LS-136
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Ambient Ground Motion at the 7 GeV Site at Argonne National Laboratory over Extended Time Periods

by

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Background

Successful operation of the APS facility requires a very stable particle beam. Vibration coupled through mechanical systems, such as magnet supports, beam tube supports, and other paths can cause deterioration of the particle beam. There are two sources of vibration: external, or far field, which is generated external to the APS site and internal, or near field, which is generated on site and associated with operation of the facility. Internal vibration sources can be controlled or minimized using good design practices to eliminate or reduce vibration amplitudes of machinery and equipment. Depending on their origin, external vibration sources may or may not be controllable, therefore it is necessary to have sufficient knowledge of their amplitude level and frequency content to predict any adverse effects on the operation of the APS facility.

Objective

The primary objective of this study was to measure the far field ground vibration at the 7 GeV site over long time periods to get an accurate representation of its frequency and amplitude characteristics.

Location and Time

Accelerometer locations were chosen to monitor the ambient noise level simultaneously at 60° increments along the proposed circumference of the site, Fig. 1. A more precise location description is shown in Table 1. The accelerometers are coupled to the soil with 1-1/8 in. diameter stakes driven 22 inches into the soil. The accelerometers were mounted vertically to the stakes and isolated from random sound excitation and weather by several layers of foam rubber, cloth, and plastic.

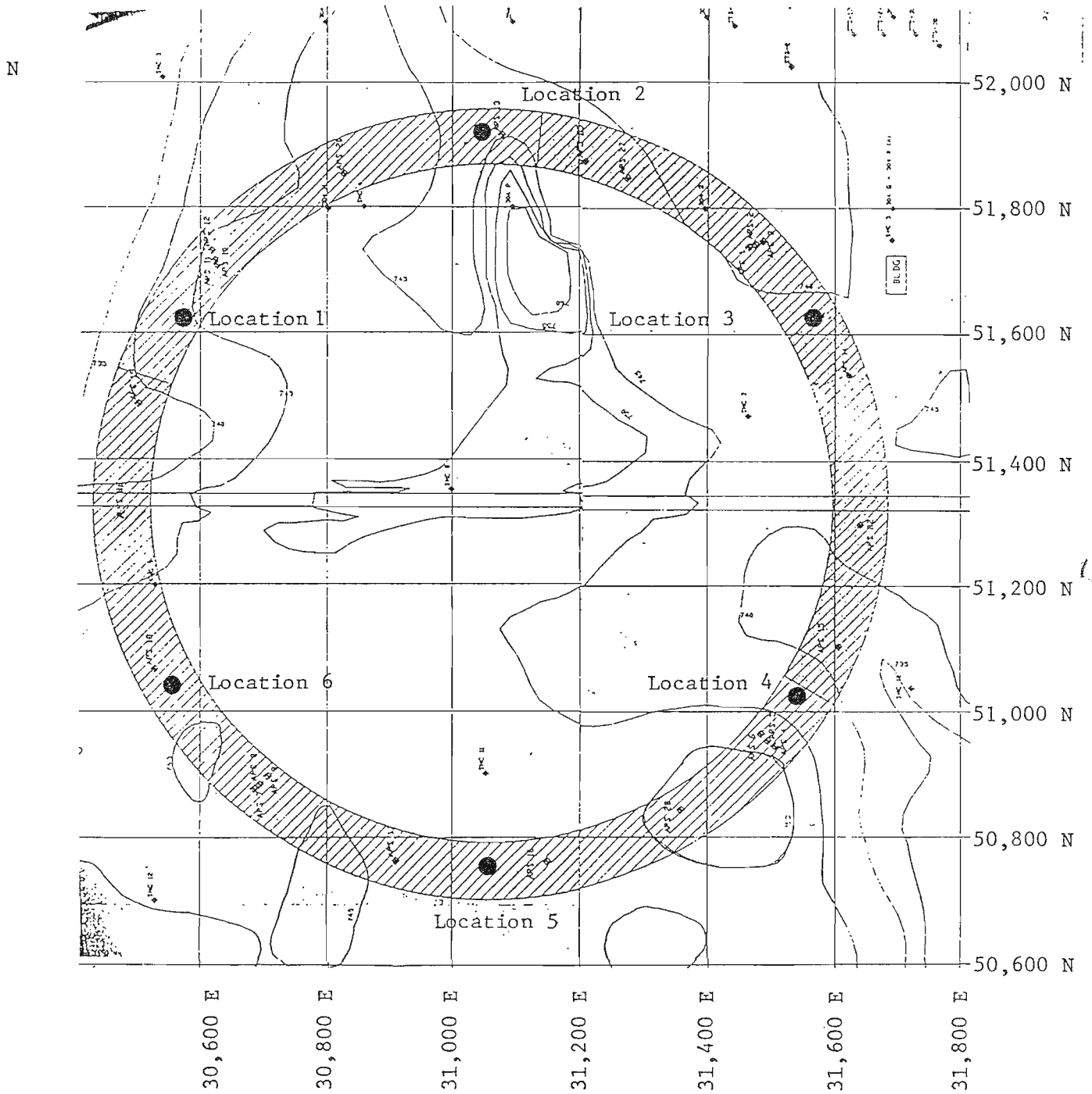

Fig. 1. Accelerometer Locations

Table 1. Accelerometer Locations

Accelerometer	Location	N Coord.	E Coord.
1	1	51,616	30,570
2	2	51,950	30,025
3	3	51,602	31,562
4	4	51,036	31,552
5	5	50,757	31,050
6	6	51,037	30,563

The accelerometers were mounted, instrumentation set up, and cabling run on the morning of 5/11/88. After verifying the operation of the instrumentation, measurements commenced at 11:24 AM and ended at 11:55 AM on 5/12/88. Data was recorded continuously from 11:24 AM on 5/11/88 to 3:00 AM on 5/12/88. Recording was again started at 5:40 AM on 5/12/88 and ended at the completion of the test at 11:55 AM on 5/12/88. For convenience in relating measurement time in minutes to 24 hr time, Table 2 is provided.

The weather was clear and warm, high temperature of about 70°F, on Wednesday, 5/11/88, with a slight breeze. Thunderstorms occurred between 2:00 AM and 5:40 AM on 5/12/88. The temperature was very warm with clear skies the remainder of the day.

Measurement Techniques and Data Analysis

The accelerations at each location were measured via the accelerometers, transmitted through 700 ft of RG-58 c/u coaxial cable to the PCB 480A10 double integrating amplifiers. Double integrator amplifier outputs, which are displacements, were then amplified by the PCB 480D06 amplifier with a gain of 100, then recorded on the Teac MR30 tape recorder, Fig. 2. Data was recorded at tape speed of 17/32 in./sec (1.2 cm/s) with a frequency response of DC to 313 Hz. At this speed, the continuous recording time was 3 hours per each cassette tape. The frequency response of the total data acquisition system is from ≈ 4 Hz to 313 Hz.

Accelerometer identification and system sensitivity is listed in Table 3.

Data analysis, Fig. 3, is accomplished by playing back the tape cassettes on the same recorder on which the data was recorded. Power spectral density plots and RMS displacements are calculated with a Hewlett Packard 5451C Fast Fourier Analyzer. Each PSD plot or displacement data point represents an 8 minute average.

Total Measured Displacement

The total measured displacement for locations 1 and 2, 3 and 4, and 5 and 6 are shown in Figs. 4, 5, and 6, respectively. Plots of power spectral density from which the displacements were calculated are shown in Figs. 7 to 12. The plots are presented to a sufficiently high frequency to show any significant response. Mean square displacements are obtained by

Table 2. Time Relationship

Time (min.)	(Real Time)	Time (min.)	(Real Time)	Time (min.)	(Real Time)	Time (min.)	(Real Time)	Time (min.)	(Real Time)
0	11:24	248	15:32	509	19:53	786	0:30	1200	7:24
8	11:32	256	15:40	517	20:01	794	0:38	1208	7:32
16	11:40	264	15:48	525	20:09	802	0:46	1216	7:40
24	11:48	272	15:56	533	20:17	810	0:54	1224	7:48
32	11:56	280	16:04	541	20:25	818	1:02	1232	7:56
40	12:04	288	16:12	549	20:33	826	1:10	1240	8:04
48	12:12	296	16:20	571	20:55	834	1:18	1248	8:12
56	12:20	304	16:28	579	21:03	842	1:26	1256	8:20
64	12:28	312	16:36	587	21:11	850	1:34	1264	8:28
72	12:36	320	16:44	595	21:19	858	1:42	1272	8:36
80	12:44	328	16:52	603	21:27	866	1:50	1294	8:58
88	12:52	336	17:00	611	21:35	874	1:58	1302	9:06
96	13:00	344	17:08	619	21:43	882	2:06	1310	9:14
104	13:08	352	17:16	627	21:51	890	2:14	1318	9:22
112	13:16	360	17:24	635	21:59	898	2:22	1326	9:30
120	13:24	381	17:45	643	22:07	906	2:30	1334	9:38
128	13:32	389	17:53	651	22:15	914	2:38	1342	9:46
136	13:40	397	18:01	659	22:23	922	2:46	1350	9:54
144	13:48	405	18:09	667	22:31	930	2:54	1358	10:02
152	13:56	413	18:17	675	22:39	1104	5:48	1366	10:10
160	14:04	421	18:25	683	22:47	1112	5:56	1374	10:18
176	14:20	437	18:41	699	23:03	1128	6:12	1390	10:34
–	–	445	18:49	707	23:11	1136	6:20	1398	10:42
192	14:36	453	18:57	715	23:19	1144	6:28	1406	10:50
200	14:44	461	19:05	723	23:27	1152	6:36	1414	10:58
208	14:52	469	19:13	731	23:35	1160	6:44	1422	11:06
216	15:00	477	19:21	739	23:43	1168	6:52	1430	11:14
224	15:08	485	19:29	762	0:06	1176	7:00	1438	11:22
232	15:16	493	19:37	770	0:14	1184	7:08	1446	11:30
240	15:24	501	19:45	778	0:22	1192	7:16	1454	11:38
								1462	11:46

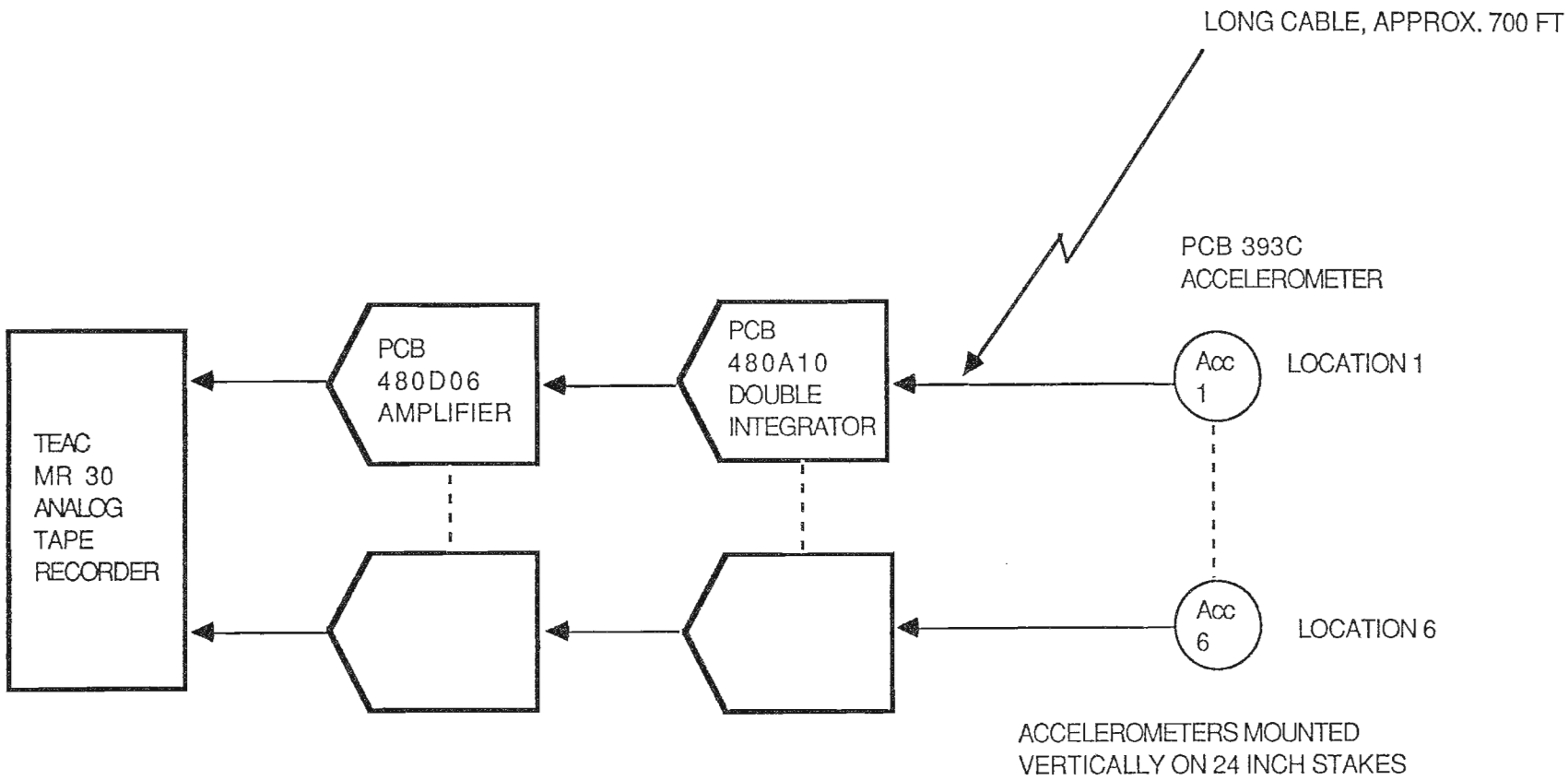

Fig. 2. Instrumentation Configuration

Table 3. Accelerometer Sensitivities

Accelerometer	Serial No.	Sensitivity, micron/volt
1	857	0.3259
2	861	0.3244
3	858	0.3283
4	860	0.3187
5	812	0.3120
6	856	0.3176

