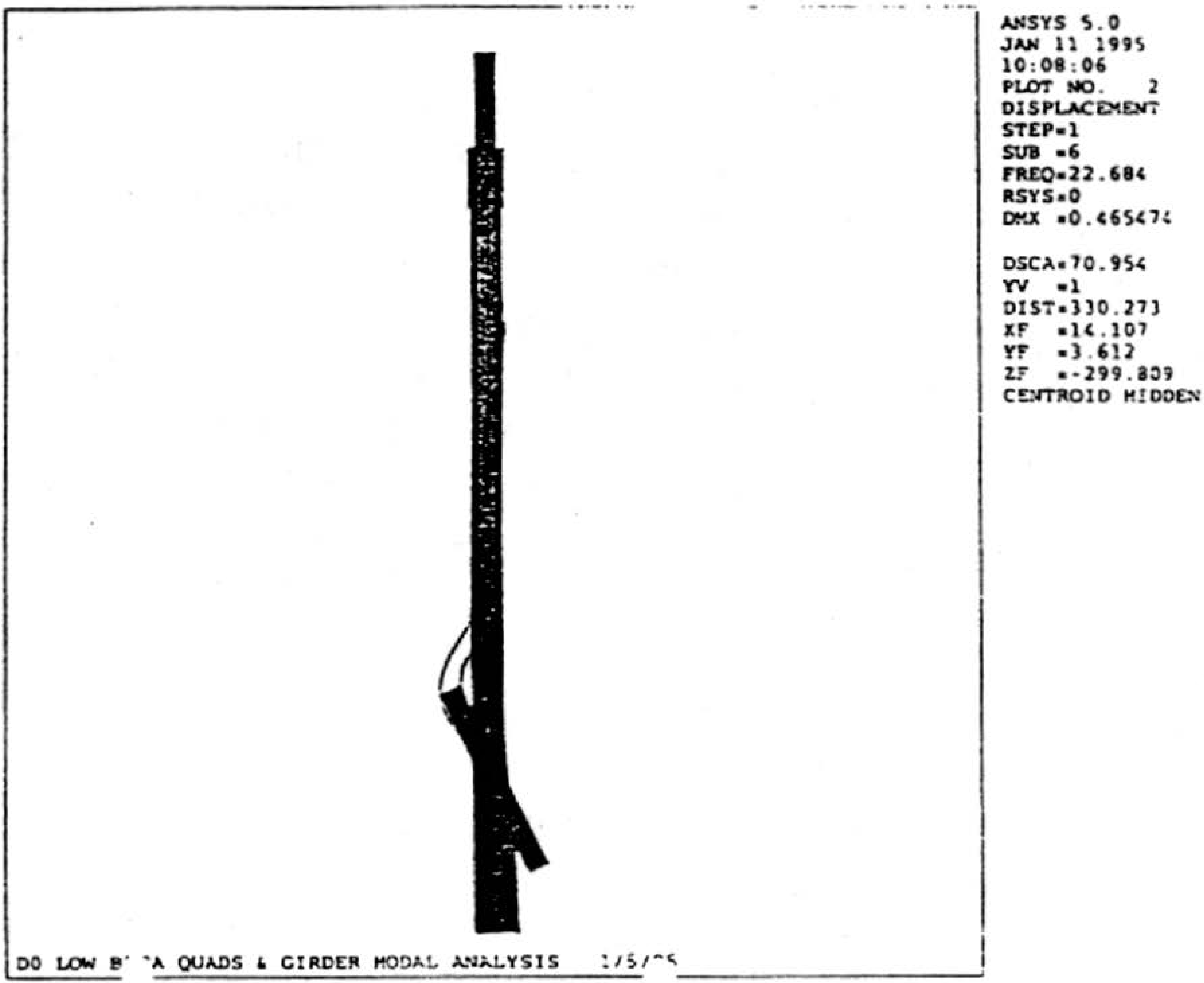
YF =3.73
ZF =-300.504
CENTROID HIDDEN
DO LOW
QUADS & GIRDER MODAL ANALYSIS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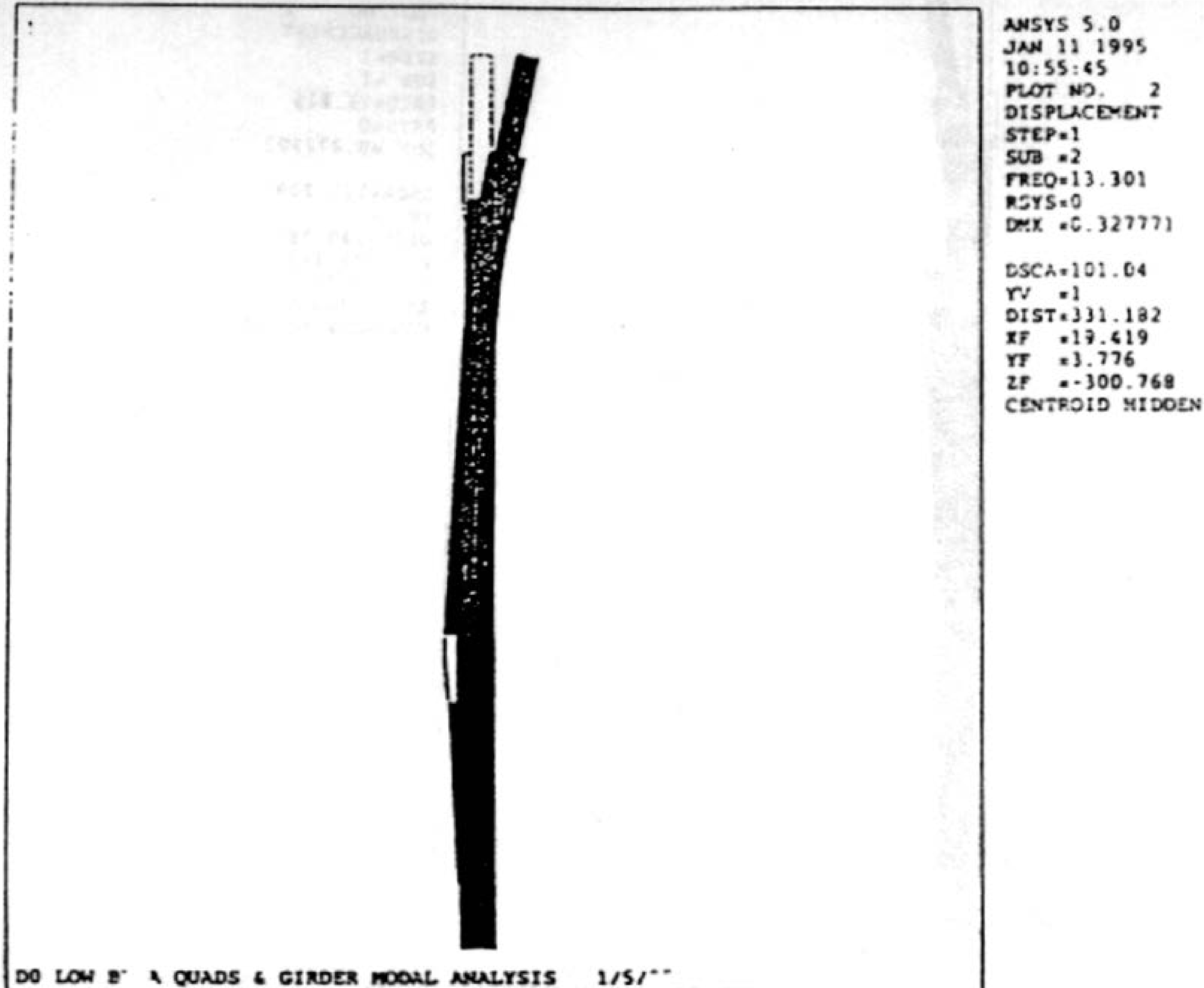
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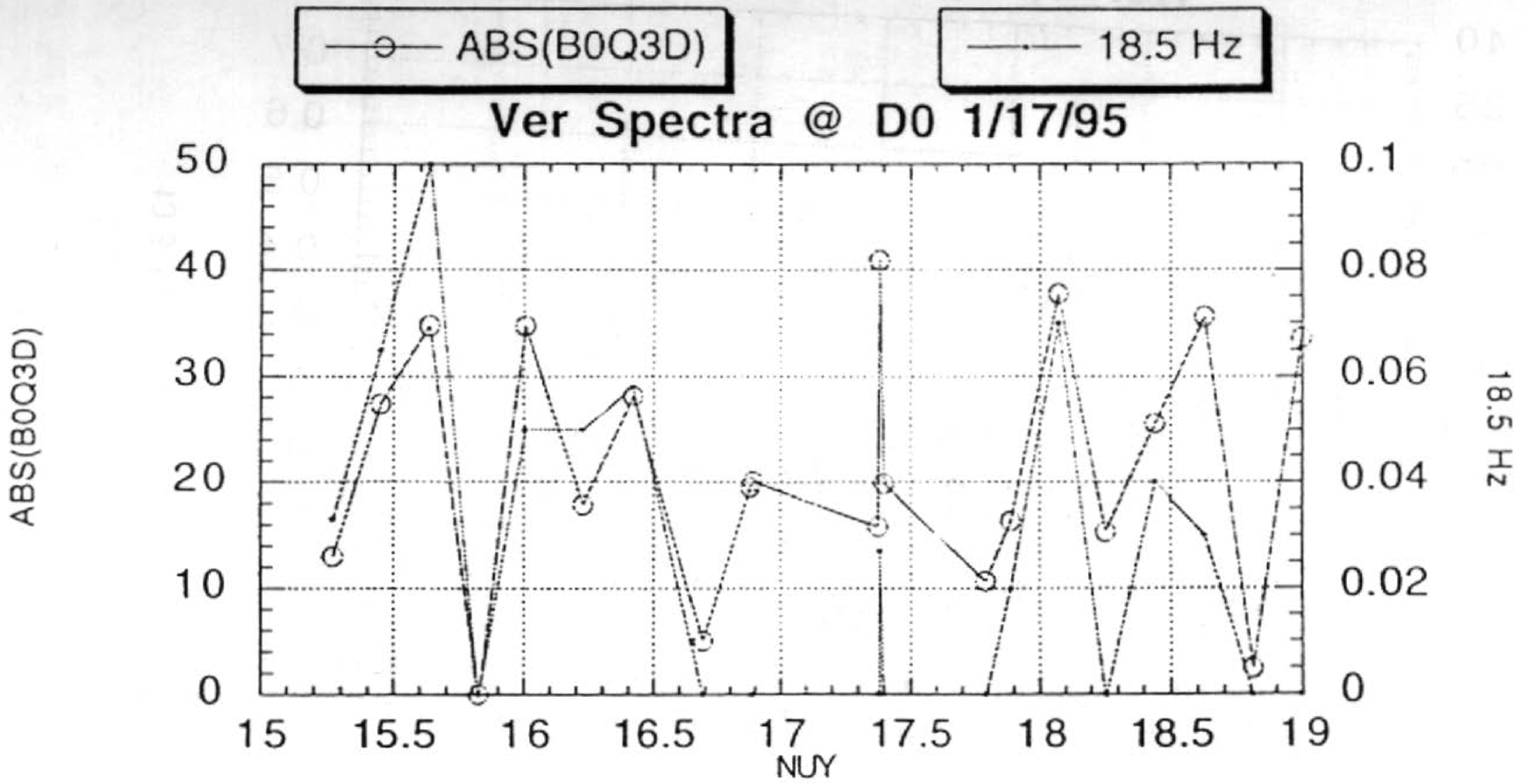
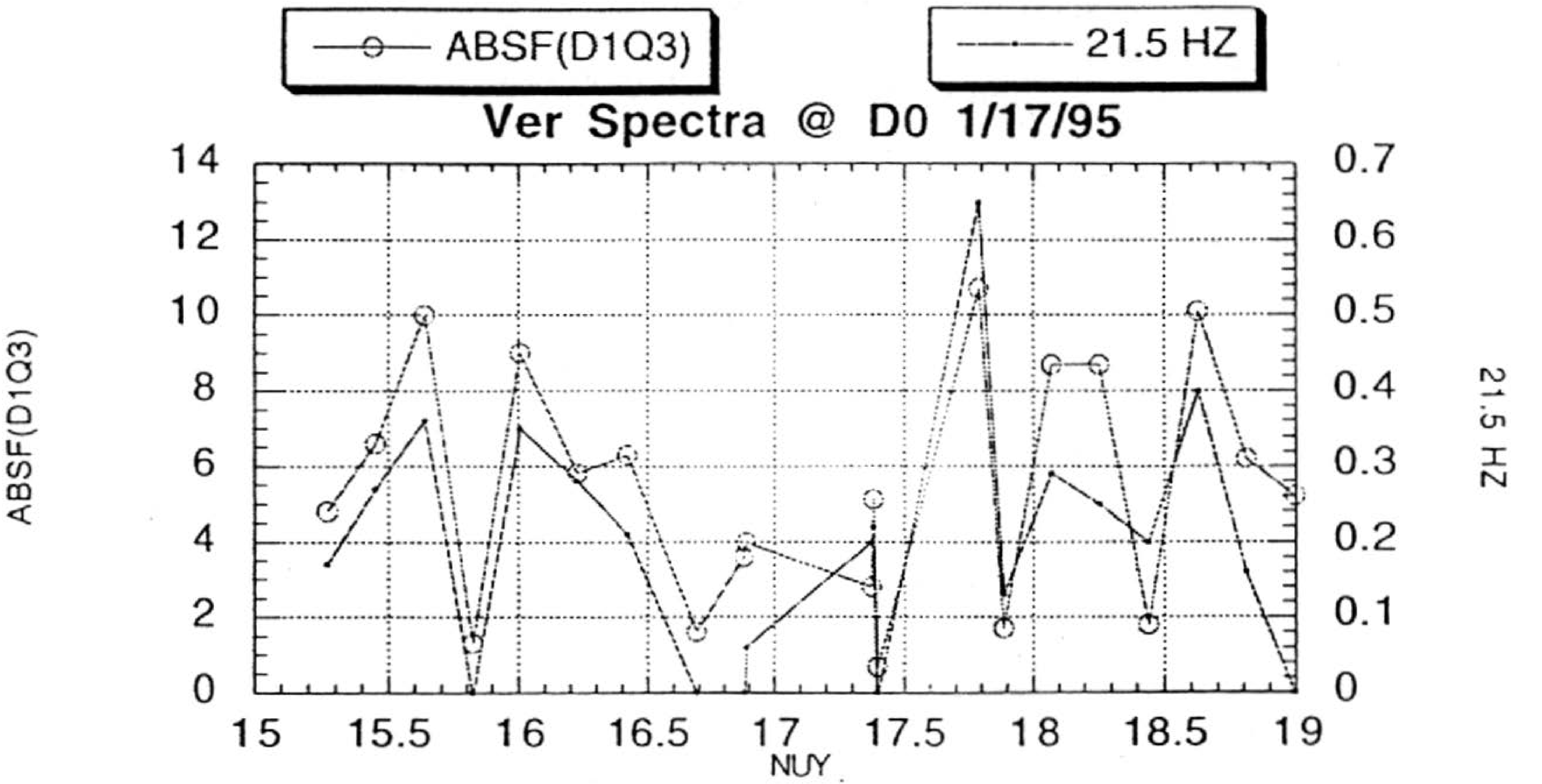
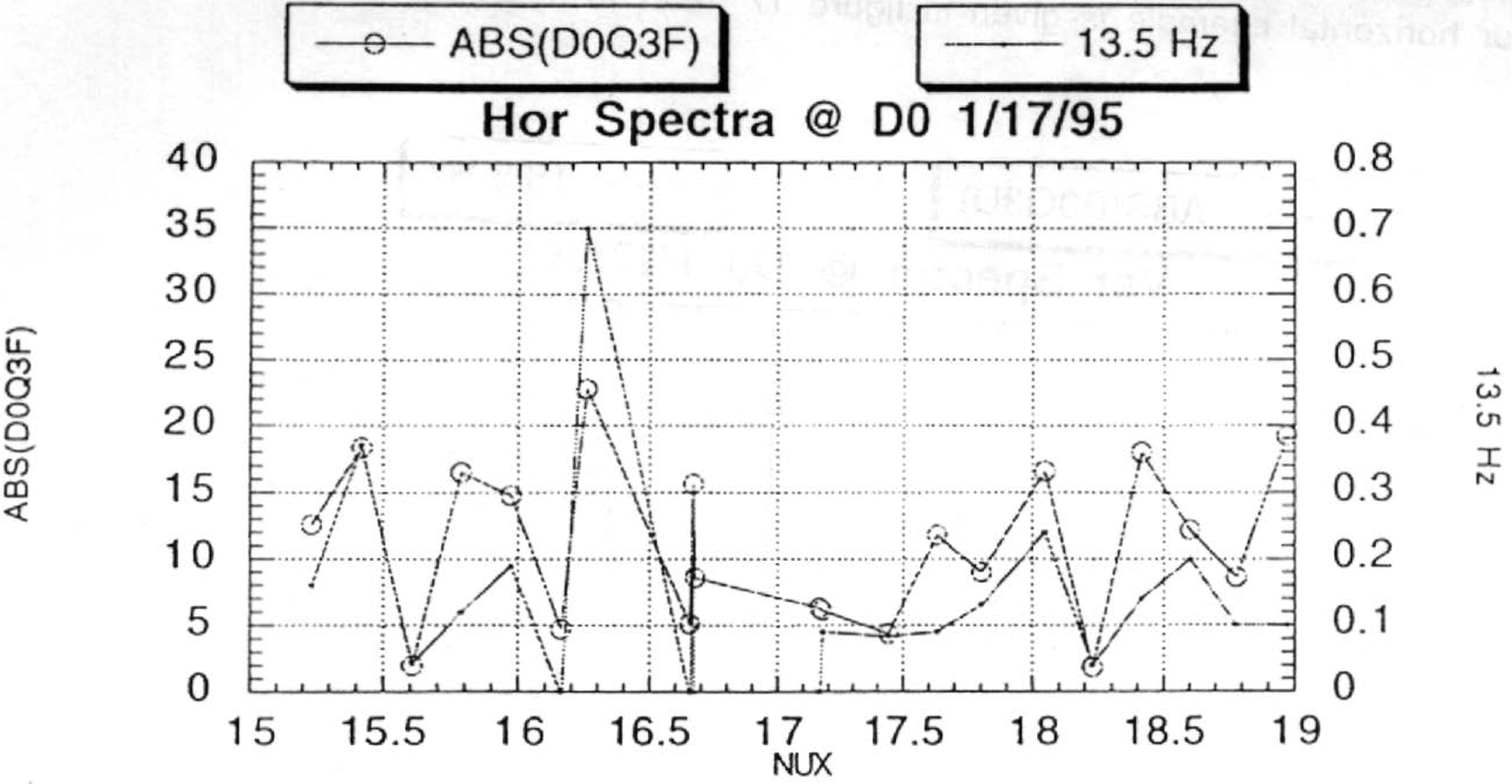


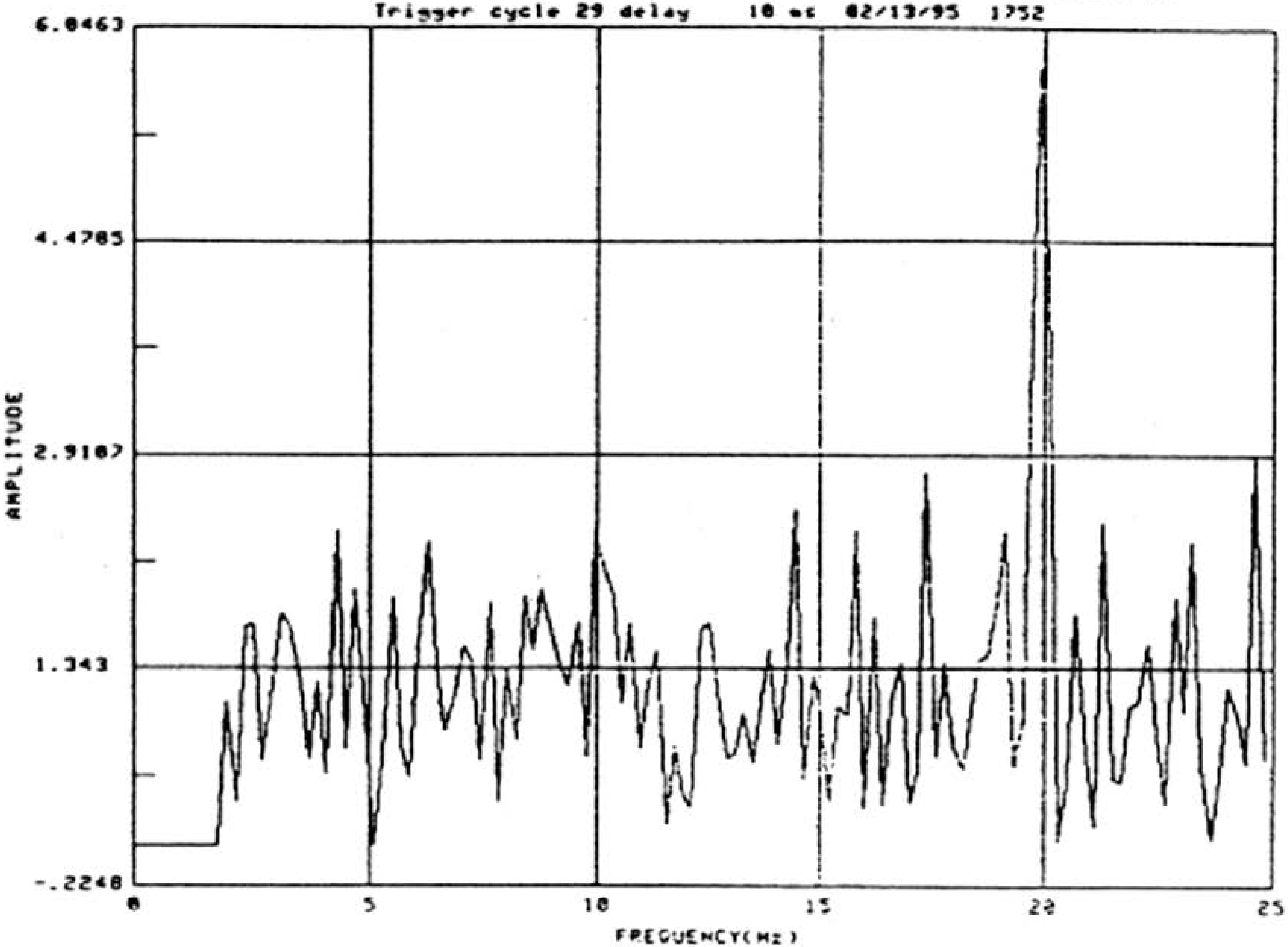
ABS(B0Q3D)
18.5 Hz
Ver Spectra @ D0 1/17/95
50
40
30
20
10
0
0.1
0.08
0.06
0.04
0.02
0
15
15.5
16
16.5
17
17.5
18
18.5
19
NUY
ABS(B0Q3D)
18.5 Hz



ABSF(D1Q3)
21.5 HZ
Ver Spectra @ D0 1/17/95