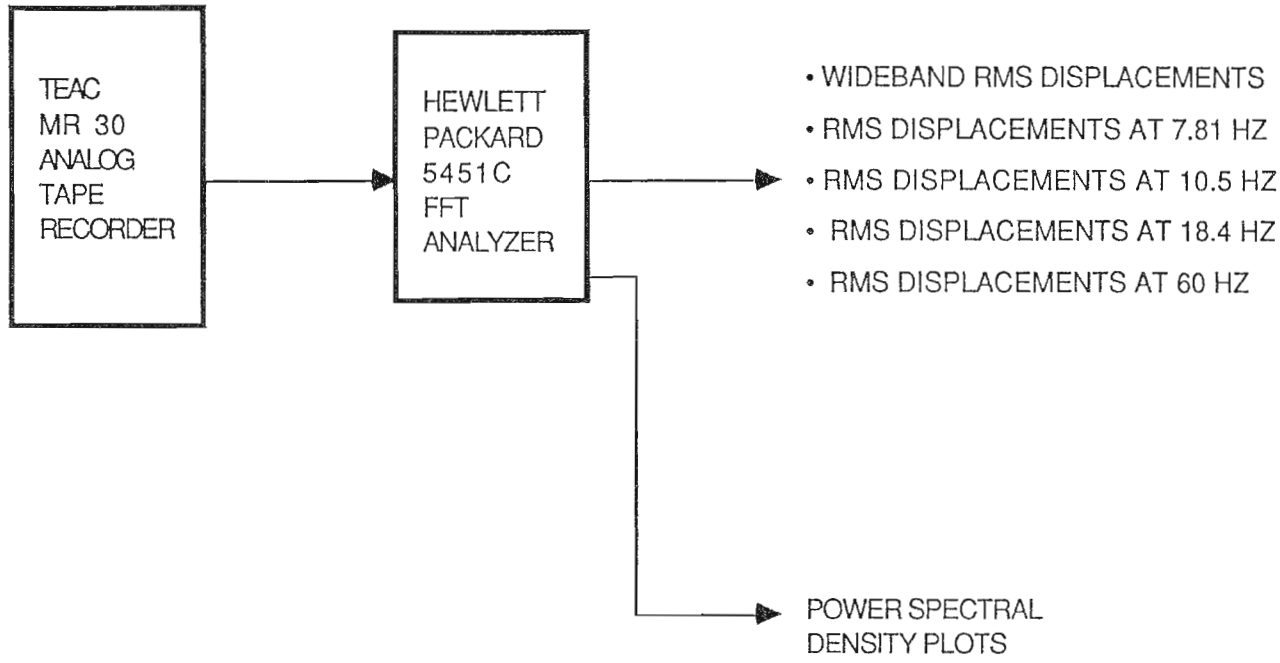

Fig. 3. Data Analysis

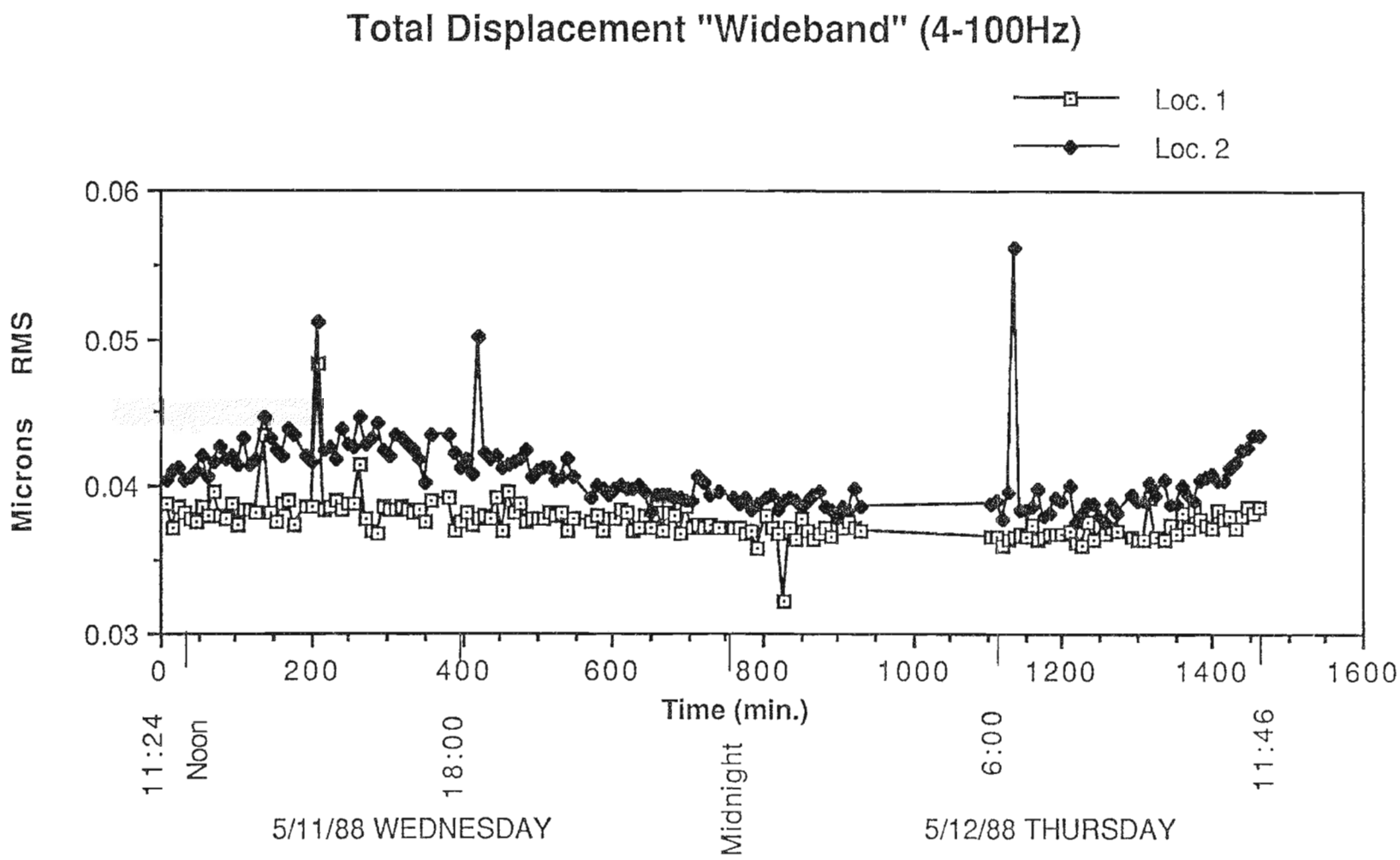

Fig. 4. Total Displacement in Microns for Locations 1 and 2

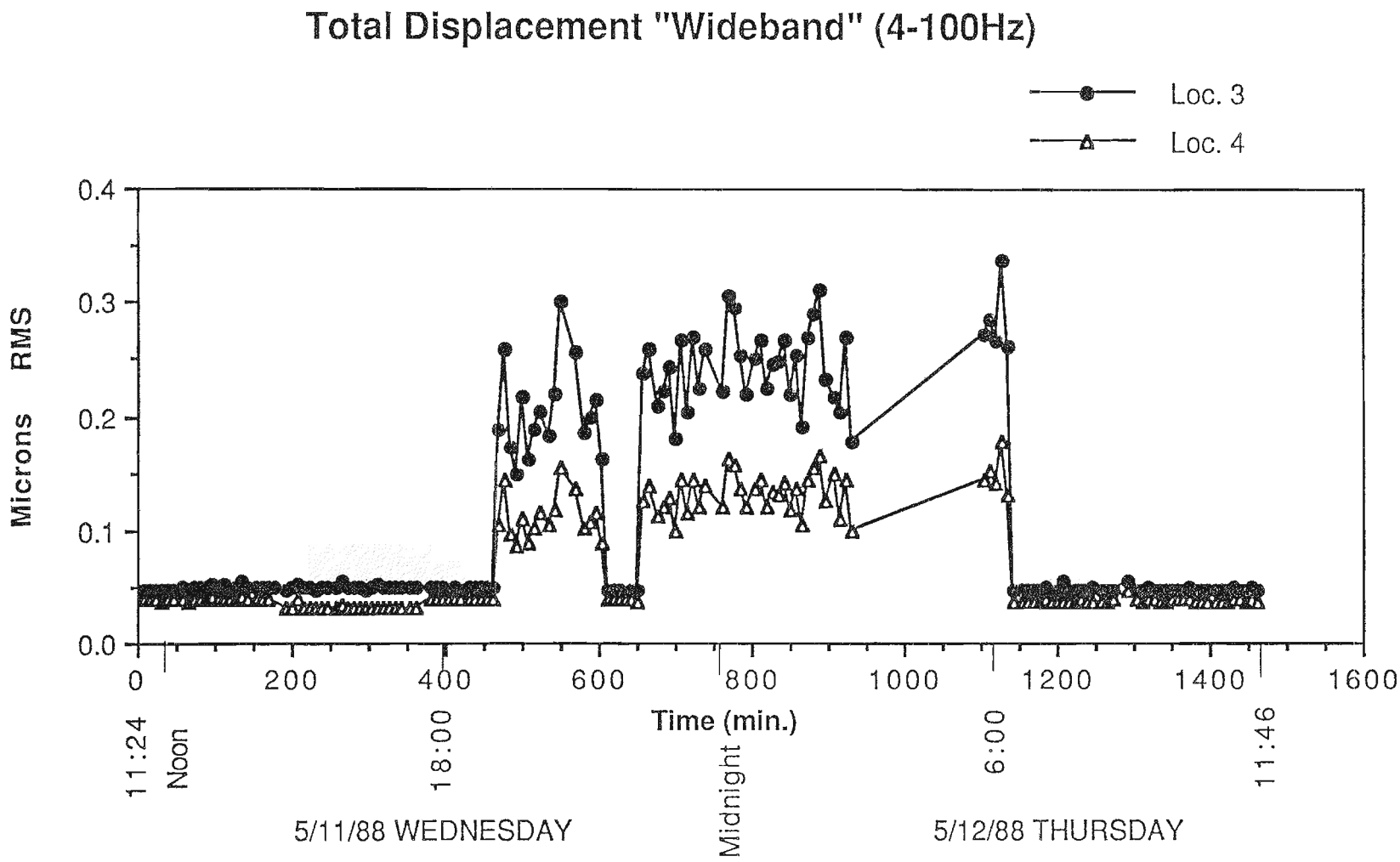

Fig. 5. Total Displacement in Microns for Locations 3 and 4

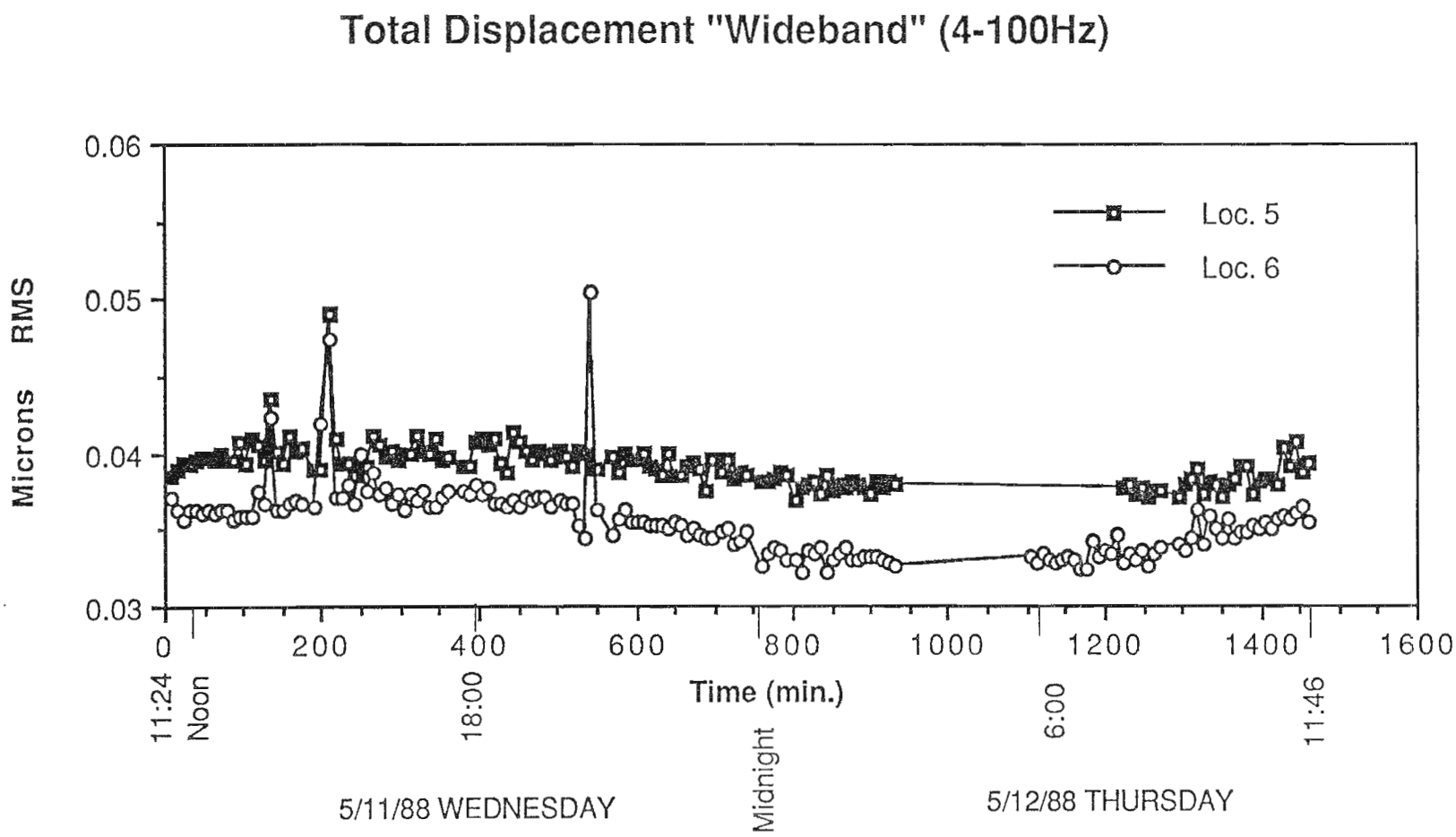

Fig. 6. Total Displacement in Microns for Locations 5 and 6

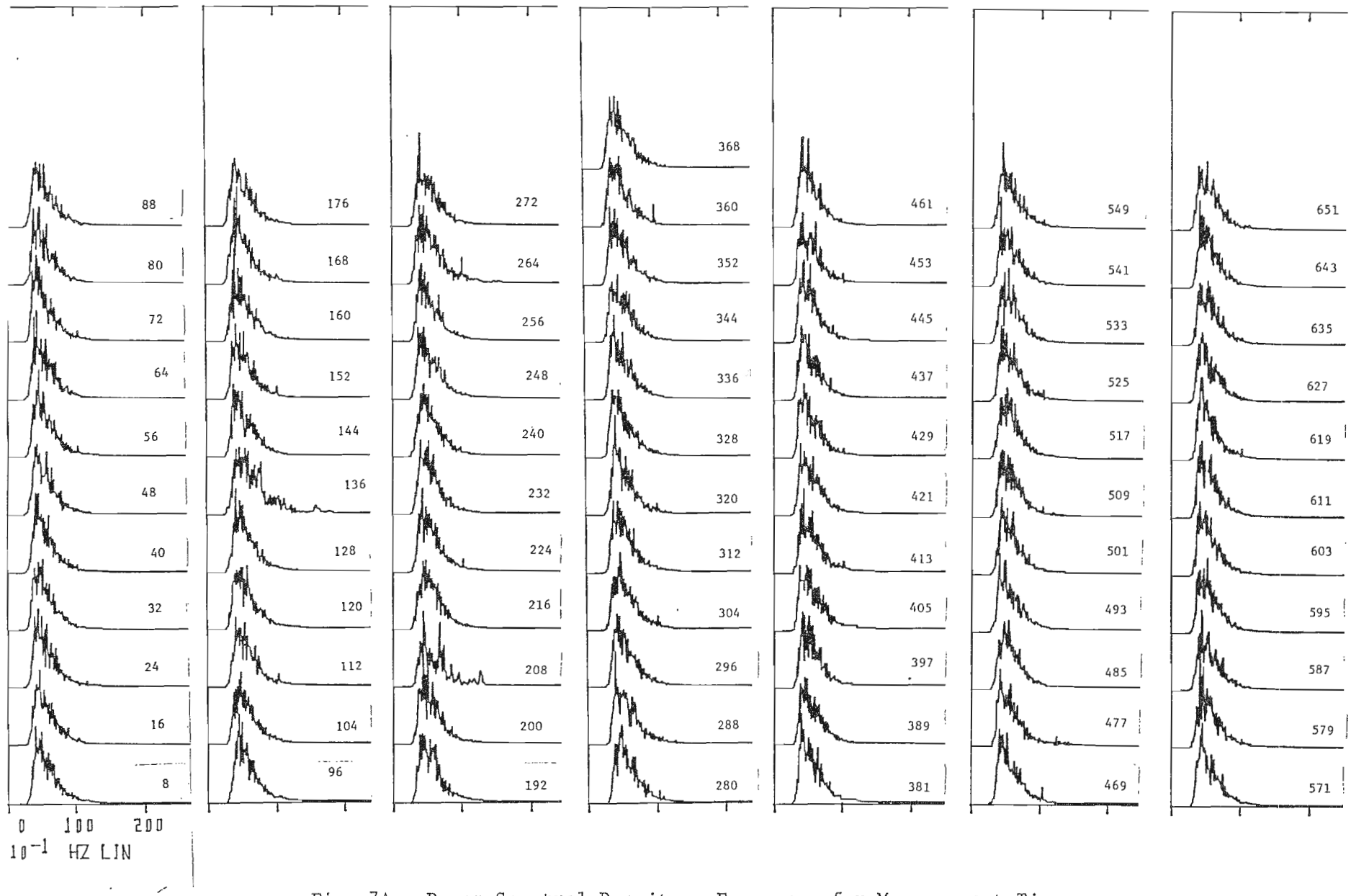

Fig. 7A. Power Spectral Density - Frequency for Measurement Time of 8 to 651 Minutes at Location 1

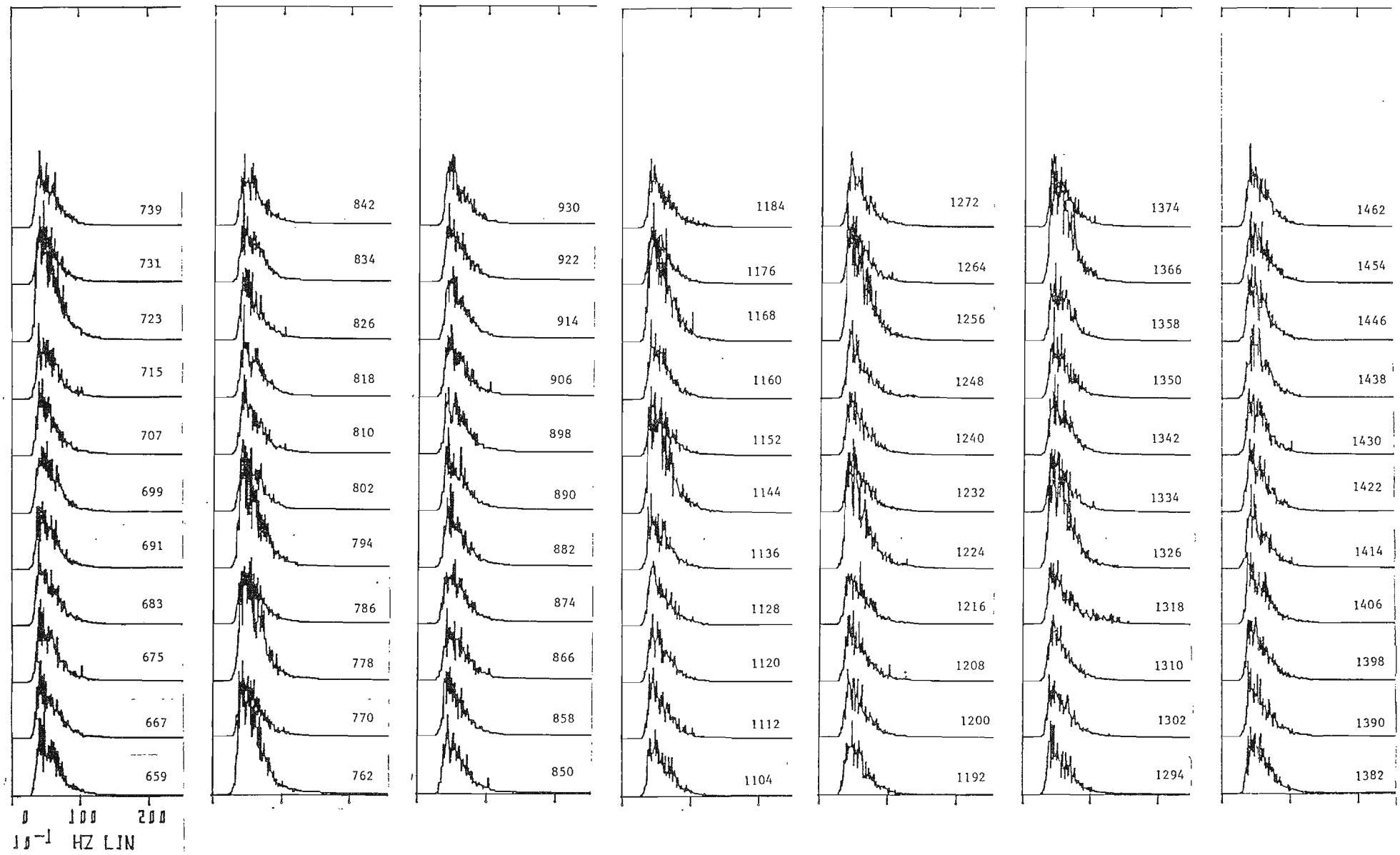

Fig. 7B. Power Spectral Density - Frequency for Measurement Time of 659 to 1462 Minutes at Location 1

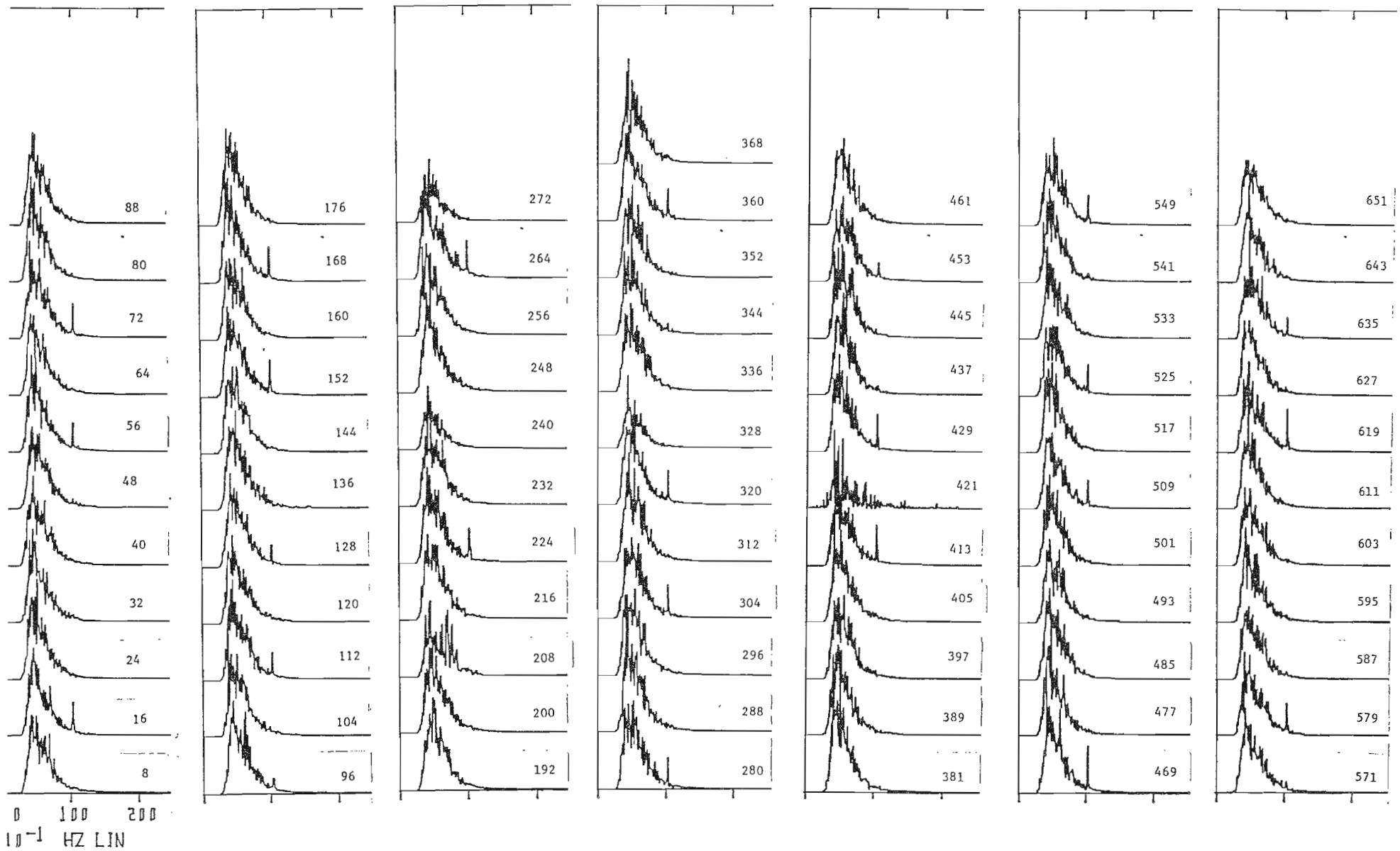

Fig. 8A. Power Spectral Density - Frequency for Measurement Time of 8 to 651 Minutes at Location 2

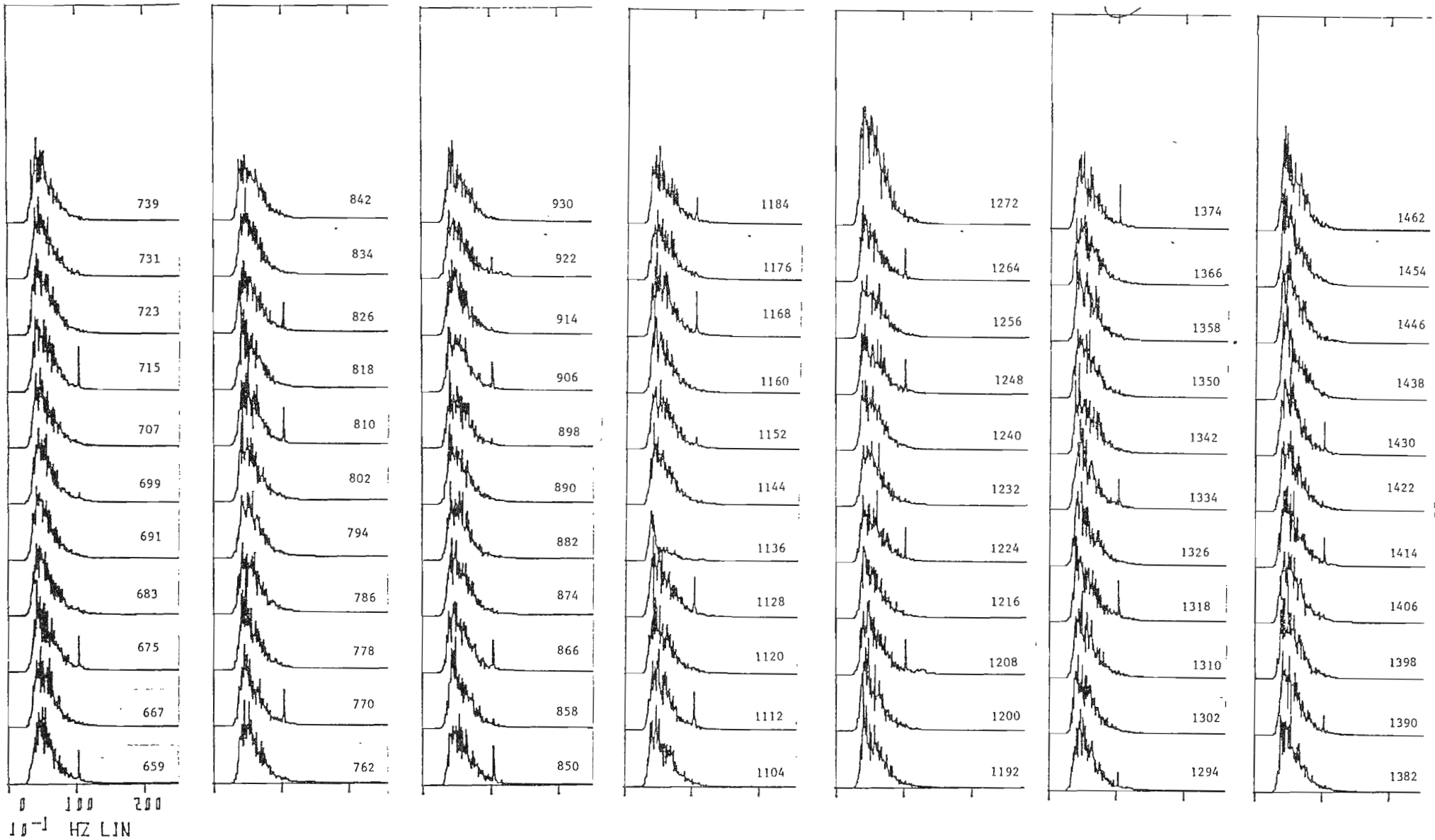

Fig. 8B. Power Spectral Density - Frequency for Measurement Time of 659 to 1462 Minutes at Location 2

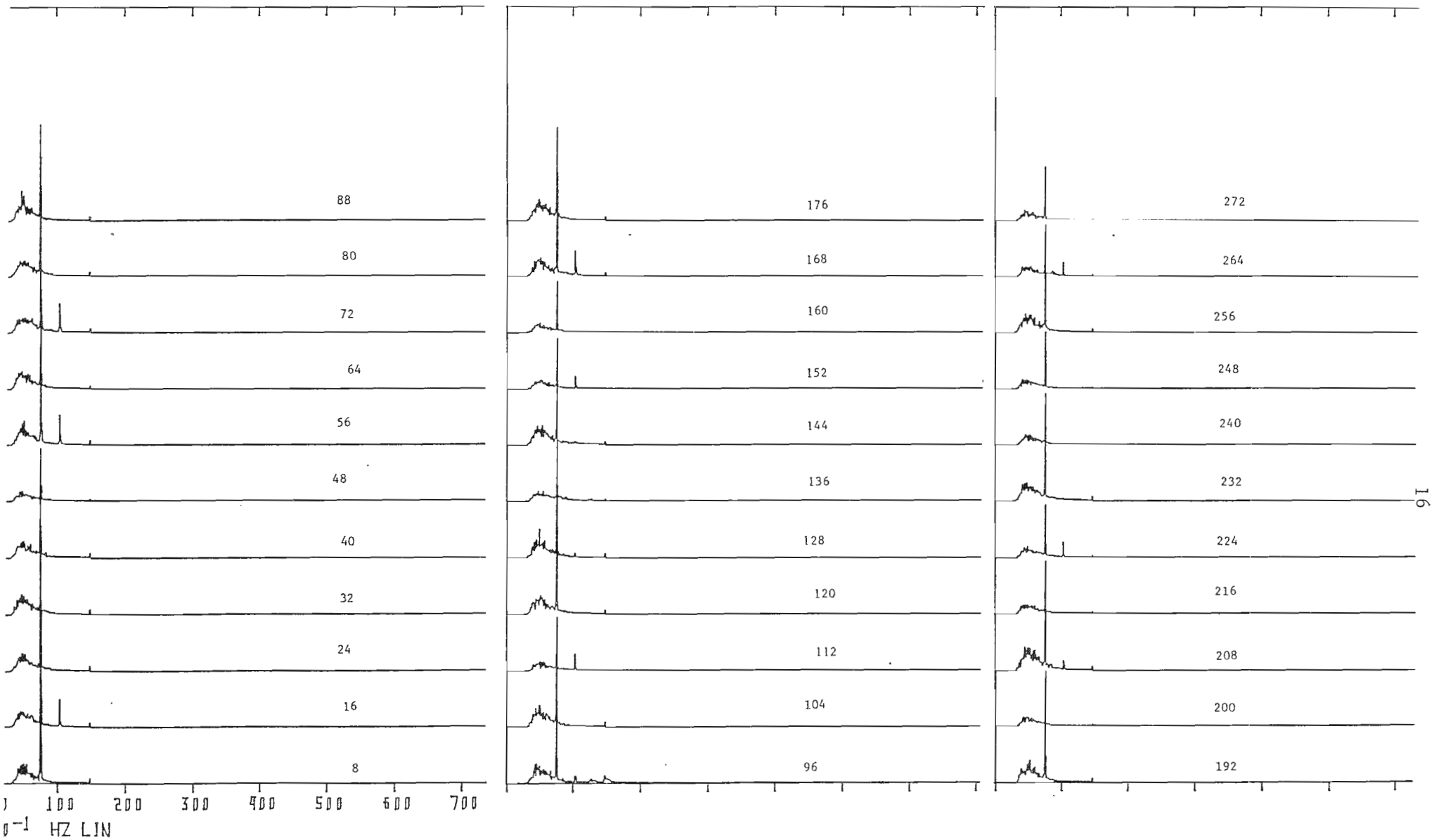

Fig. 9A. Power Spectral Density - Frequency for Measurement Time of 8 to 272 Minutes at Location 3

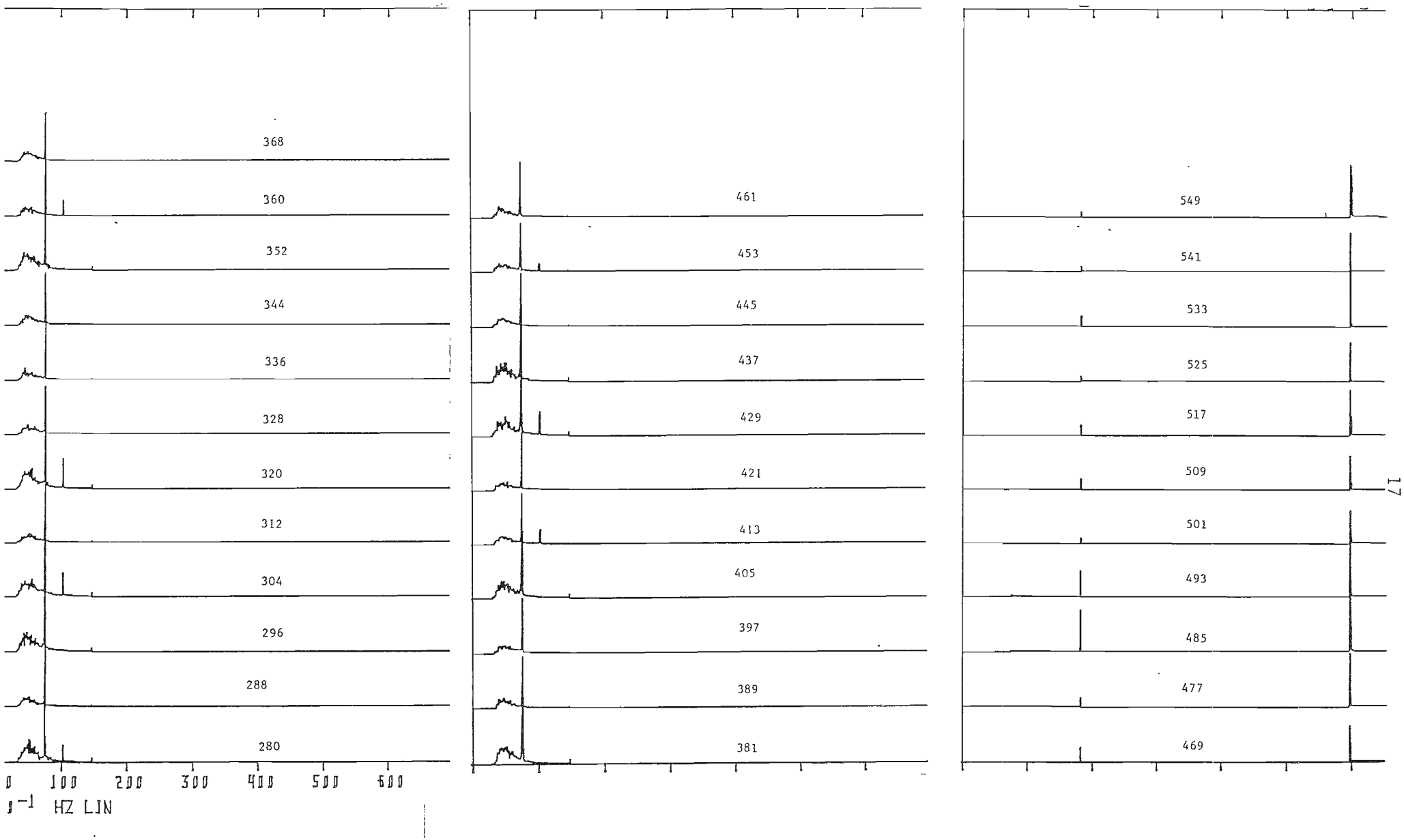

Fig. 9B. Power Spectral Density - Frequency for Measurement Time of 280 to 549 Minutes at Location 3

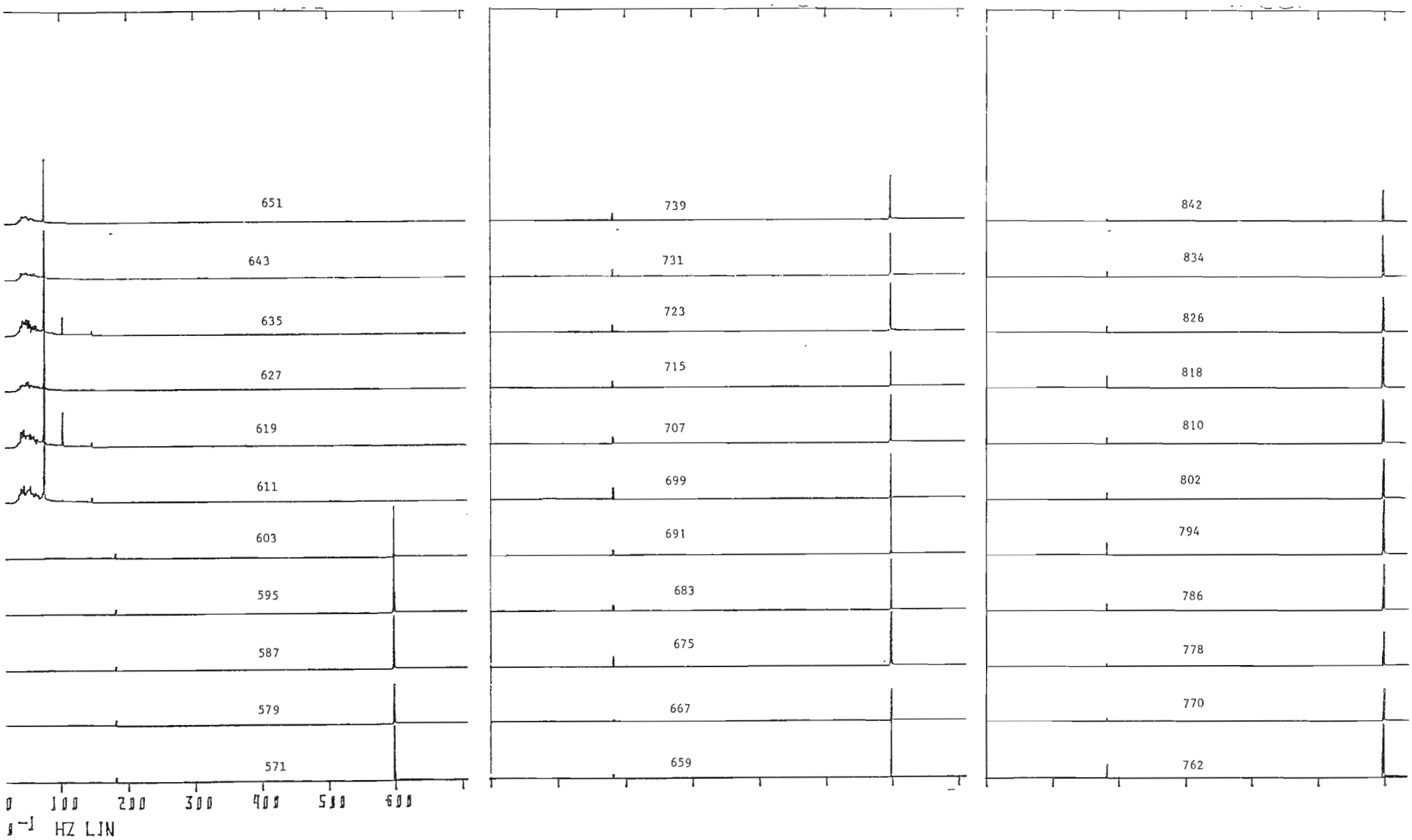

Fig. 9C. Power Spectral Density - Frequency for Measurement Time of 571 to 842 Minutes at Location 3

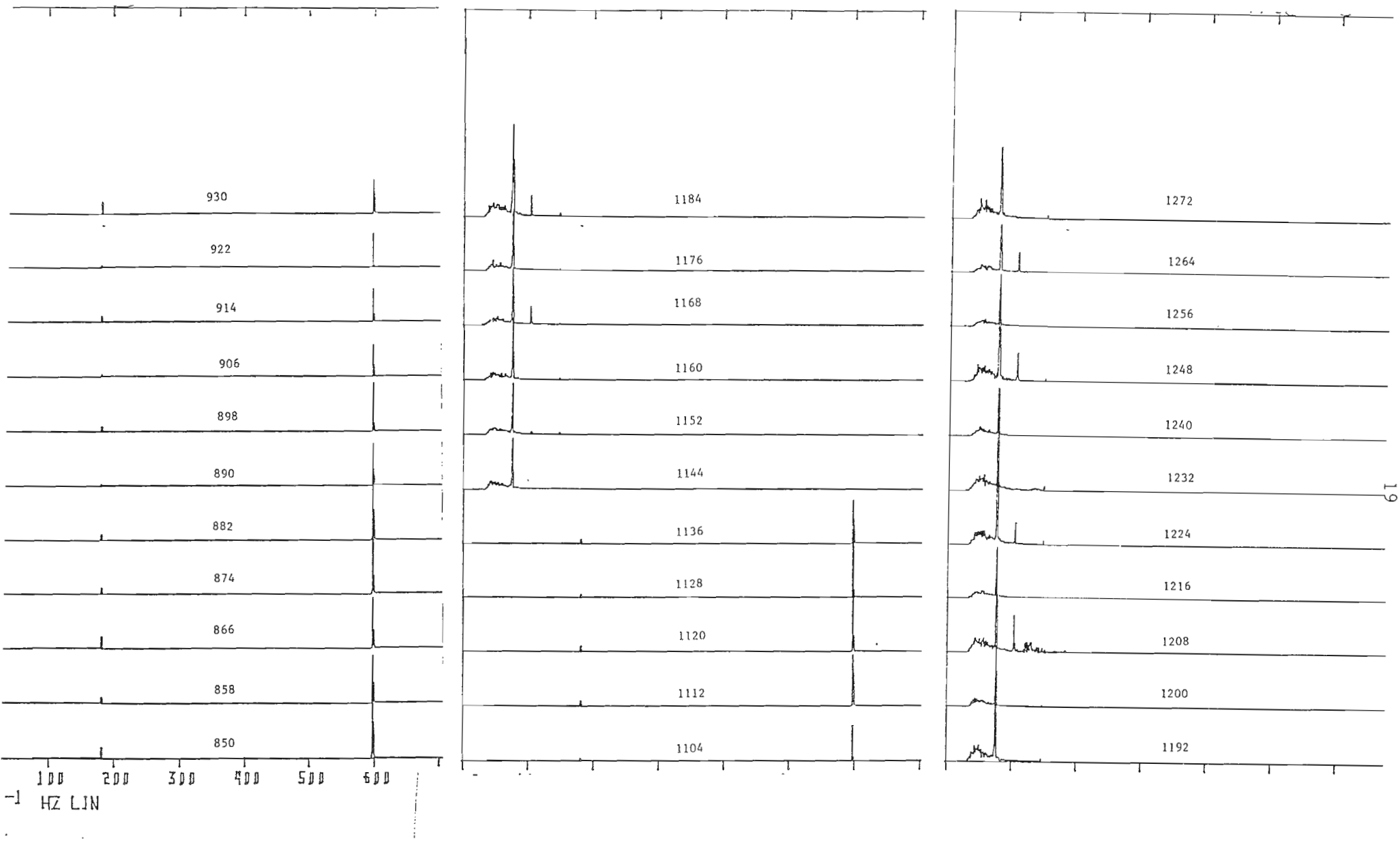

Fig. 9D. Power Spectral Density - Frequency for Measurement Time of 850 to 1272 Minutes at Location 3

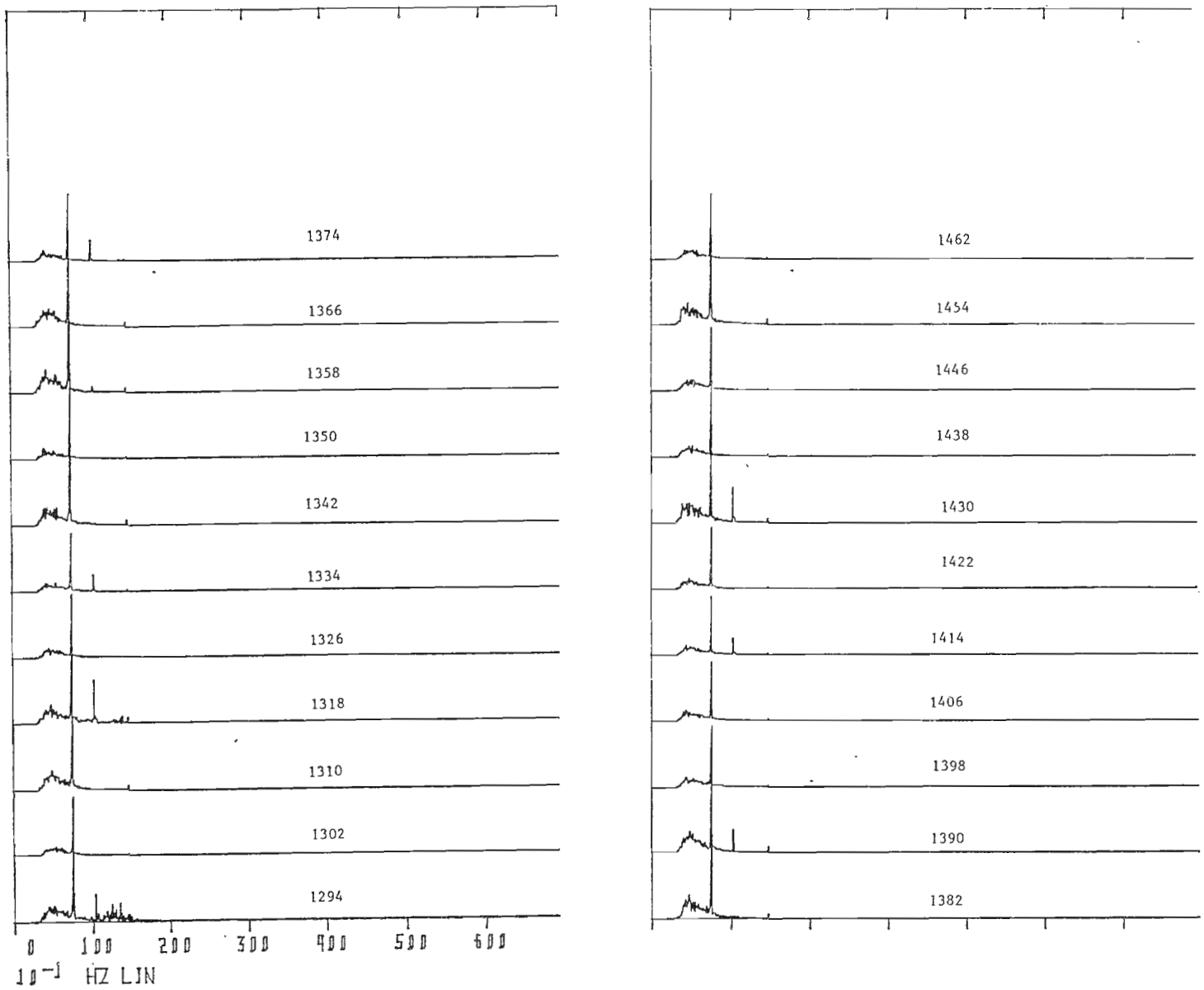

Fig. 9E. Power Spectral Density - Frequency for Measurement Time of 1294 to 1462 Minutes at Location 3

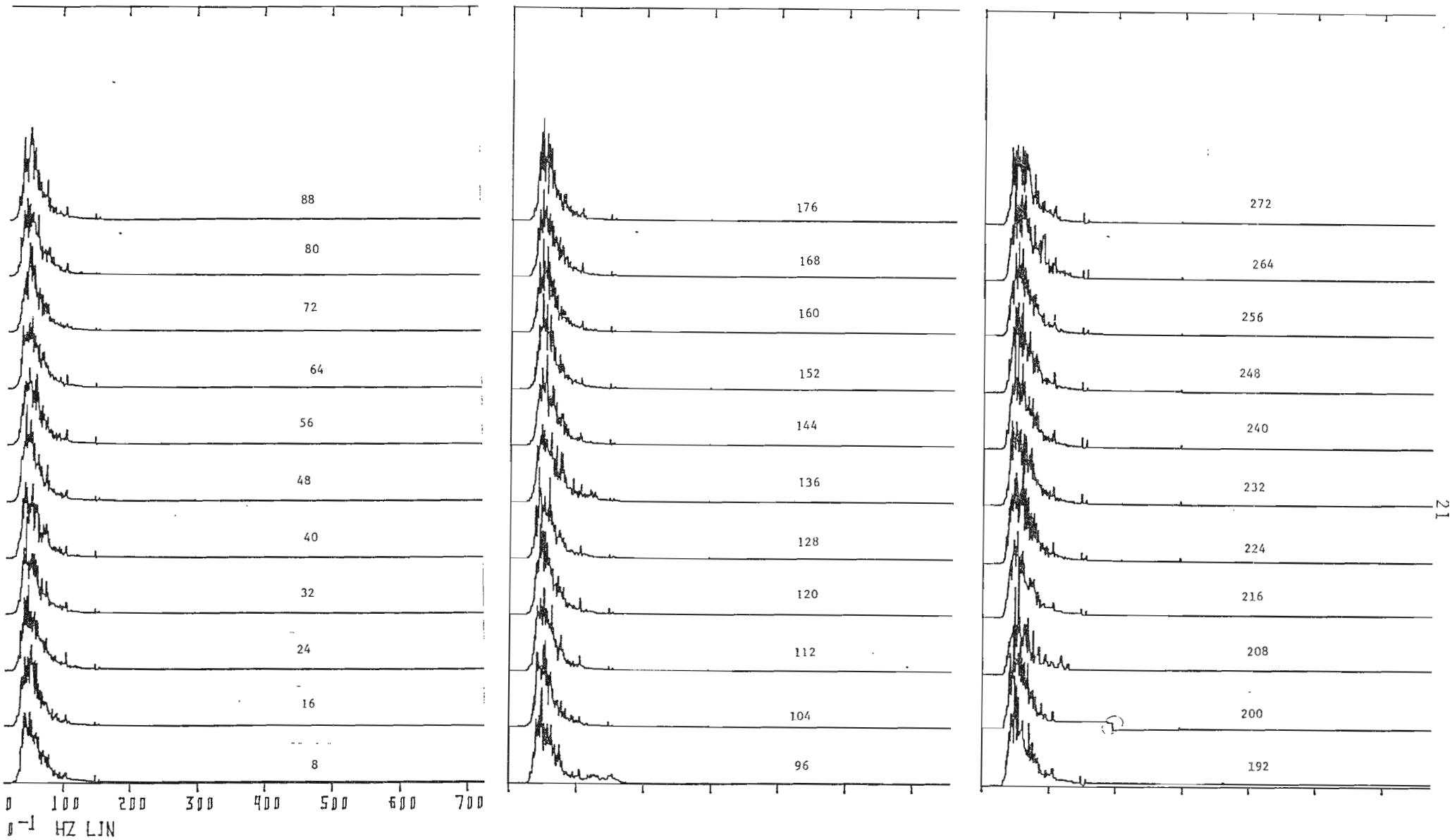

Fig. 10A. Power Spectral Density - Frequency for Measurement Time of 8 to 272 Minutes at Location 4

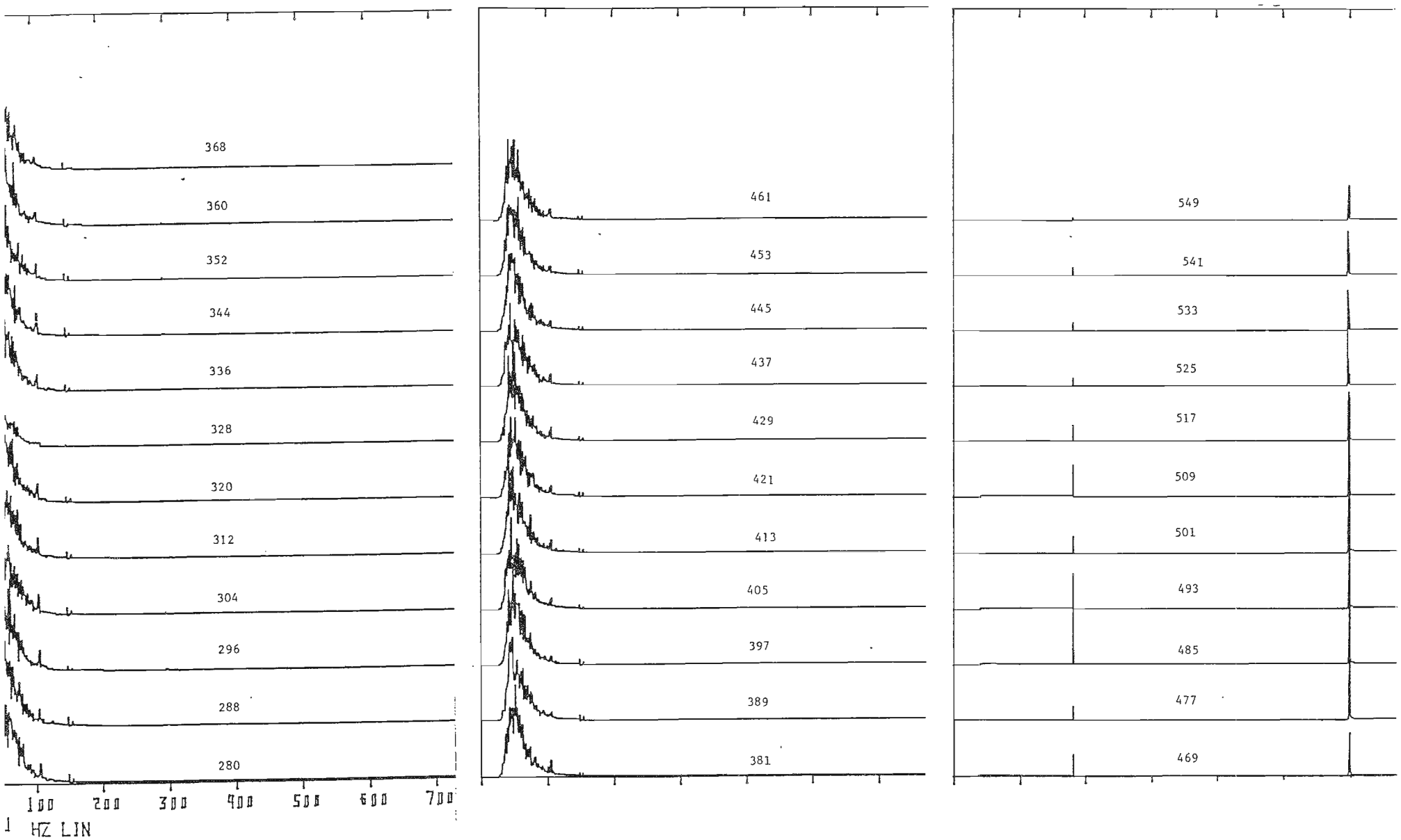

Fig. 10B. Power Spectral Density - Frequency for Measurement Time of 280 to 549 Minutes at Location 4