14
12
10
8
6
4
2
0
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
15
15.5
16
16.5
17
17.5
18
18.5
19
NUY
ABSF(D1Q3)
21.5 HZ


ABS(D0Q3F)
13.5 Hz
Hor Spectra @ D0 1/17/95
40
35
30
25
20
15
10
5
0
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
15
15.5
16
16.5
17
17.5
18
18.5
19
NUX
ABS(D0Q3F)
13.5 Hz

FREQUENCY DOMAIN DATA FROM C:LOSTF



	STATION #	NUY	4.5 Hz	10.5 Hz	17.5 Hz	18.5 Hz	21.5 HZ	24 HZ	ABS(B0O3D)	ABSF(D1Q3)	ABS(D0O4F)
0	33.000	15.269	0.0000	0.0000	0.043000	0.033000	0.17000	0.17000	13.000	4.8000	6.3300
1	35.000	15.452	0.0000	0.070000	0.10000	0.065000	0.27000	0.28000	27.400	6.6000	6.9100
2	37.000	15.637	0.020000	0.040000	0.14000	0.10000	0.36000	0.40000	34.700	10.000	11.800
3	39.000	15.824	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.3000	2.4000
4	43.000	16.009	0.0000	0.11000	0.050000	0.050000	0.35000	0.38000	34.700	9.0000	9.8900
5	45.000	16.229	0.10000	0.090000	0.10000	0.050000	0.28000	0.27000	17.800	5.8000	7.2600
6	47.000	16.420	0.0000	0.040000	0.060000	0.058000	0.21000	0.21000	28.200	6.3000	6.3000
7	48.000	16.690	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5.0000	1.6000	2.0900
8	49.000	16.880	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	19.500	3.6000	2.8500