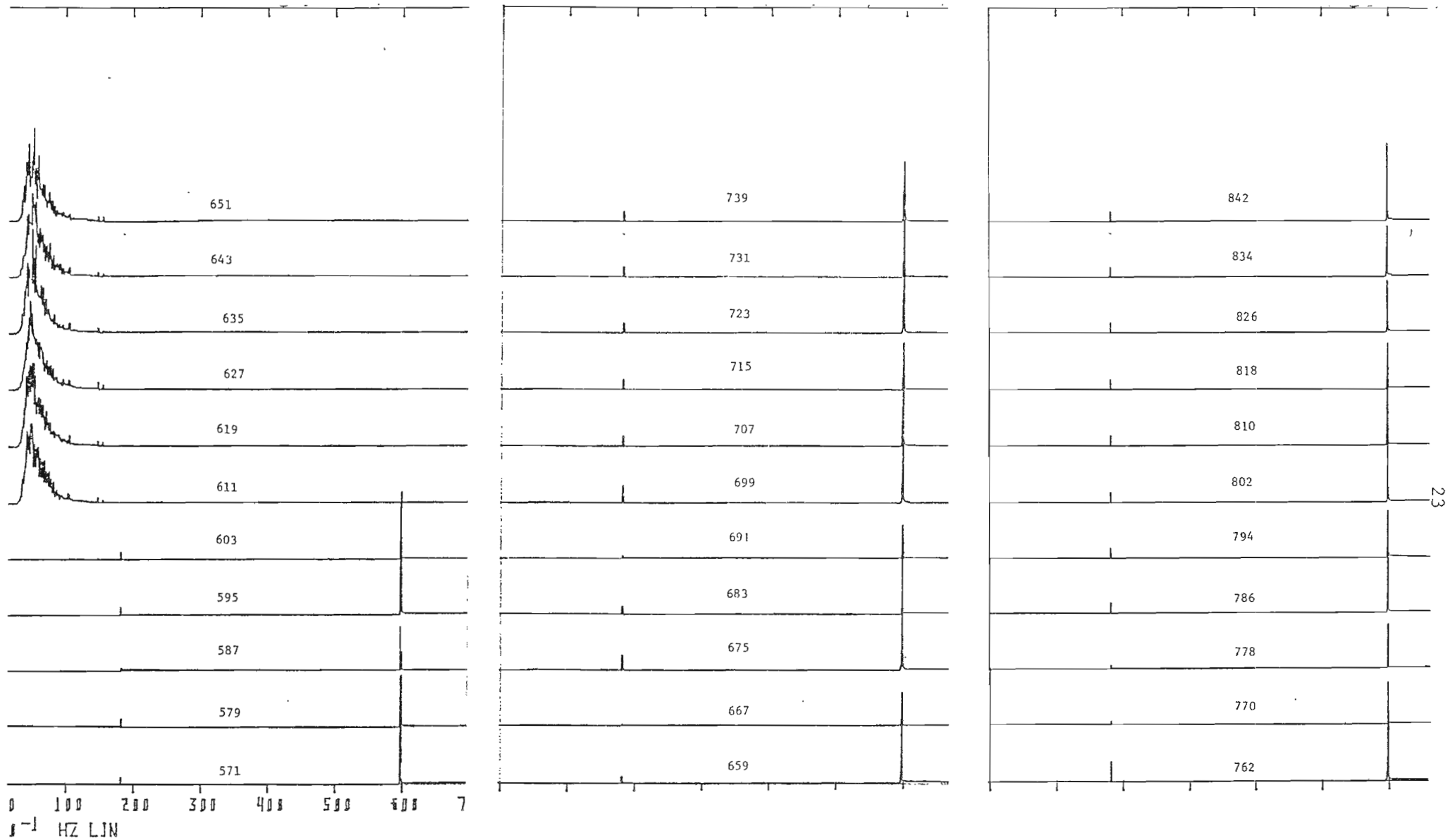

Fig. 10C. Power Spectral Density - Frequency for Measurement Time of 571 to 842 Minutes at Location 4

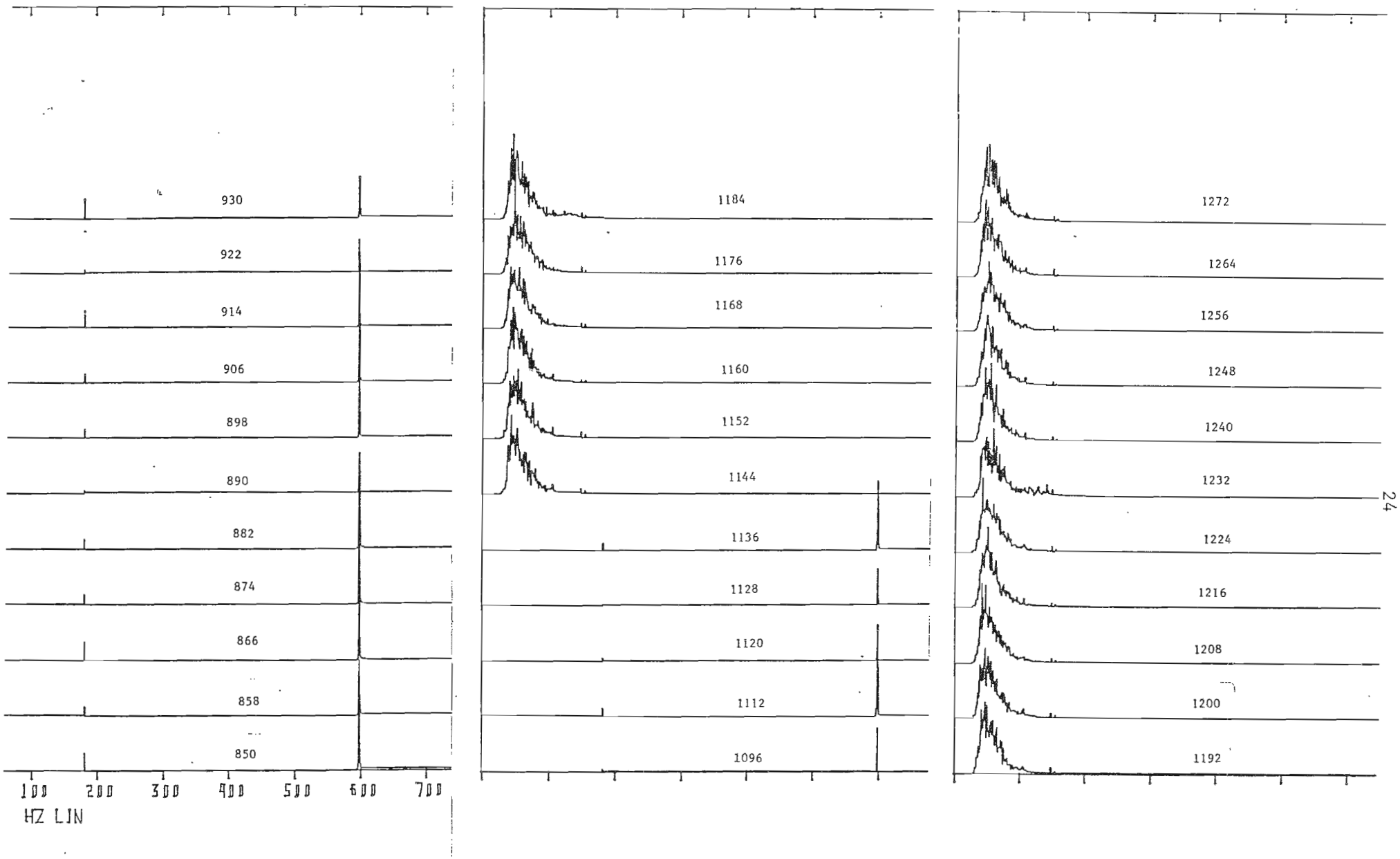

Fig. 10D. Power Spectral Density - Frequency for Measurement Time of 850 to 1272 Minutes at Location 4

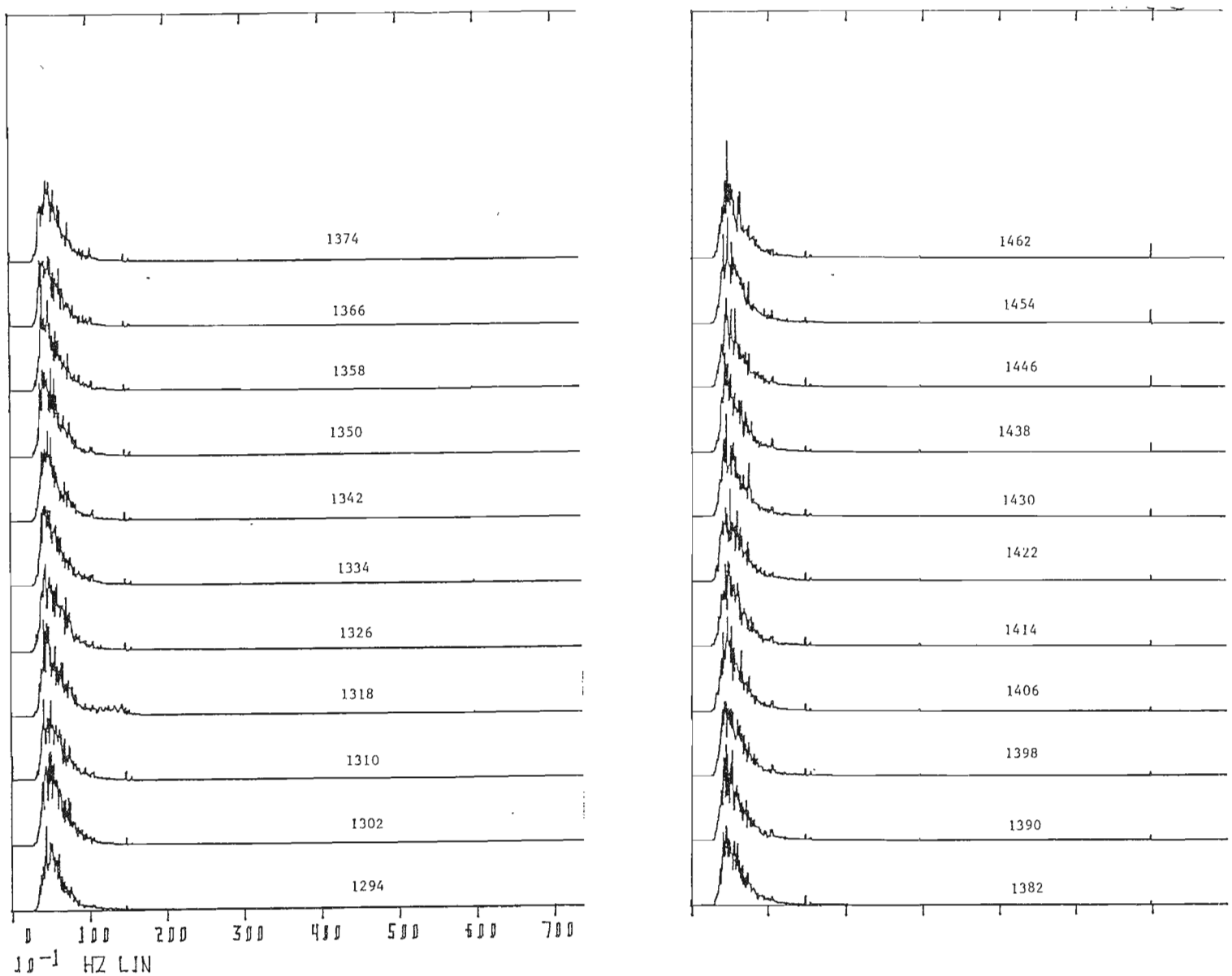

Fig. 10E. Power Spectral Density - Frequency for Measurement Time of 1294 to 1462 Minutes at Location 4

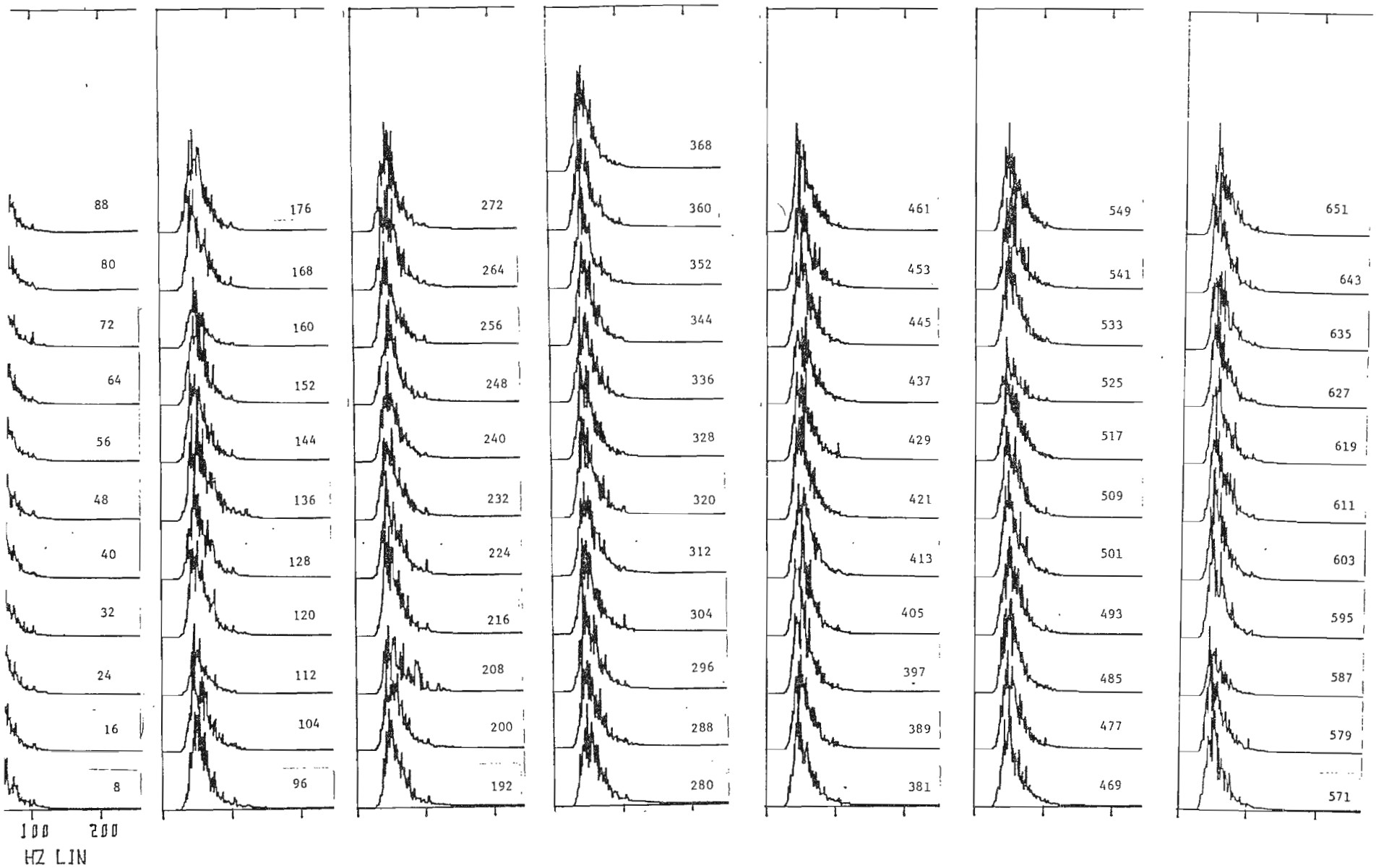

Fig. 11A. Power Spectral Density - Frequency for Measurement Time of 8 to 651 Minutes at Location 5

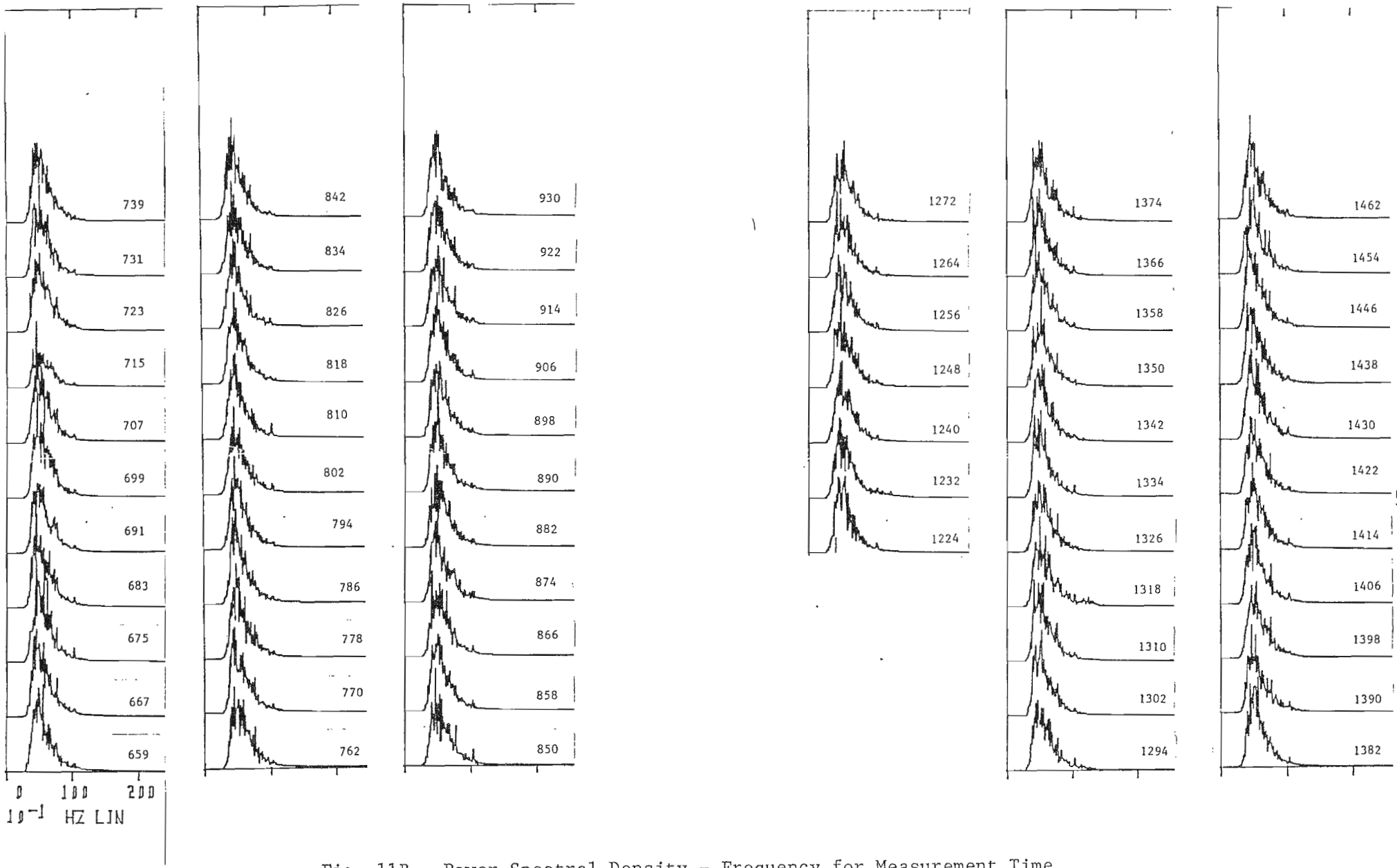

Fig. 11B. Power Spectral Density - Frequency for Measurement Time of 659 to 1462 Minutes at Location 5

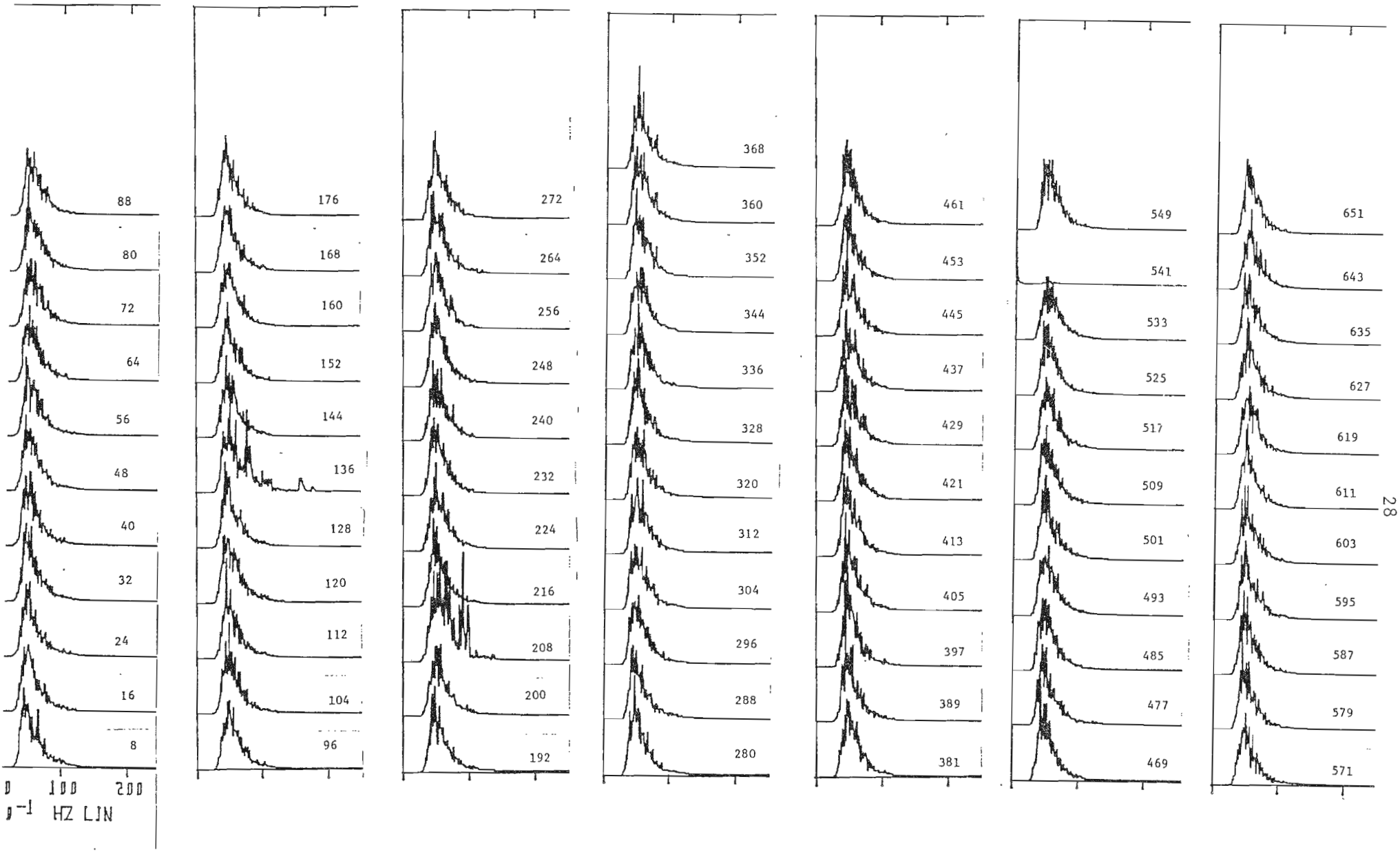

Fig. 12A. Power Spectral Density - Frequency for Measurement Time of 8 to 651 Minutes at Location 6

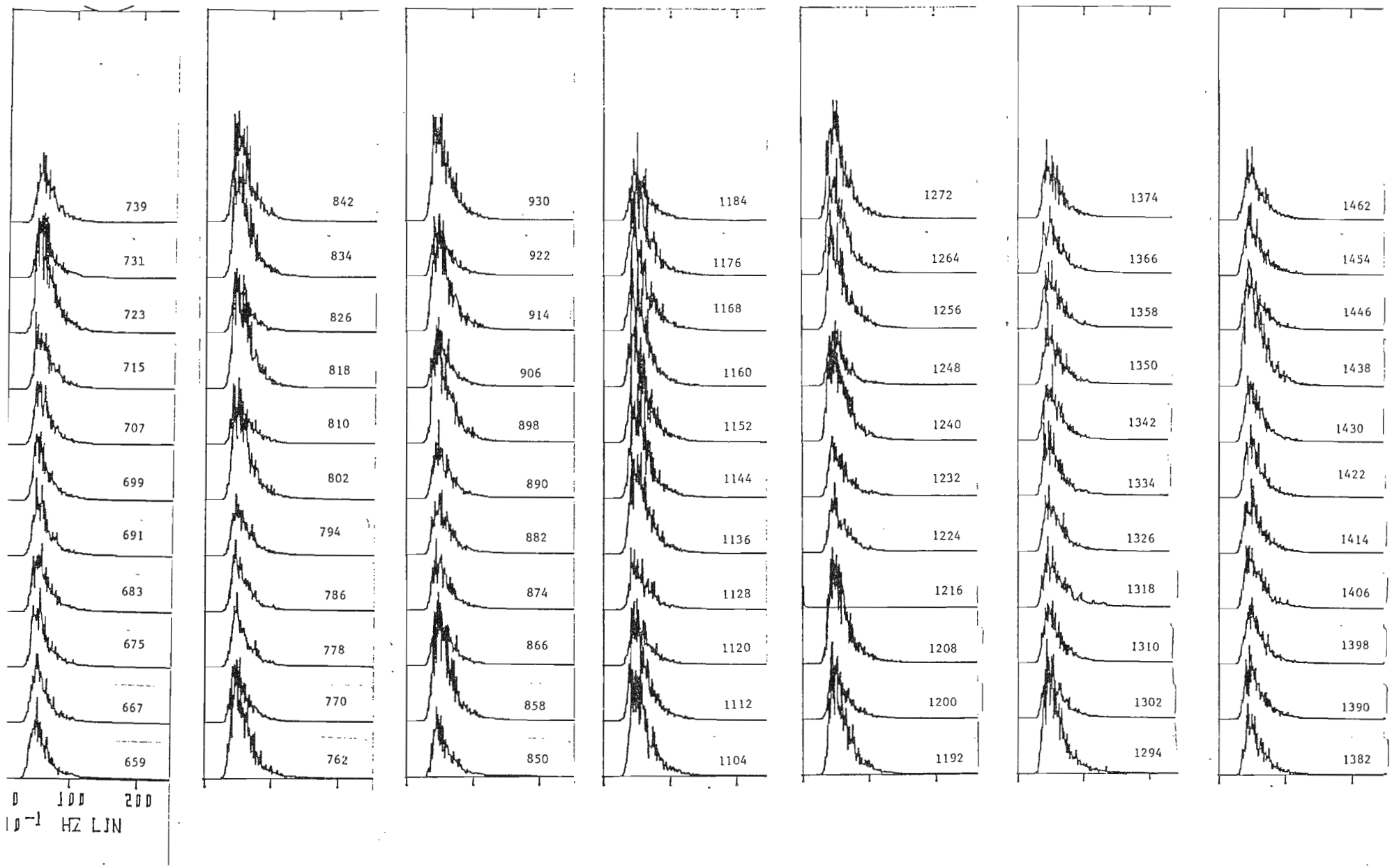

Fig. 12B. Power Spectral Density - Frequency for Measurement Time of 659 to 1462 Minutes at Location 6

integration of the plots; from 0 to 100 Hz for the wideband displacements and within narrow frequency bands for the specific frequencies under investigation. At frequencies below 10 Hz, the exponential amplitude decay is the result of the double integration technique used and should not be considered as actual ground motion. This exponential response is included in all RMS measurements, thus giving a degree of conservatism. Vertical amplitude, power spectral density ((Displacement)^2/Hz), is not to scale, but is auto-ranged to allow easy comparison of frequencies. Times are listed in minutes from the start of measurement (11:24 AM, 5/11/88) to the completion of the specific average power spectral density.

Displacement at location 1, Fig. 4, averages approximately 0.038 micron RMS with several larger amplitude "spikes" at times of 136 and 208 minutes. Very slight gradual increases of displacement can be correlated to the active time at the ANL site (7:00 AM to 6:00 PM). Several distinct peaks can be seen in the power spectral density-frequency plots of Figs. 7A and 7B. A 10.5 Hz peak is observed on 224, 264, 280, 304, 320 and other records. Other unusual records are at 136 and 208 which correspond to the above mentioned "spikes."

The displacement at location 2, also shown on Fig. 4, averages approximately 0.041 micron RMS with a distinctly larger response corresponding to the active time at the ANL site. Since this location is closer to site activity, a larger displacement amplitude is to be expected. As in location 1 data, distinct "spikes" can be seen at 136 and 208. Two additional "spikes" are at 421 and 1136. All of the spikes are observed as unusual responses on the power spectral density-frequency plots of Figs. 8A and 8B. Also the 10.5 Hz peak is present on a larger percentage of the plots and is usually a higher amplitude than at location 1.

Total displacement at location 3 is shown in Fig. 5. An average displacement value of approximately 0.048 micron RMS was measured from 0 to 461 with a much larger amplitude, ≈ 0.25 micron, from 461 to 603 and 659 to 1139. The amplitude then decreased to its former value of 0.048 micron from 1150 to the conclusion of measurements at 1462. More detailed plots of the low amplitude regions is shown in Figs. 13 and 14. Several distinct frequencies can be seen in the power spectral density-frequency plots of Figs. 9A to 9E. At times of low displacement, that is, at times of 0-461, 611-651, and 1144-1462, there is a strong 7.81 Hz component with an intermittent 10.5 Hz component. The frequency content of the high amplitude displacement signal is 18.4 Hz and 60 Hz. Due to the automatic auto-ranging of the Fast Fourier Analyzer, the 7.81 and 10.5 Hz displacements are not observed on the power spectral density-

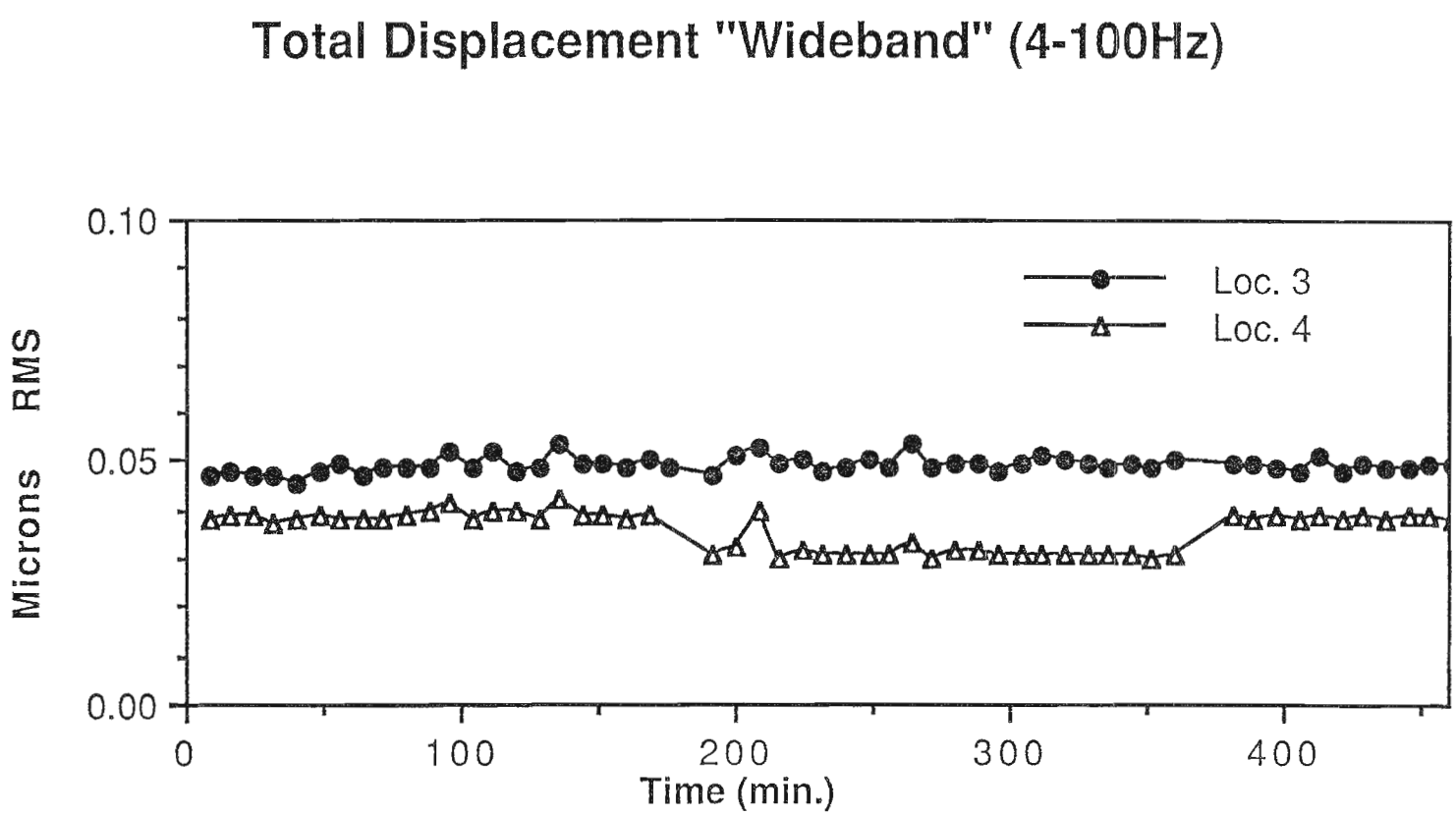

Fig. 13. Total Displacement in Microns at Locations 3 and 4 from 0 to 461 Minutes

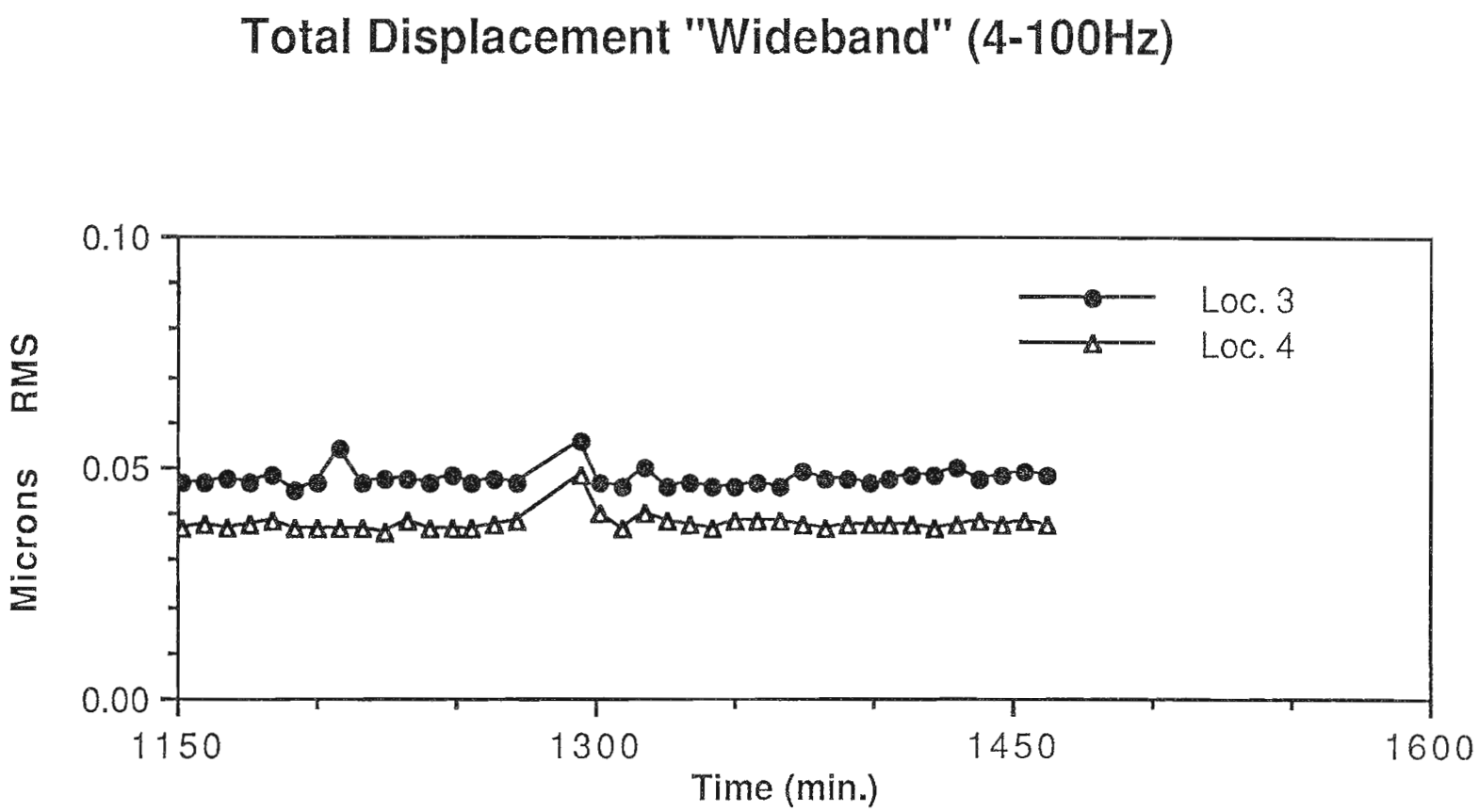

Fig. 14. Total Displacement in Microns at Locations 3 and 4 from 1150 to 1462 Minutes

frequency plots when the high amplitude (18.4 and 60 Hz) displacements occur, but are still present. The "spikes" which are present at locations 1 and 2 at 136 and 208 ar also present at location 3, see Fig. 13. Another interesting observation is that the "spike" present at location 2 at 1136 corresponds to the last measurement (1136) where the large amplitude 18.4 Hz and 60 Hz displacement is present at locations 3 and 4.

Measured displacement at location 4, Figs. 13 and 14, average approximately 0.038 micron RMS when a similar 18.4 Hz and 60 Hz displacement signal as was observed at location 3 is not present. From Fig. 5, a direct relationship of both amplitudes with time of the high amplitude displacements at locations 3 and 4 can be seen. The power spectral density–frequency plots of the measured displacements at location 4, as shown in Figs. 10A–10E are similar to those of location 3. Several other frequency components, 14.5 Hz, 15.5 Hz, and 30 Hz are also present but are very small in amplitude and are disregarded. Also, a small 60 Hz component is present from 1318 to 1462.

Average measured displacement for location 5, Fig. 6, is approximately 0.039 microns RMS. The larger displacement can again be associated with increased site activity. "Spikes" are also present at 136 and 208. Power spectral density–frequency plots are shown in Figs. 11A and 11B. Displacement measurements from 938 to 1216 were not available as a result of a connector problem.

Measured displacements at location 6, Fig. 6, average 0.035 micron RMS, again, with the largest amplitudes correlated to increased site activity. "Spikes" are also present at 136 and 208. The "spike" at 541 is an invalid data point. The "spikes" at 136 and 208 are present in the power spectral density–frequency plots of Figs. 12A and 12B along with the invalid data point at 541.

From the above total displacement data, there are several features to be investigated. They are:

1) 7.81 Hz displacement
2) 10.5 Hz displacement
3) 18.4 Hz and 60 Hz displacements
4) Transient displacements.

1) 7.81 Hz Displacement

The calculated power spectral densities are digitally filtered to exclude all frequencies except the 7.81 Hz component. Displacement as a function of time is shown in Figs. 15, 16, and 17 for locations 1–2, 3–4, and 5–6, respectively. Average RMS displacement for each location is summarized in Table 4. The largest average amplitude displacement is measured at location 3. Location 3 is close to the Building 329–330 complex, Fig. 18, therefore it is assumed that the 7.81 Hz displacement originates there. 7.81 Hz displacement amplitude at three specific time measurement periods for all 6 locations is shown in Fig. 19. Again the amplitudes are similar to those in Table 4. From similar measurements near Building 335 [1], a similar low frequency displacement component was observed and it was determined a large portion of the signal was produced by the 7-1/2 HP building air compressor. Since the signal at location 3 is only 0.0245 micron RMS, no attempt will be made to positively identify its source.

Data is omitted on the plots of locations 4, 5, and 6 (Figs. 16 and 17) from 762 to 930 as a result of an analyzer malfunction.

The transient "spikes" which were present in the total displacement data are also observed in this data.

2) 10.5 Hz Displacement

The 10.5 Hz displacements are also obtained by digitally filtering the original power spectral densities. Locations 1–2, 3–4, and 5–6 are shown in Figs. 20, 21, and 22, respectively. The intermittent nature of the displacement can clearly be seen at locations 2 and 3. Amplitude is greatest at location 3 with a smaller amplitude at location 2, both of which occur during a specific time period. From this, we can assume the source is also the Building 329–330 complex. Amplitude ratios of location 2 to location 3 for specific time periods of large 10.5 Hz displacements are shown in Table 5. The average ratio is 0.526. This, along with the measured distances from the outside foundation of Building 330 to the two locations can be used to calculate an approximate attenuation factor (α) of the soil, assuming uniform soil properties [2]. Attenuation to locations 1 and 4 are also calculated. Attenuation is calculated by:

$$W_o = W_1 \sqrt{\frac{R_1}{R_o}} \; e^{-\alpha(R_o - R_1)}$$

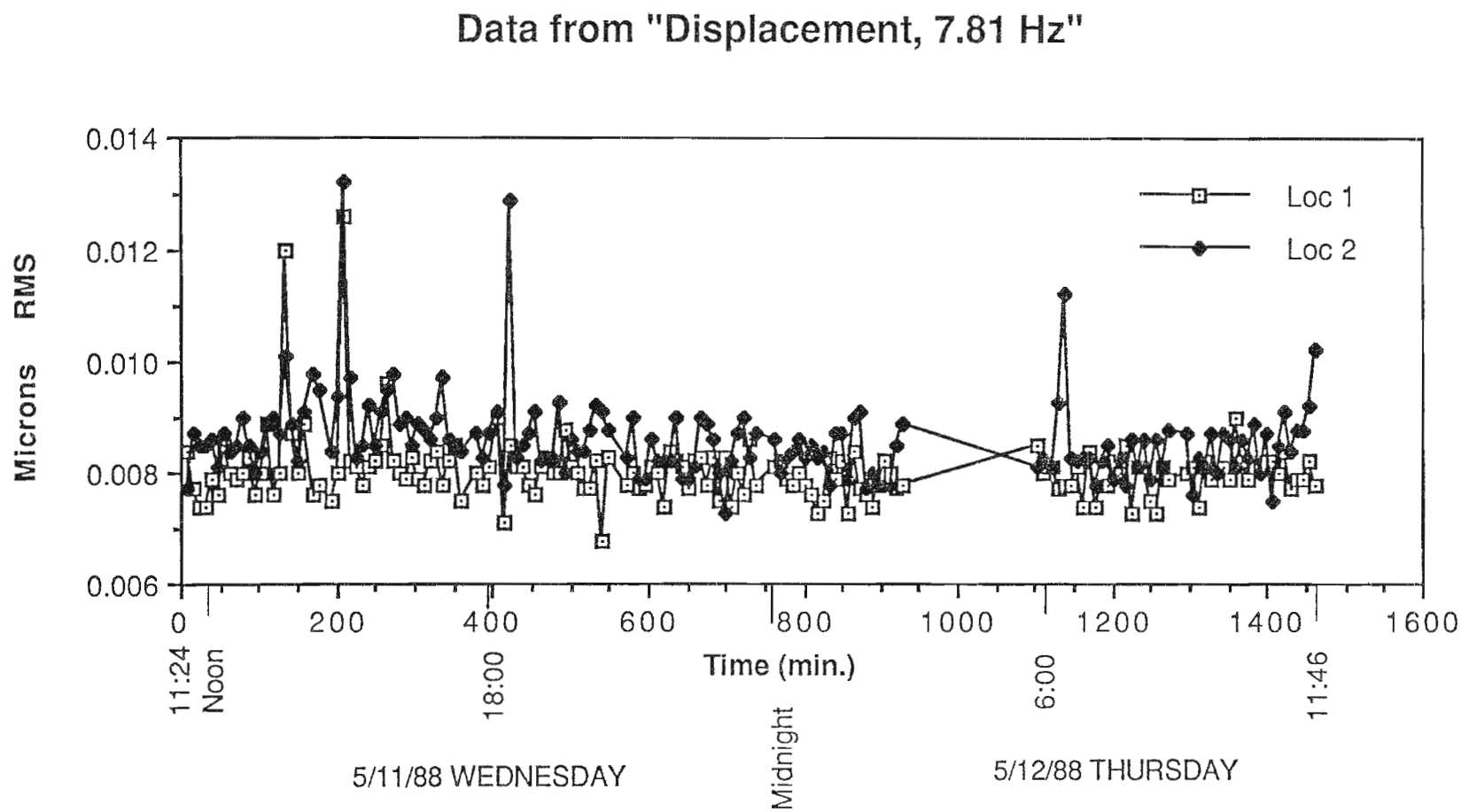

Fig. 15. 7.81 Hz Displacements at Locations 1 and 2

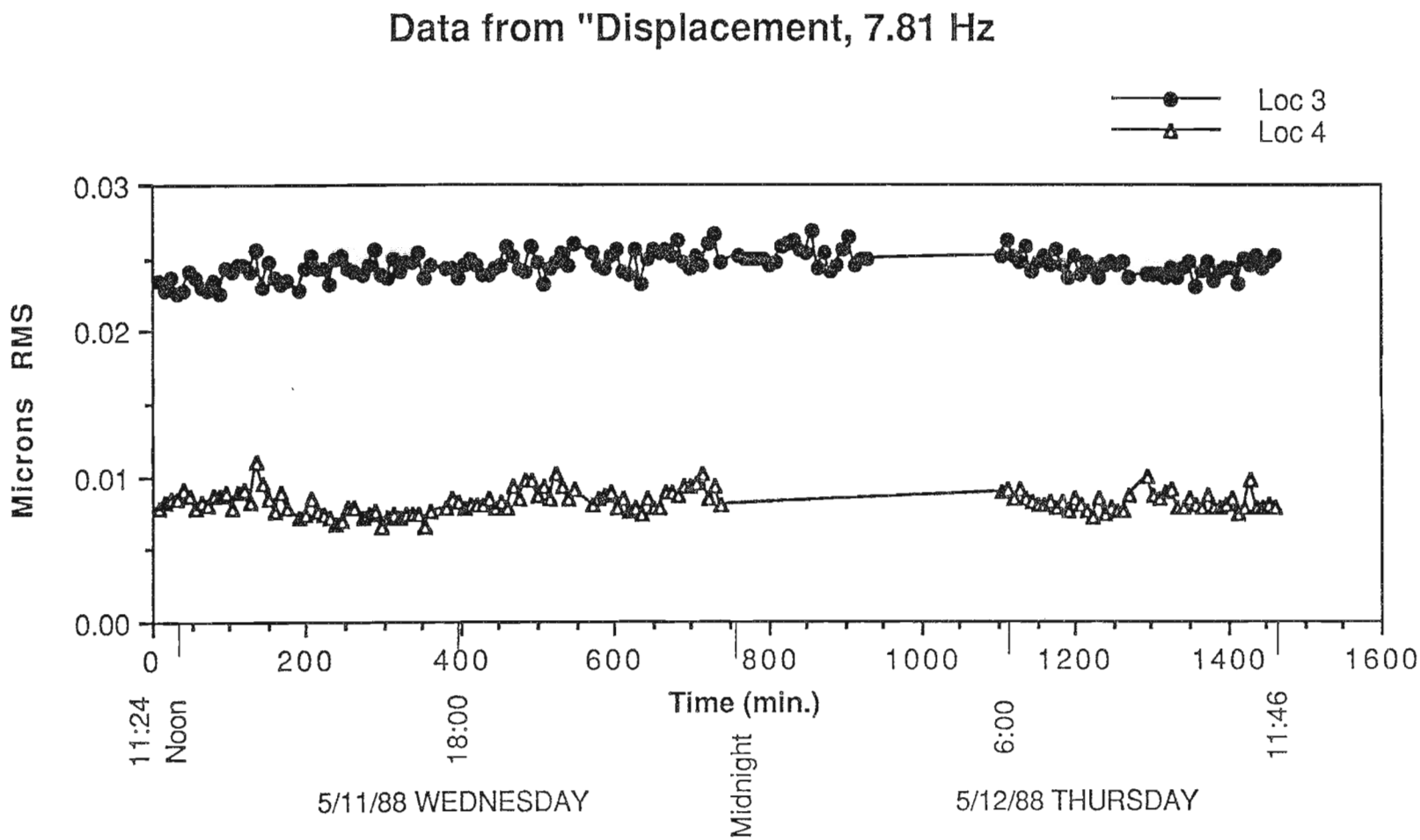

Fig. 16. 7.81 Hz Displacements at Locations 3 and 4

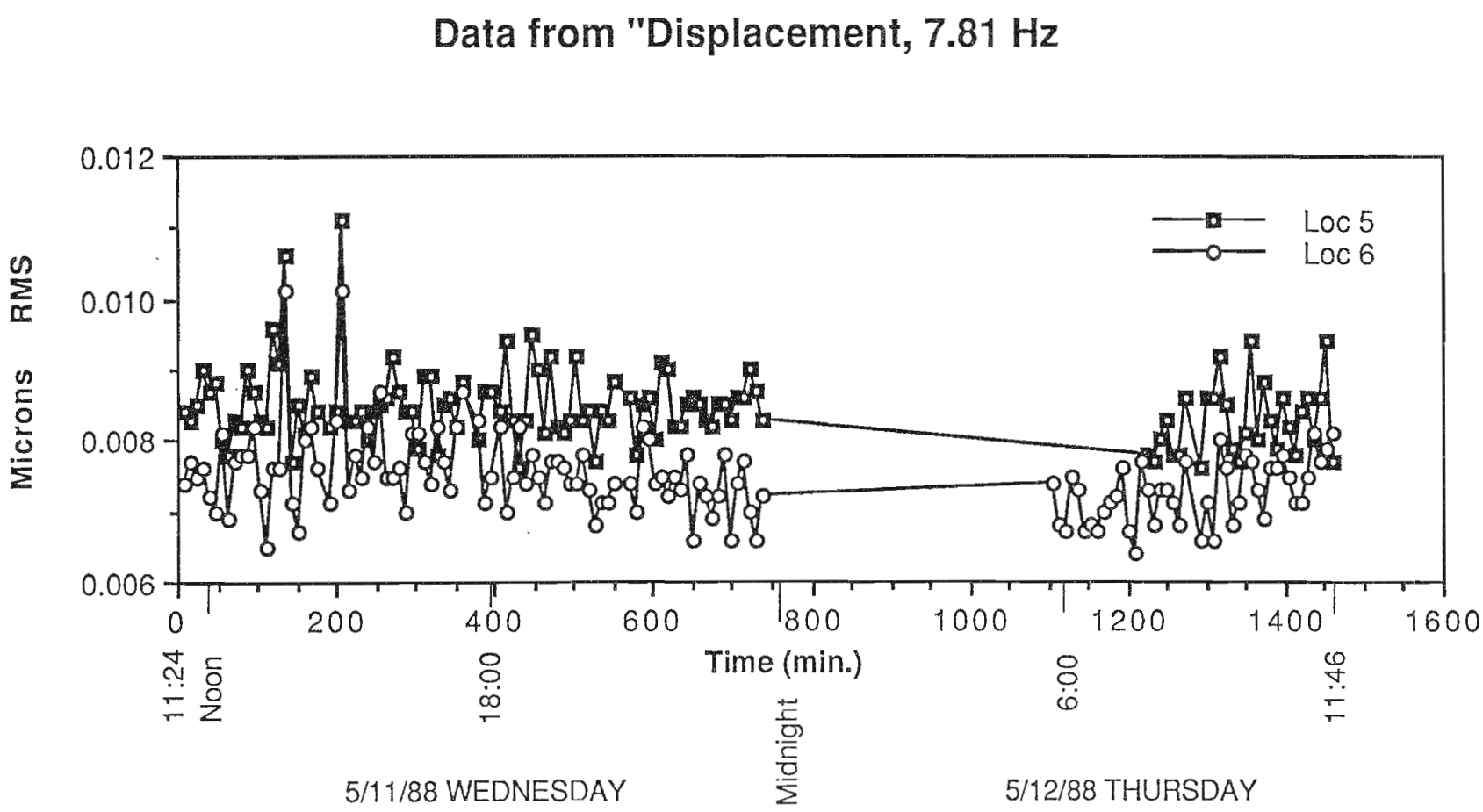

Fig. 17. 7.81 Hz Displacements at Locations 5 and 6

Table 4. RMS Displacement at 7.81 Hz

Location	Displacement microns, RMS
1	0.0080
2	0.0088
3	0.0245
4	0.0085
5	0.0086
6	0.0075

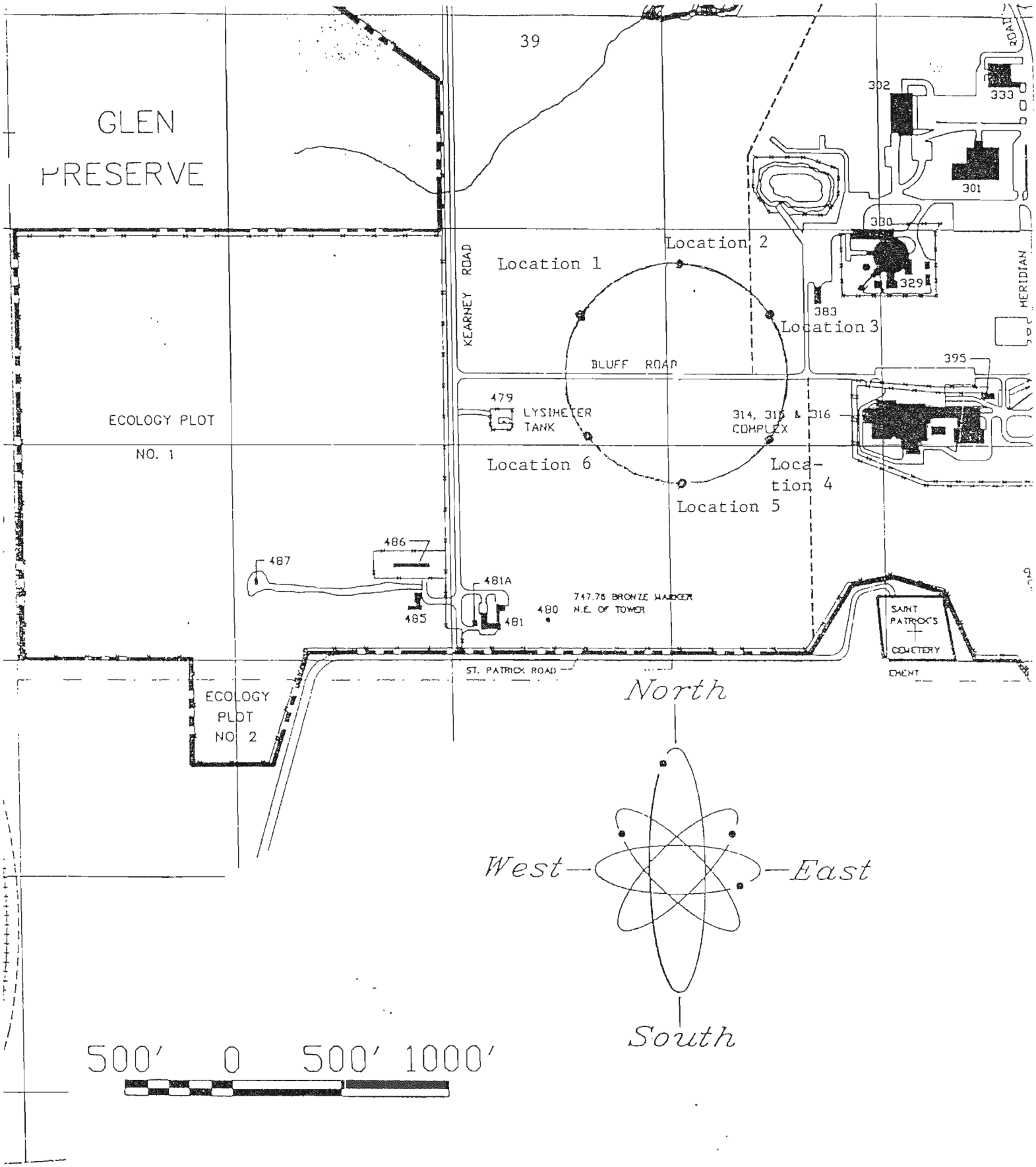

Fig. 18. Position of Existing Argonne Buildings with Respect to the APS Site

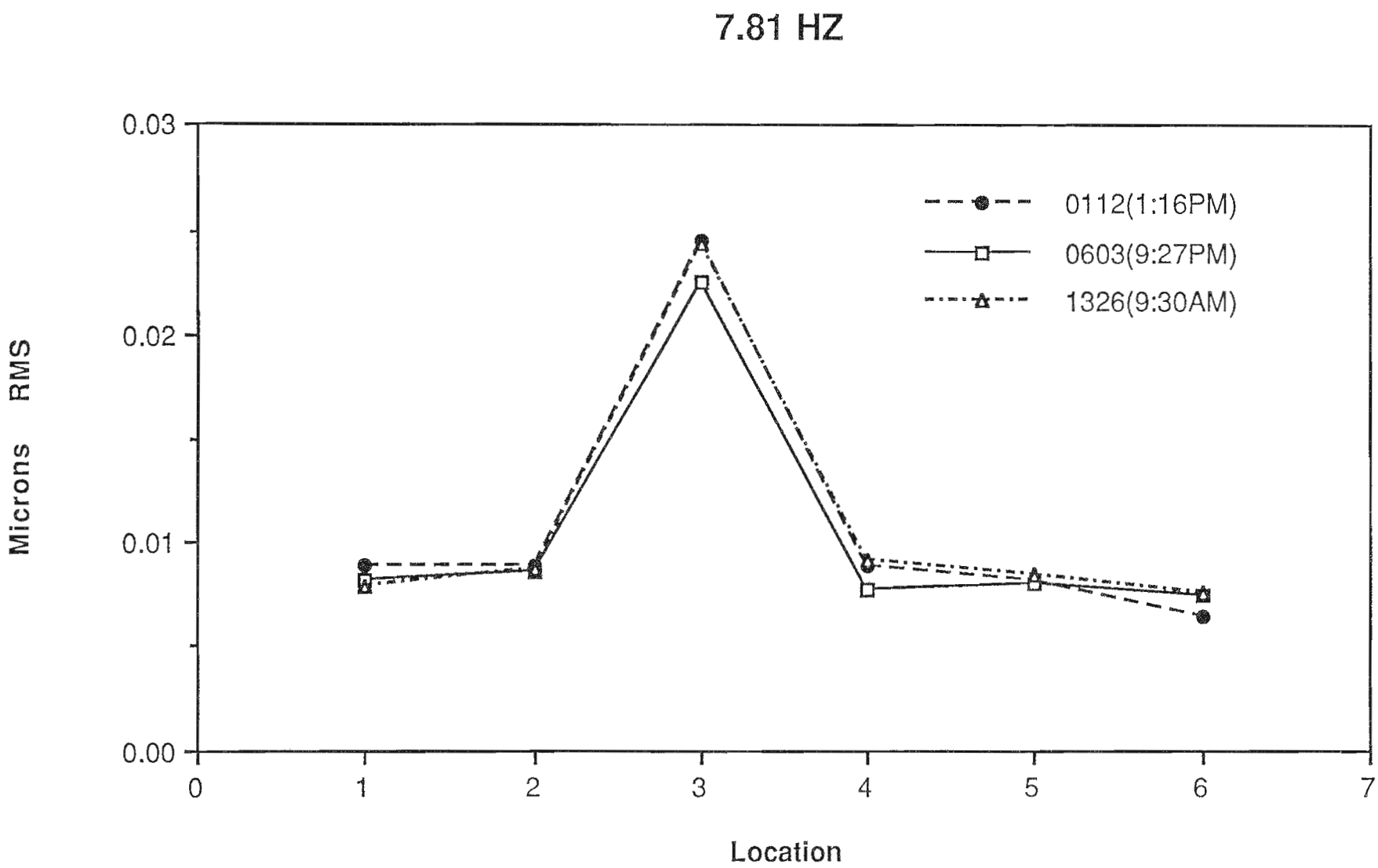

Fig. 19. 7.81 Hz Displacement Amplitude at the 6 Measurement Locations for Three Time Measurement Periods

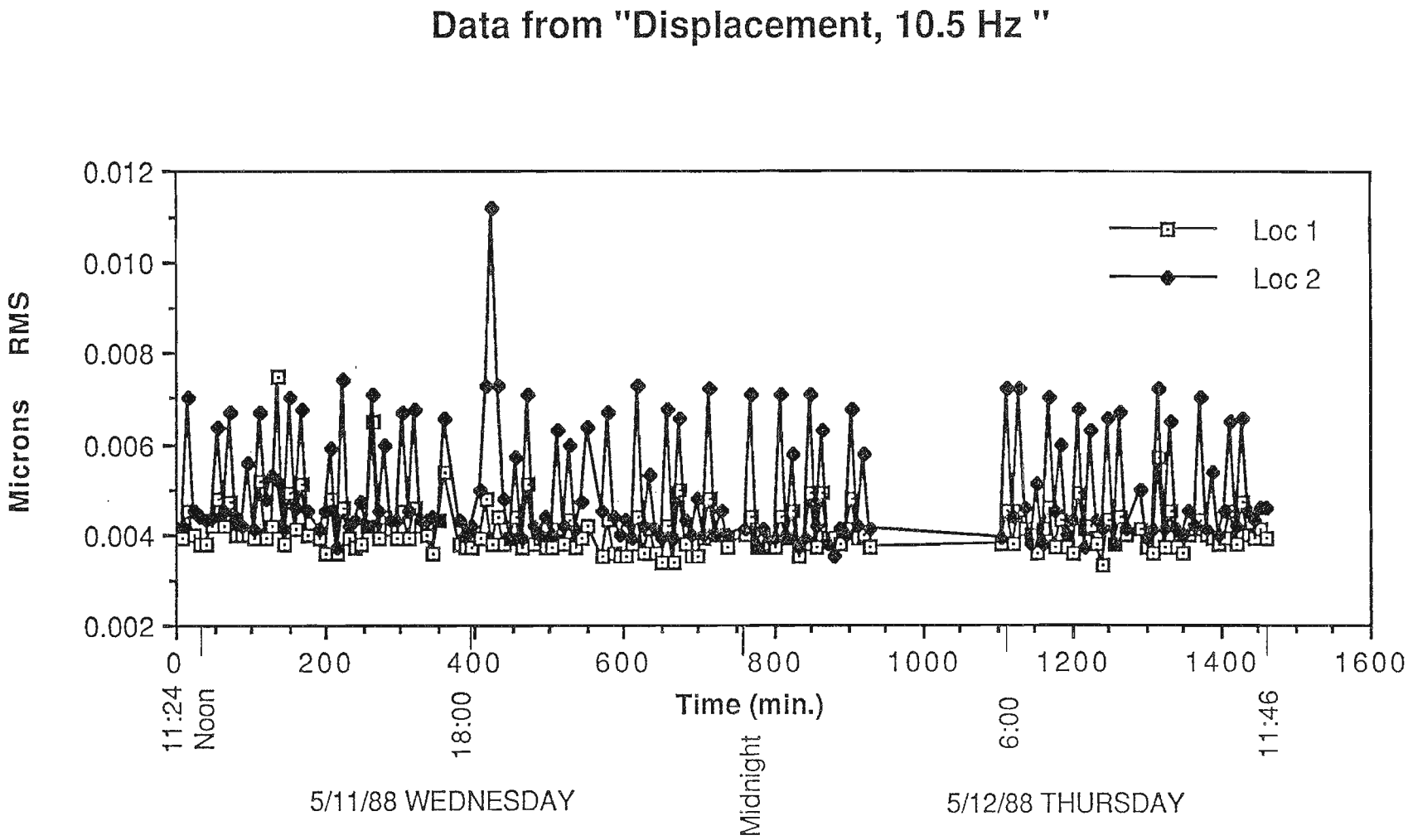

Fig. 20. 10.5 Hz Displacements at Locations 1 and 2

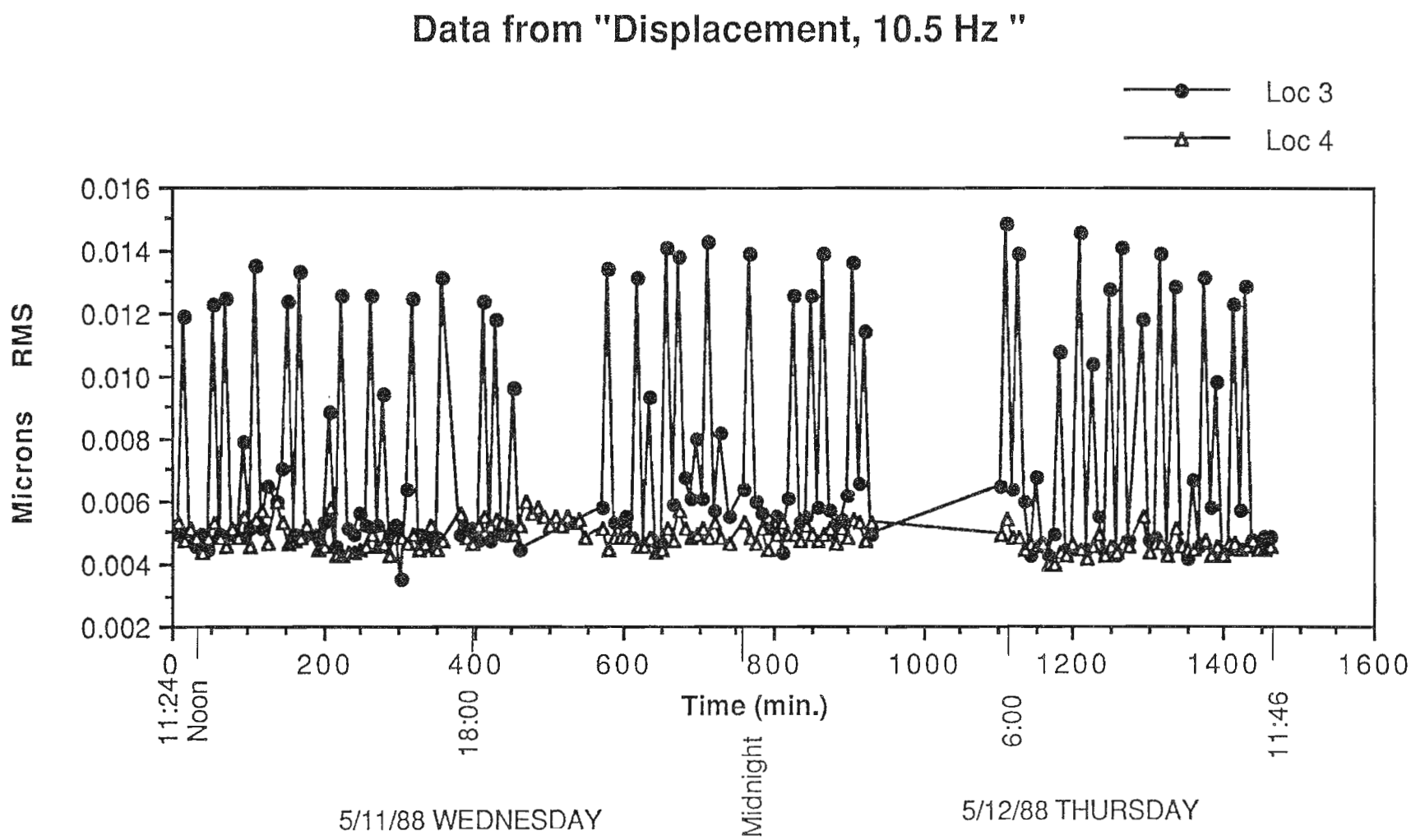

Fig. 21. 10.5 Hz Displacements at Locations 3 and 4

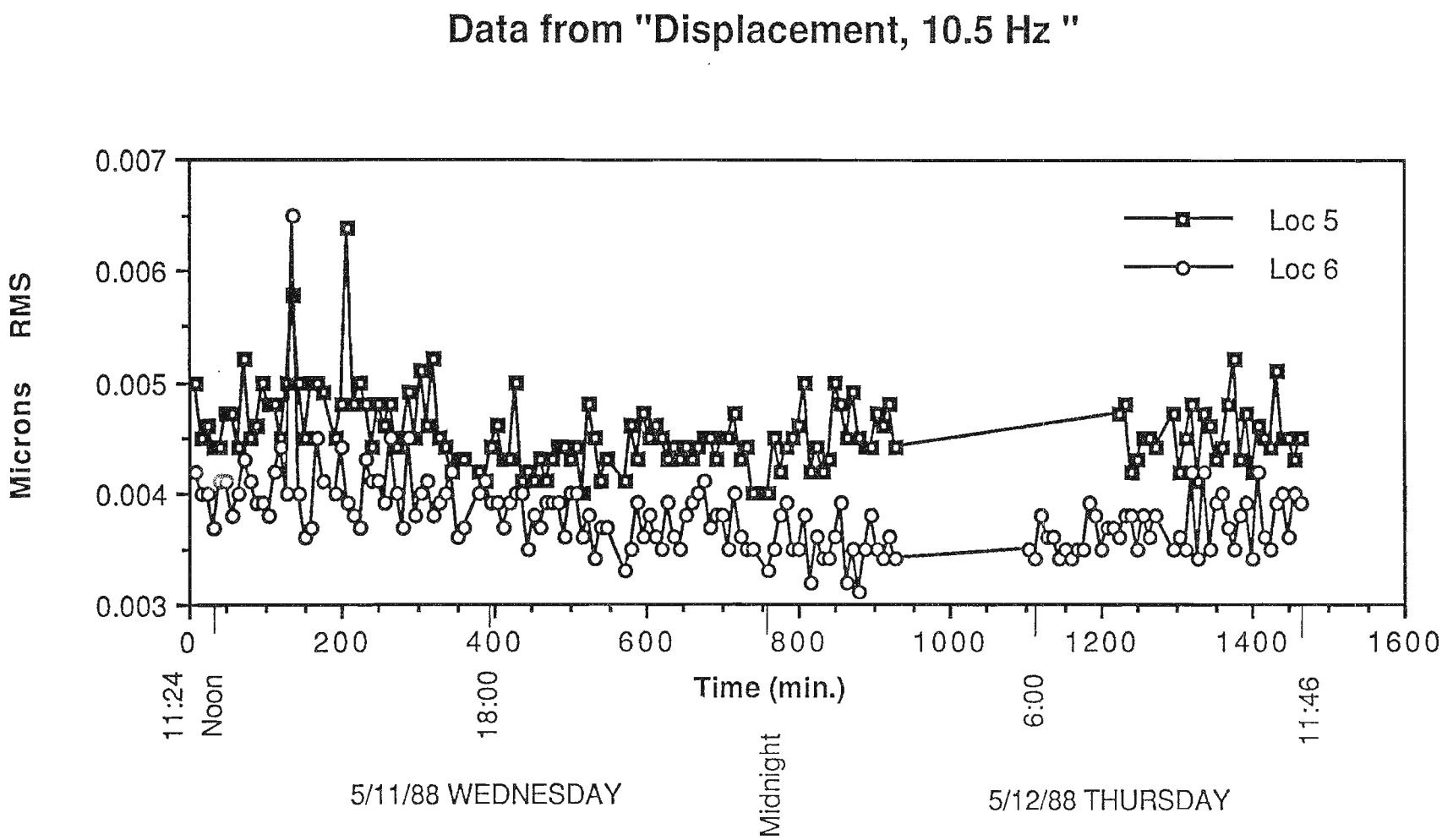

Fig. 22. 10.5 Hz Displacements at Locations 5 and 6

Table 5. Ratio of 10.5 Hz Displacement at Location 3 to Location 2 for Selected Times

Time (min.)	AMPLITUDE RATIO Displacement (Loc. 2) / Displacement (Loc. 3)
16	0.588
56	0.521
72	0.538
112	0.498
152	0.565
164	0.510
208	0.629
264	0.565
280	0.363
320	0.543
360	0.505
429	0.617
453	0.595
579	0.500
619	0.535
635	0.571
659	0.483
675	0.478
699	0.602
715	0.503
731	0.549
770	0.510
826	0.461
850	0.565
866	0.452
906	0.500
922	0.508
1122	0.485
1128	0.518
1184	0.556
1208	0.465
1224	0.606
1248	0.515
1264	0.476
1294	0.424
1318	0.518
1334	0.505
1374	0.535
1390	0.552
1414	0.529
1430	0.513
	0.526 = Average Value

where W_0 = amplitude of "R" wave at point 0
W_1= amplitude of "R" wave at point 1
R_0 = Distance from source to point 0
R_1 = Distance from source to point 1

For our calculations, subscripts will denote locations. Therefore:

R_1 = 1240 ft
R_2 = 750 ft
R_3 = 460 ft
R_4 = 840 ft
$W_3 \cong 0.0125\ \mu_{RMS}$

$$\frac{W_2}{W_3} = 0.526 \quad \text{(from Table 5)}$$

and by Eq. 1, $\alpha = 0.00137$. Using this value of α results in ratios of W_1/W_3 = 0.209 and W_4/W_3 = 0.440. The above calculated ratios cannot be verified due to the ambient noise level of the data acquisition/reduction systems which are in the same range as the displacements. Although the signals are in the noise, the response peaks can still be seen on the Power Spectral Density–Frequency plots of Figs. 7–11.