9	50.000	16.889	0.0000	0.0000	0.0000	0.0000	0.060000	0.085000	20.100	4.0000	3.2500
10	51.000	17.375	0.0000	0.0000	0.0000	0.0000	0.20000	0.30000	15.800	2.8000	4.6000
11	11.000	17.383	0.0000	0.060000	0.077000	0.027000	0.22000	0.18000	40.900	5.1000	8.4000
12	12.000	17.400	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	19.800	0.67000	1.7500
13	14.000	17.790	0.0000	0.0000	0.0000	0.0000	0.65000	0.63000	10.700	10.700	13.300
14	16.000	17.888	0.0000	0.0000	0.0000	0.020000	0.13000	0.13000	16.300	1.7000	2.9000
15	18.000	18.071	0.0000	0.0000	0.080000	0.070000	0.29000	0.21000	37.700	8.7000	9.5000
16	21.000	18.255	0.0000	0.0000	0.0000	0.0000	0.25000	0.25000	15.300	8.7000	10.500
17	23.000	18.440	0.0000	0.0000	0.0000	0.040000	0.20000	0.20000	25.600	1.8000	1.1800
18	25.000	18.627	0.0000	0.060000	0.0000	0.030000	0.40000	0.27000	35.600	10.100	11.450
19	27.000	18.811	0.0000	0.0000	0.0000	0.0000	0.16000	0.14000	2.4300	6.2000	7.8000
20	29.000	18.997	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	33.600	5.2000	5.2000

Table 2

Vertical BPM signal above background for BPMs around D0

Station #	NUX	13.5 Hz	17.5 Hz	D0O4F	ABS(D0O4F)	D0O3F	ABS(D0O3F)
32.000	15.235	0.16000	0.39000	3.2000	3.2000	-12.600	12.600