3) 18.4 Hz and 60 Hz Displacements

The 18.4 Hz and 60 Hz displacements appear to be related so they will be discussed together below. 18.4 Hz displacements for the six locations are shown in Figs. 23–25 and the 60 Hz displacements are shown in Figs. 26–28. Transient type displacements, such as those at times of 136 and 1136 minutes, will be omitted from this discussion. The measured displacement at 18.4 Hz for locations 1 and 2, Fig. 23, average approximately 0.001 micron RMS. No variation of amplitude level with site activity can be observed as the signal is at the noise level of the system. The 60 Hz displacements at locations 1 and 2, Fig. 26, are also similar. Amplitude of displacement for 18.4 Hz and 60 Hz at locations 3 and 4 are shown in Figs. 24 and 27, respectively. The level is very small until 469 minutes (19:13) when an abrupt increase occurs. It then decreases to its former level for the time interval of 611 minutes (21:35) to 659 minutes (22:23) after which it then increases until 1144 minutes (6:28) on the morning of 5/12/88. A distinct amplitude relationship between locations 3 and 4 at both frequencies can clearly be seen. At 18.4 Hz an average ratio of

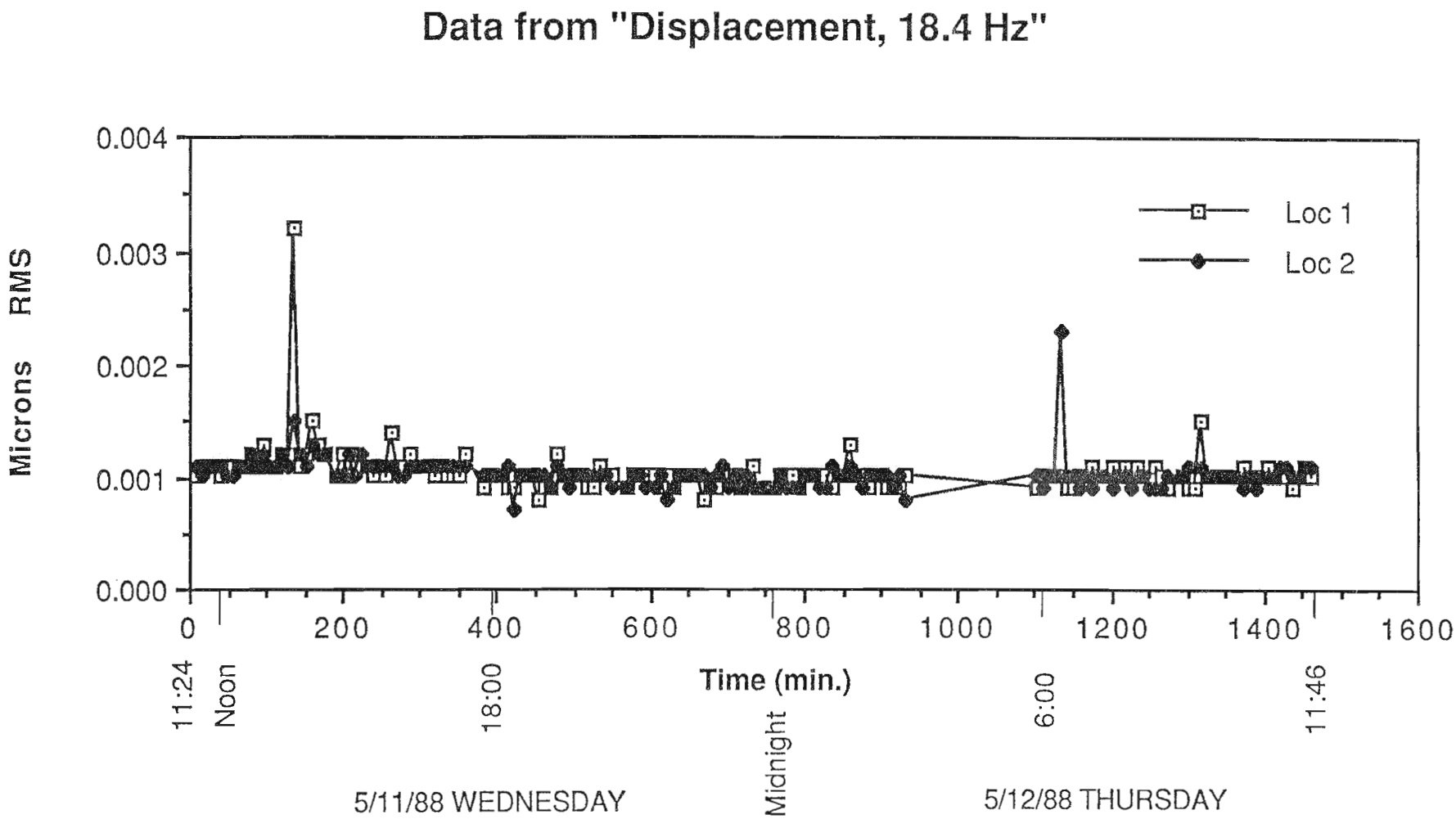

Fig. 23. 18.4 Hz Displacements at Locations 1 and 2

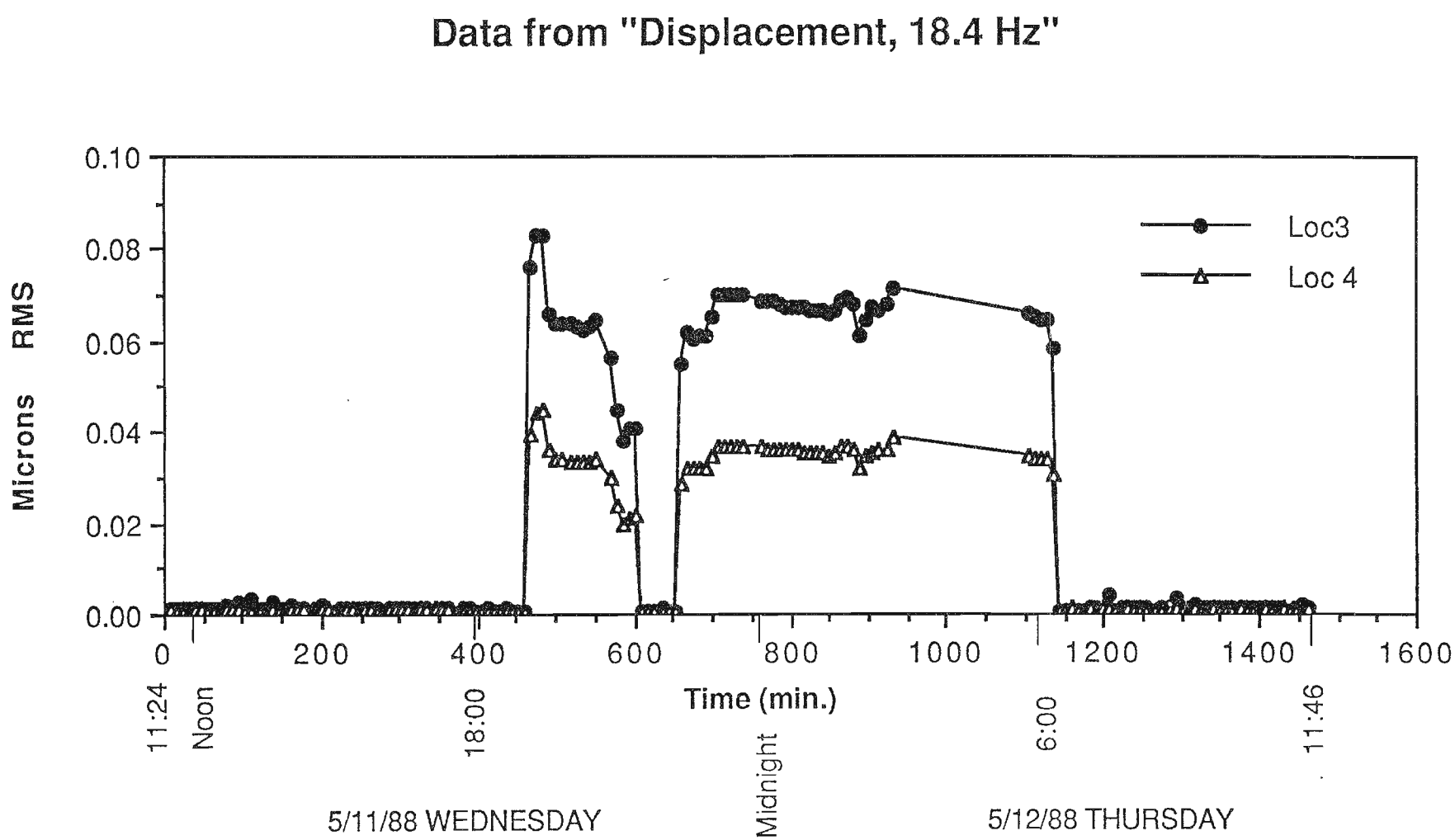

Fig. 24. 18.4 Hz Displacements at Locations 3 and 4

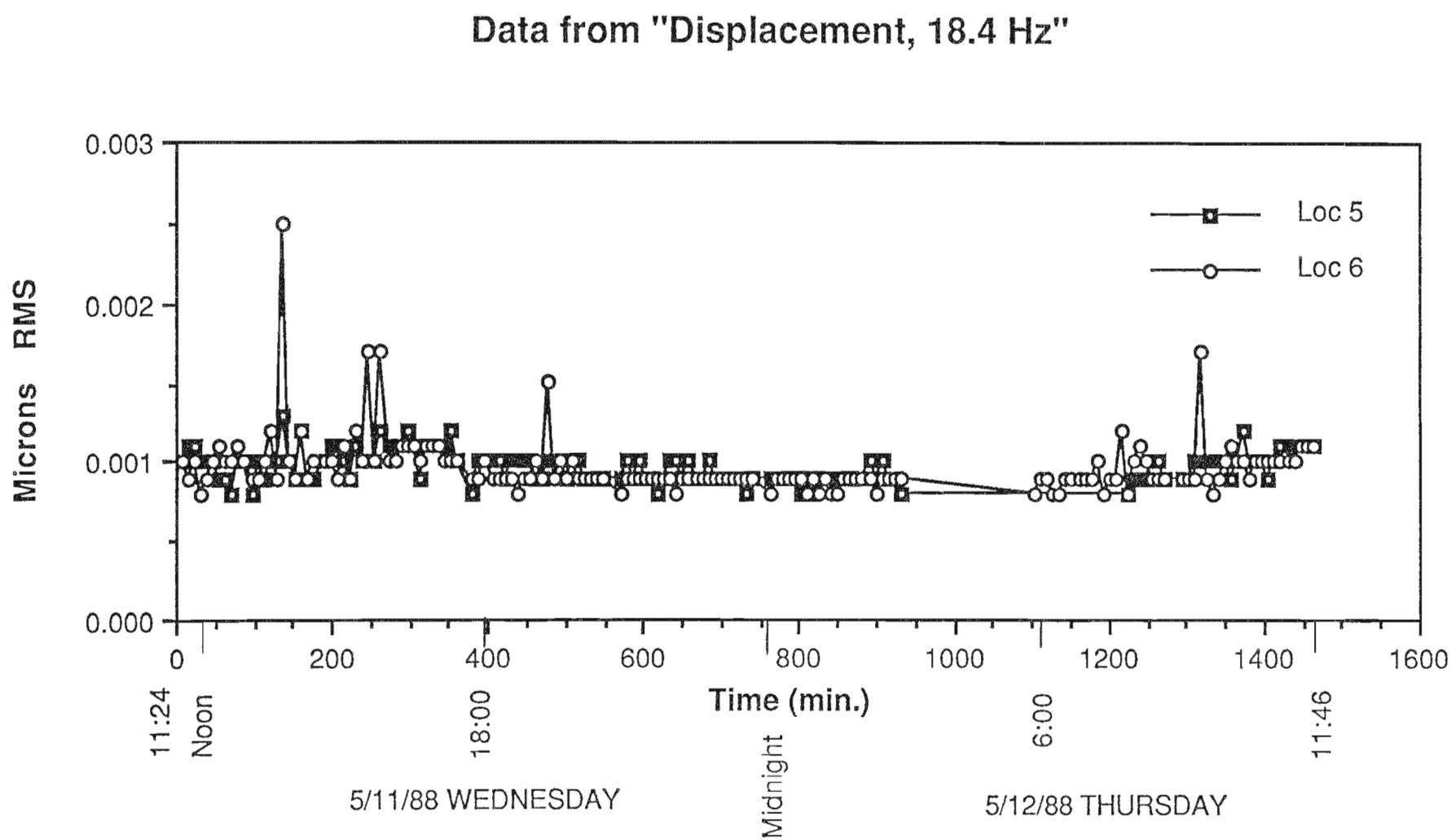

Fig. 25. 18.4 Hz Displacements at Locations 5 and 6

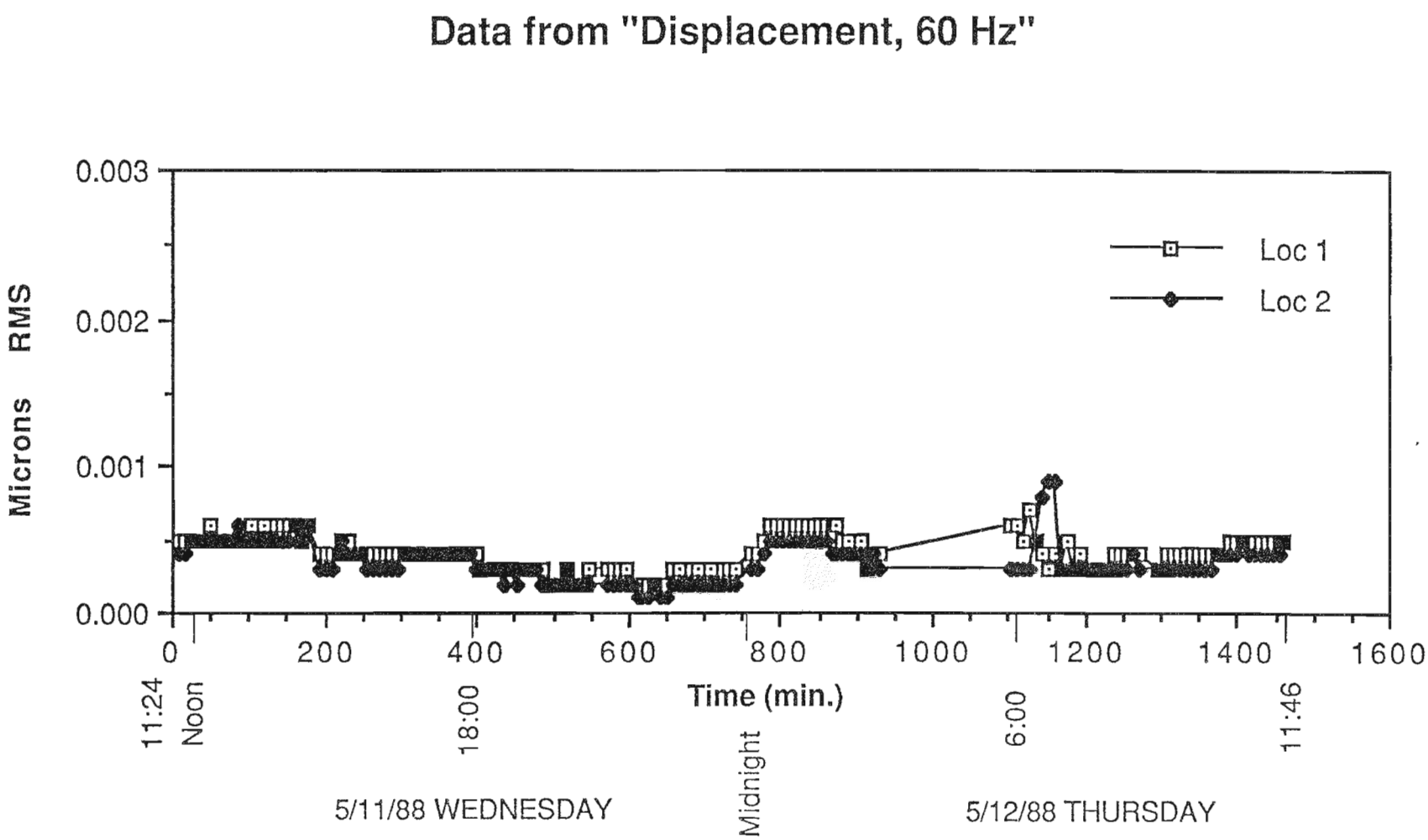

Fig. 26. 60 Hz Displacements at Locations 1 and 2

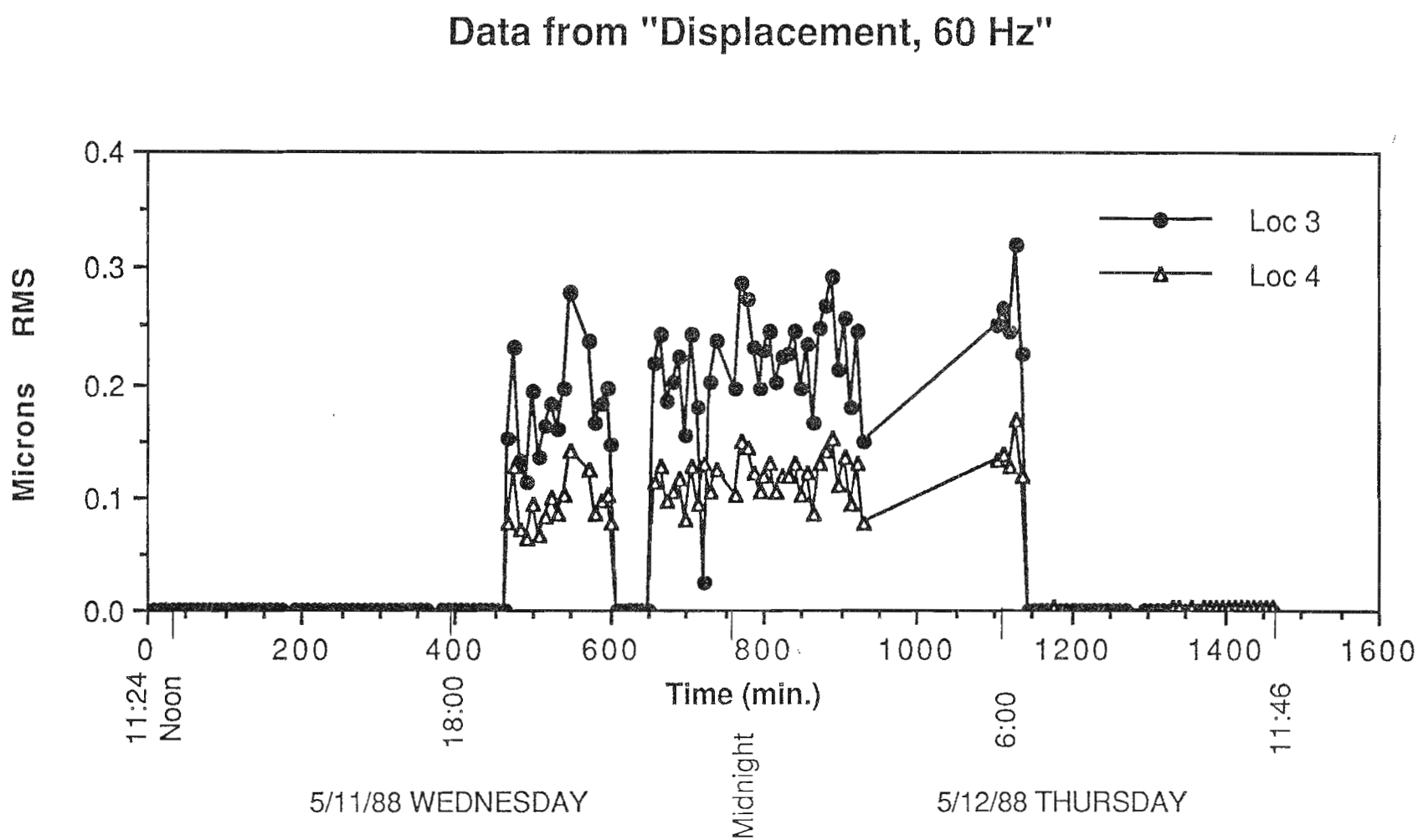

Fig. 27. 60 Hz Displacements at Locations 3 and 4

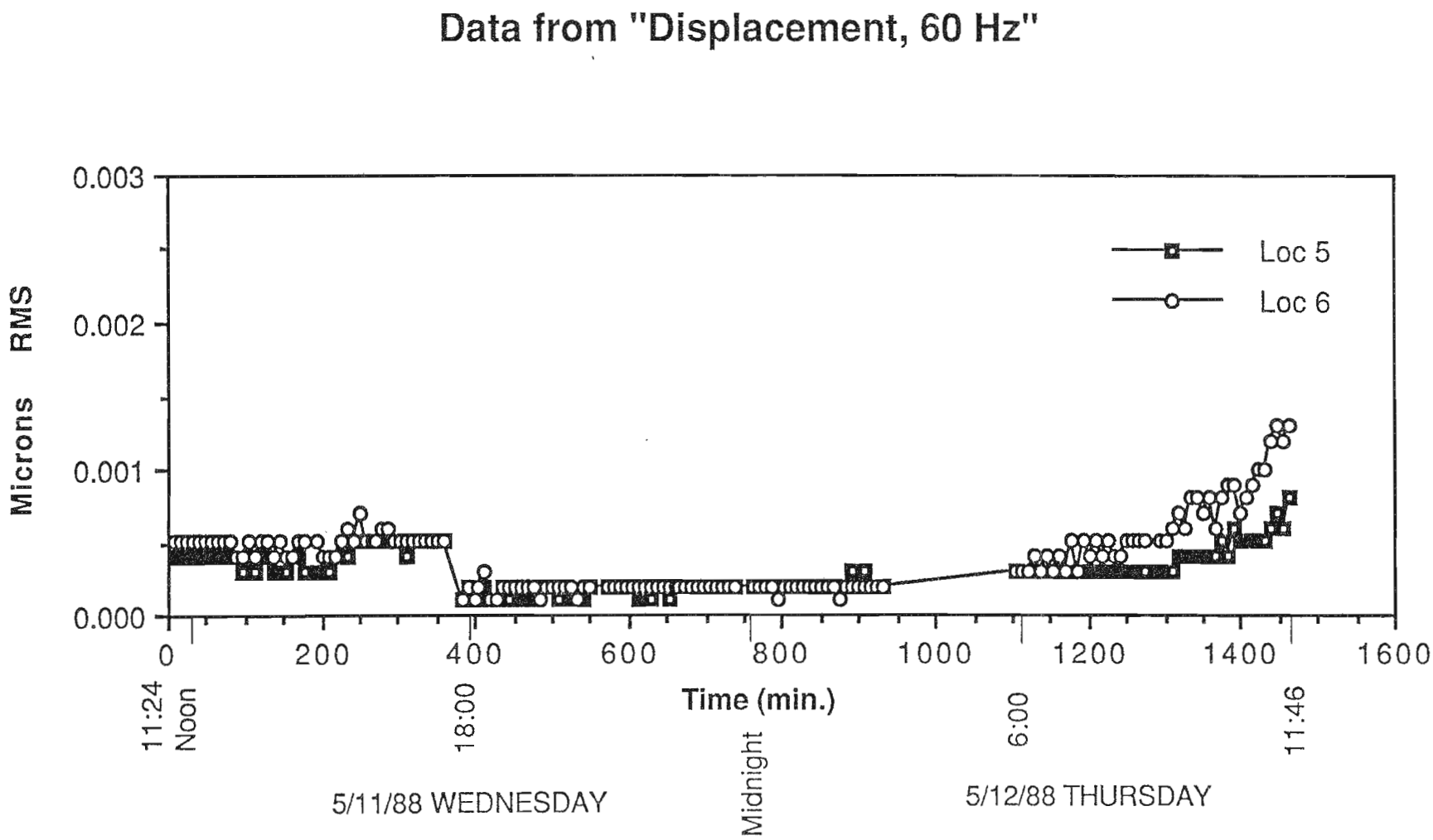

Fig. 28. 60 Hz Displacements at Locations 5 and 6

amplitude at location 3 to location 4 (Table 6) is 1.89 and similar calculation for 60 Hz is 1.92. This indicates a common excitation source exists. Another indication of a common source is Table 7, the ratio of 60 Hz displacement to 18.4 Hz displacement at locations 3 and 4. The ratio is not constant with time but is correlated between location 3 and location 4. A coarse investigation of the phase of the 60 Hz displacement at various times yielded a constant phase shift of 112° between the two locations.