34.000	15.420	0.37000	0.60000	5.1000	5.1000	-18.300	18.300
36.000	15.607	0.043000	0.0000	0.92000	0.92000	-2.0000	2.0000
38.000	15.788	0.12000	0.36000	-4.3000	4.3000	16.500	16.500
42.000	15.973	0.19000	0.37000	-4.2800	4.2800	14.800	14.800
44.000	16.160	0.0000	0.11000	0.95000	0.95000	-4.7000	4.7000
46.000	16.259	0.70000	1.3700	5.9000	5.9000	-22.800	22.800
48.000	16.658	0.0000	0.0000	-0.97000	0.97000	5.1000	5.1000
49.000	16.671	0.20000	0.77000	-3.3000	3.3000	15.700	15.700
50.000	16.679	0.0000	0.10000	-1.8000	1.8000	8.6000	8.6000
51.000	17.165	0.0000	0.0000	2.4000	2.4000	-6.3000	6.3000
11.000	17.177	0.090000	0.26000	2.2000	2.2000	-6.1000	6.1000
12.000	17.440	0.084000	0.10000	-1.2000	1.2000	4.4000	4.4000
13.000	17.635	0.090000	0.0000	-3.6500	3.6500	11.800	11.800
15.000	17.805	0.13000	0.42000	2.2000	2.2000	-9.0000	9.0000
17.000	18.047	0.24000	0.20000	4.8000	4.8000	-16.600	16.600
19.000	18.229	0.040000	0.35000	-0.16000	0.16000	1.9000	1.9000
22.000	18.415	0.14000	0.35000	-4.8000	4.8000	18.000	18.000
24.000	18.605	0.20000	0.0000	-3.6000	3.6000	12.200	12.200
26.000	18.783	0.10000	0.31000	2.0500	2.0500	-8.6000	8.6000
28.000	18.972	0.10000	0.18000	5.3200	5.3200	-19.200	19.200

Table 3

Horizontal BPM signal above background for BPMs around D0