Since the above measured displacements exceed the specified amplitude limit, they require additional investigation as to their source, transmission path, and elimination, or at least, reduction to an acceptable level. Due to the wavelength of the 18.4 Hz displacement with respect to the floor dimensions of the ring building, it may be the most critical frequency. From the above measurements several assumptions can be made: 1) Locations 3 and 4 are excited by a common source. 2) Based on the measurements and calculation of the soil attenuation factor (10.5 Hz displacement discussion) the source must be close to locations 3 and 4. If it was located any distance away, it will also be detected at the other four locations. Therefore, the source may be a pipeline running adjacent to locations 3 and 4 or possibly a waveguide, which is a transmission path from bedrock to the surface. It appears that, after consulting with Plant Services personnel at the ANL site, there are no utility pipelines in the area of the APS site. A similar 18.4 Hz and 60 Hz displacement (much smaller amplitude) was observed on a concrete octant of the ZGS ring building. Therefore, a reasonable theory is: the source is not located at the ANL site, but is transmitted through bedrock and coupled to the surface with a vertical channel, such as an old well casing form a residential well. The exploratory work in locating and identifying this source will be the subject of a later report.

4) Transient Displacements

The transients were first observed in Figs. 4 and 14. Table 8 summarizes the transients and the locations at which they were observed. To conserve space, only the 136 min, 208 min, and 421 min transients will be discussed as each has a unique characteristic.

The 136 min transient is shown in Figs. 29A and 29B. With a little imagination, times of arrival can be observed from the plots. These times can be used to calculate delay times (which are transit times) and are used to determine wave direction and velocity. Table 9 summarizes the 136 min delay times. From this data we can approximate an "R" wave velocity of approximately 1100 ft/sec with its source on Kearney Road about 250 ft

Table 6. Amplitude Ratios of Location 3 to Location 4

Time, min.	18.4 Hz			60 Hz		
	Loc. 3 μ, RMS	Loc. 4 μ, RMS	Loc. 3 / Loc. 4	Loc. 3 μ, RMS	Loc. 4 μ, RMS	Loc. 3 / Loc. 4
437	0.0012	0.0010	1.20	0.0008	0.0003	2.66
445	0.0010	0.0010	1.00	0.0007	0.0002	3.5
453	0.0010	0.0010	1.00	0.0005	0.0002	2.5
461	0.0010	0.0010	1.00	0.0006	0.0002	3.0
469	0.0765	0.0394	1.94	0.151	0.0761	1.98
477	0.0832	0.0443	1.88	0.233	0.127	1.83
485	0.0828	0.0449	1.84	0.132	0.0715	1.85
493	0.0657	0.0358	1.84	0.112	0.0621	1.80
501	0.0640	0.0339	1.89	0.193	0.0925	2.09
509	0.0638	0.0341	1.87	0.134	0.0655	2.05
517	0.0639	0.0335	1.91	0.163	0.0837	1.95
525	0.0632	0.0334	1.89	0.183	0.0994	1.84
533	0.0627	0.0333	1.88	0.160	0.0867	1.85
541	0.0630	0.0332	1.90	0.197	0.102	1.93
549	0.0648	0.0341	1.90	0.273	0.141	1.94
571	0.0566	0.0296	1.91	0.237	0.124	1.91
579	0.0451	0.0238	1.89	0.166	0.0867	1.92
587	0.0378	0.0198	1.91	0.183	0.0958	1.91
595	0.0405	0.0213	1.90	0.197	0.103	1.91
603	0.0408	0.0216	1.89	0.147	0.0766	1.92
611	0.0010	0.0010	1.00	0.0013	0.0009	1.44
619	0.0009	0.0009	1.00	0.00080	0.0005	1.60
		Avg. value	1.89*		Avg. value	1.92*

*Only high level amplitude averaged

Table 7. Amplitude Ratios of 60 Hz to 18.4 Hz at Locations 3 and 4

Time min.	Location 3	Location 4
437	0.666	0.300
445	0.700	0.200
453	0.500	0.200
461	0.600	0.200
469	1.97	1.93
477	2.80	2.86
485	1.59	1.59
493	1.70	1.73
501	3.01	2.73
509	2.10	1.92
517	2.55	2.50
525	2.89	2.99
533	2.55	2.50
541	3.13	3.07
549	4.21	4.13
571	4.19	4.19
579	3.68	3.64
585	4.84	4.84
595	4.86	4.84
603	3.60	3.54
611	1.30	0.900
619	0.889	0.556

Table 8. Transient Occurrence at Locations 1–6

Location	Transient Time					
	136 min.	208 min.	421 min.	1136 min.	1208 min.	1294 min.
1	x	x				
2	x	x	x	x		x
3	x	x			x	x
4	x	x				
5	x	x				
6	x	x				

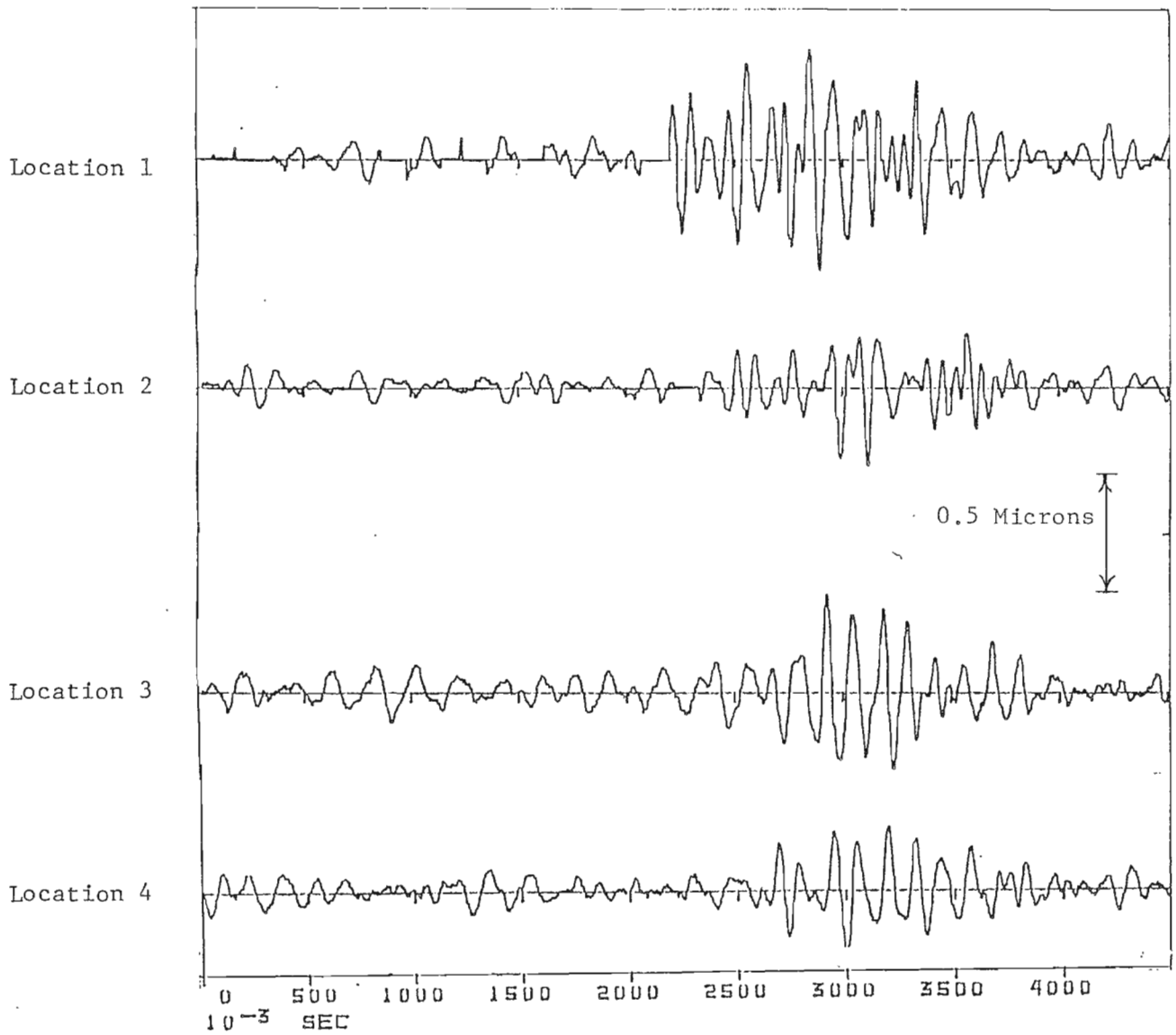

Fig. 29A. Transient Displacement at 136 Minutes for Locations 1, 2, 3, and 4

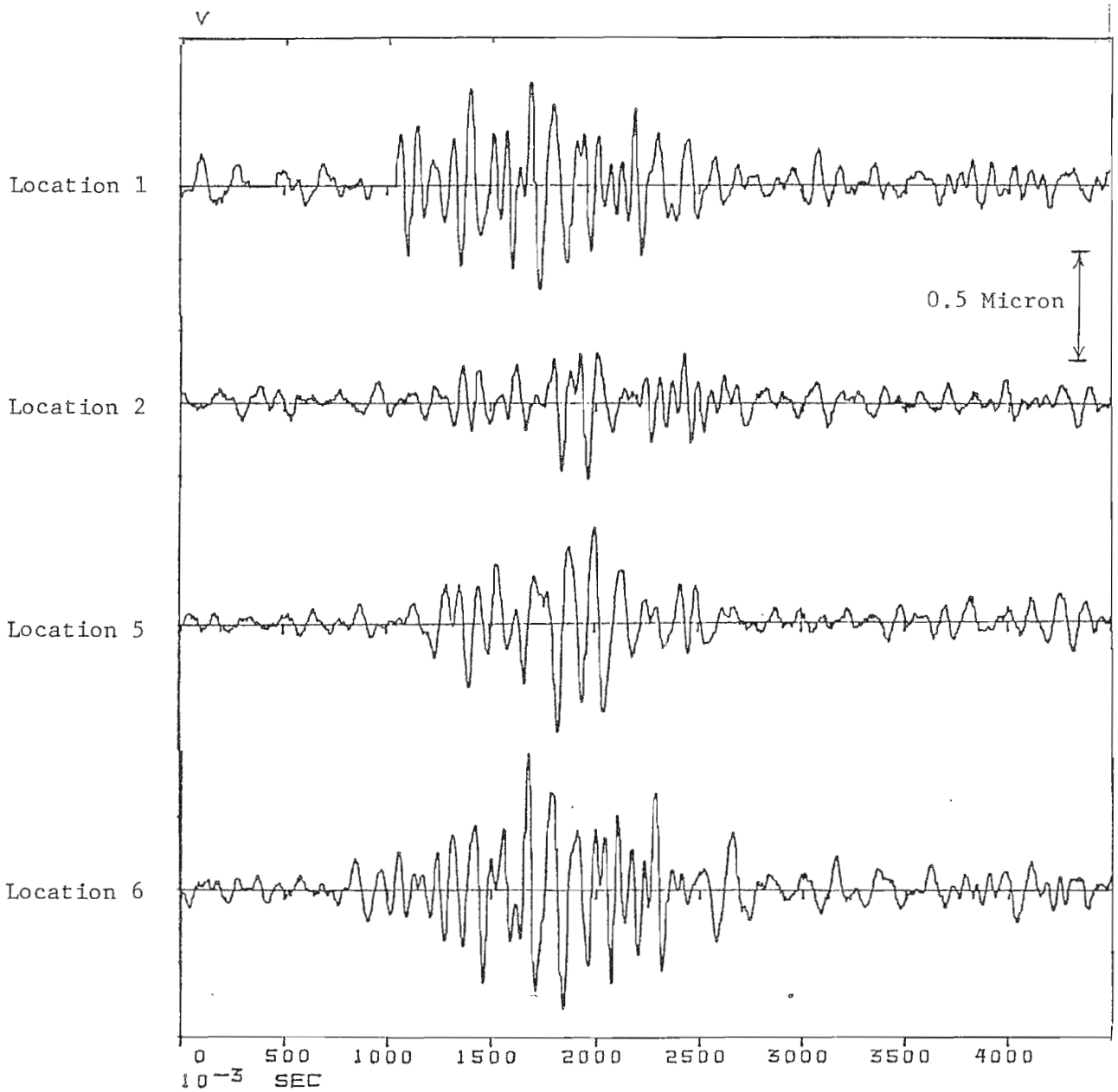

Fig. 29B. Transient Displacement at 136 Minutes for Locations 1, 2, 5 and 6

Table 9. Delay Times of 136 Minute Transient at the Six Locations

Location	Delay, sec
1	0.21
2	0.52
3	0.96
4	0.73
5	0.43
6	0–Reference

south of Bluff Road. Several large areas of the road (Kearney Road) were broken up and discontinuous. A large fork lift truck was in the area about the time the transient occurred, but no direct correlation was made.

The 208 min transient is shown in Figs. 30A and 30B. From the figures, it can be seen that this transient is much faster than the previous one. To obtain time information it was necessary to expand the time axis. Measured delay times are shown in Table 10. Here the delay times are much shorter, which results in an approximate wave speed of 19,900 ft/sec. Although this velocity appears to be very fast, after consulting with ISGS personnel, it was assessed to be a reasonable velocity for the Dolomite bedrock in the Chicago area. From the arrival times at various locations the direction of travel can be assumed to be from southwest (near the Lemont area) to northeast. The amplitude variation at the six locations is considerably less than that of the 136 min transient, which indicates that the transient was not caused by a local event.

Another transient occurred at 421 min, Fig. 31, which corresponds to a time of 6:25 PM. However, the transient was localized to the location 2 area. White deer were seen in the vicinity from about 6:00 PM to 7:30 PM and may have generated the transient by running near the transducer.

In summary, three types of transients were observed: 1) a local disturbance of sufficient energy to be detected at all locations (136 min), 2) a far field event which was also detected at all locations (208 min), and 3) a local disturbance in the vicinity of one location of too low an energy level to be measured at the other locations.

Concluding Remarks

The ambient ground motions measured have been investigated in detail to provide a basis to investigate further the following two areas of concern.

- The 18.4–60 Hz excitations at locations 3 and 4,
- Transient excitations.

The 18.4–60 Hz excitations are of primary concern because (1) the vibration amplitudes exceed the vibration criterion for the APS magnets and (2) the 18.4 Hz frequency is in a "range of concern" as it is in the range of expected soil–foundation resonant frequencies and is close to the upper bound on the frequencies which can be corrected by the APS control systems. To investigate the 18.4–60 Hz excitations, a continuous monitor

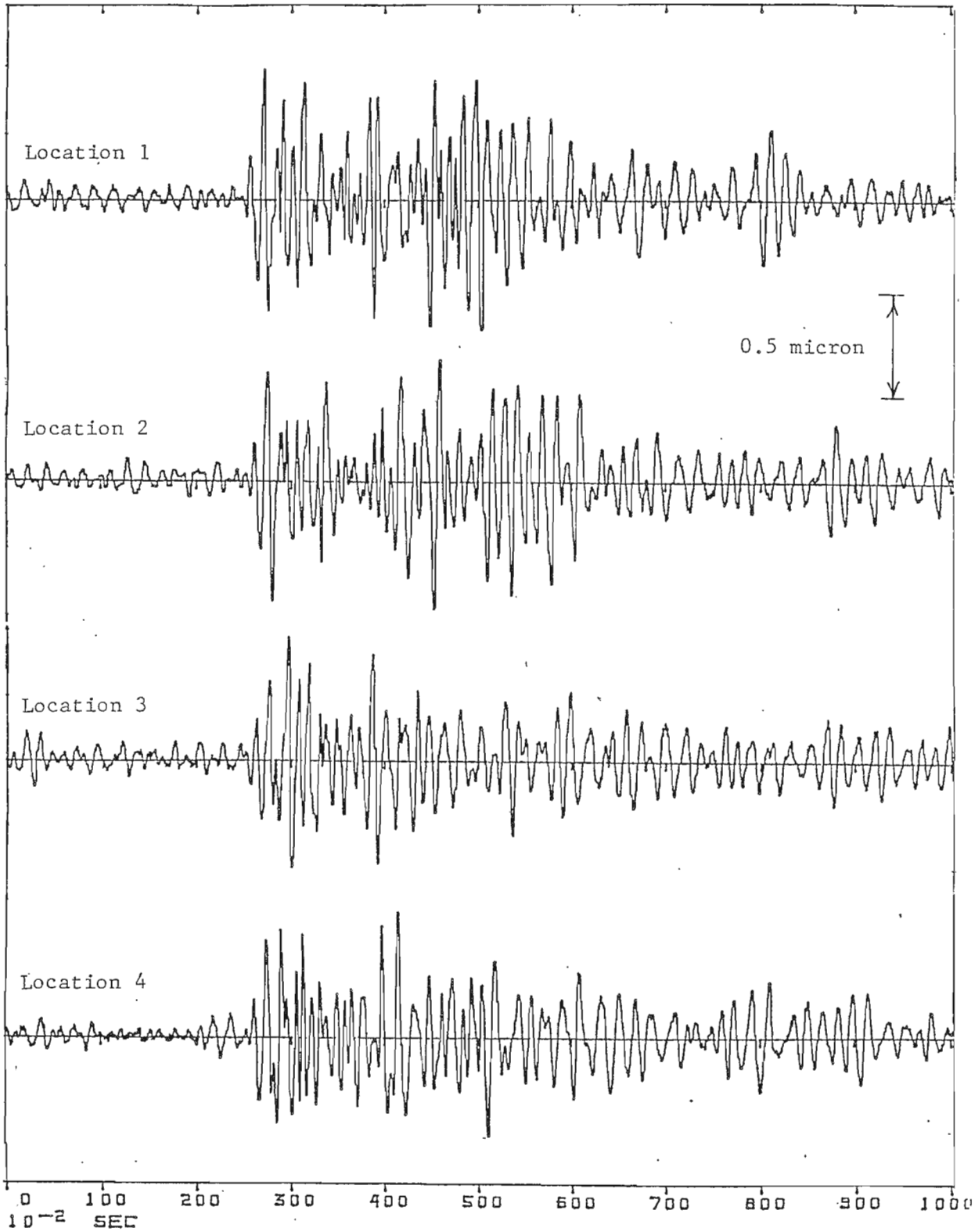

Fig. 30A. Transient Displacement at 208 Minutes for Locations 1, 2, 3, and 4

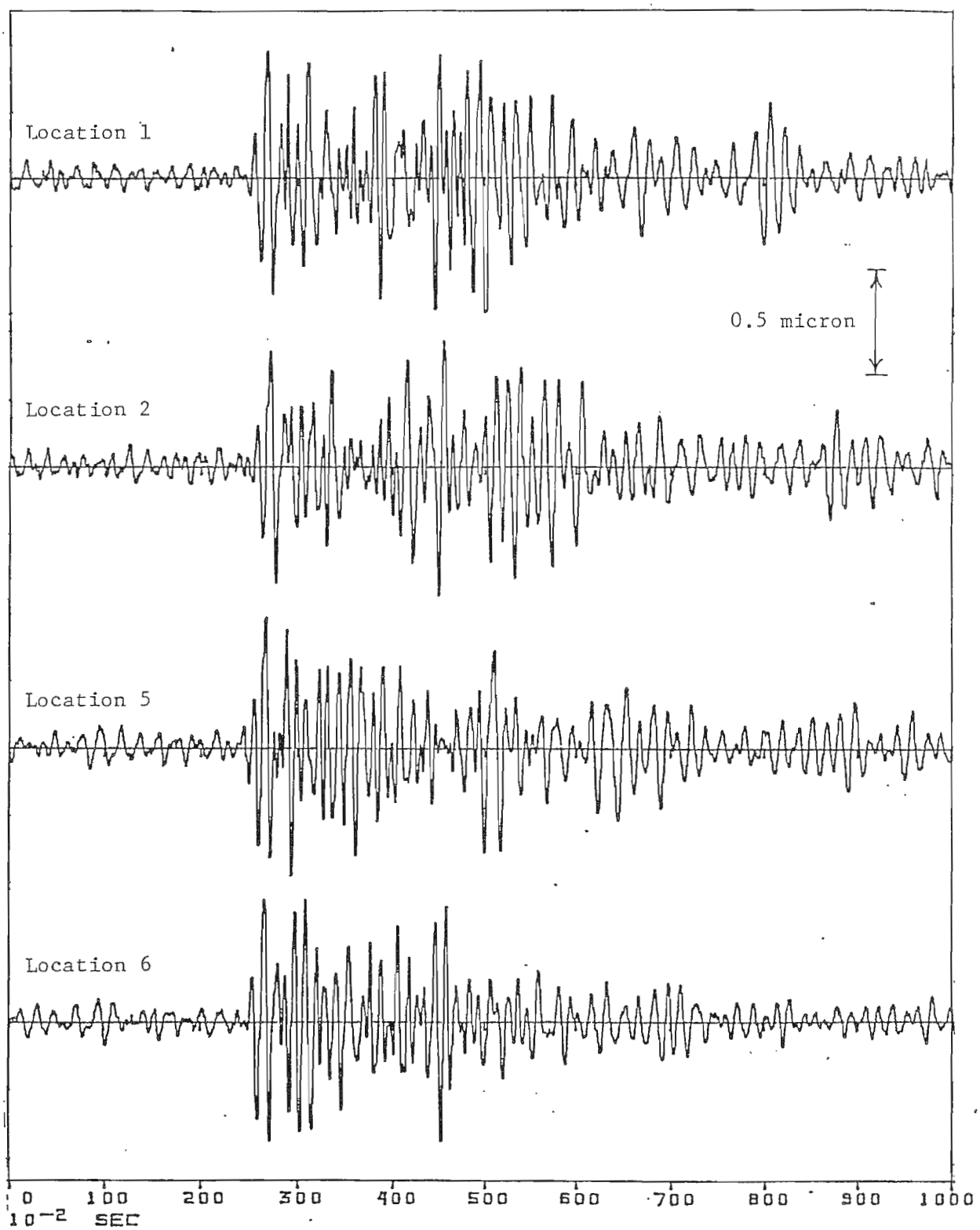

Fig. 30B. Transient Displacement at 208 Minutes for Locations 1, 2, 5, and 6

Table 10. Delay Times of 208 Minute Transient at the Six Locations

Location	Delay, sec
1	0.014
2	0.045
3	0.060
4	0.030
5	0.000–Reference
6	0.016*

*Questionable delay time

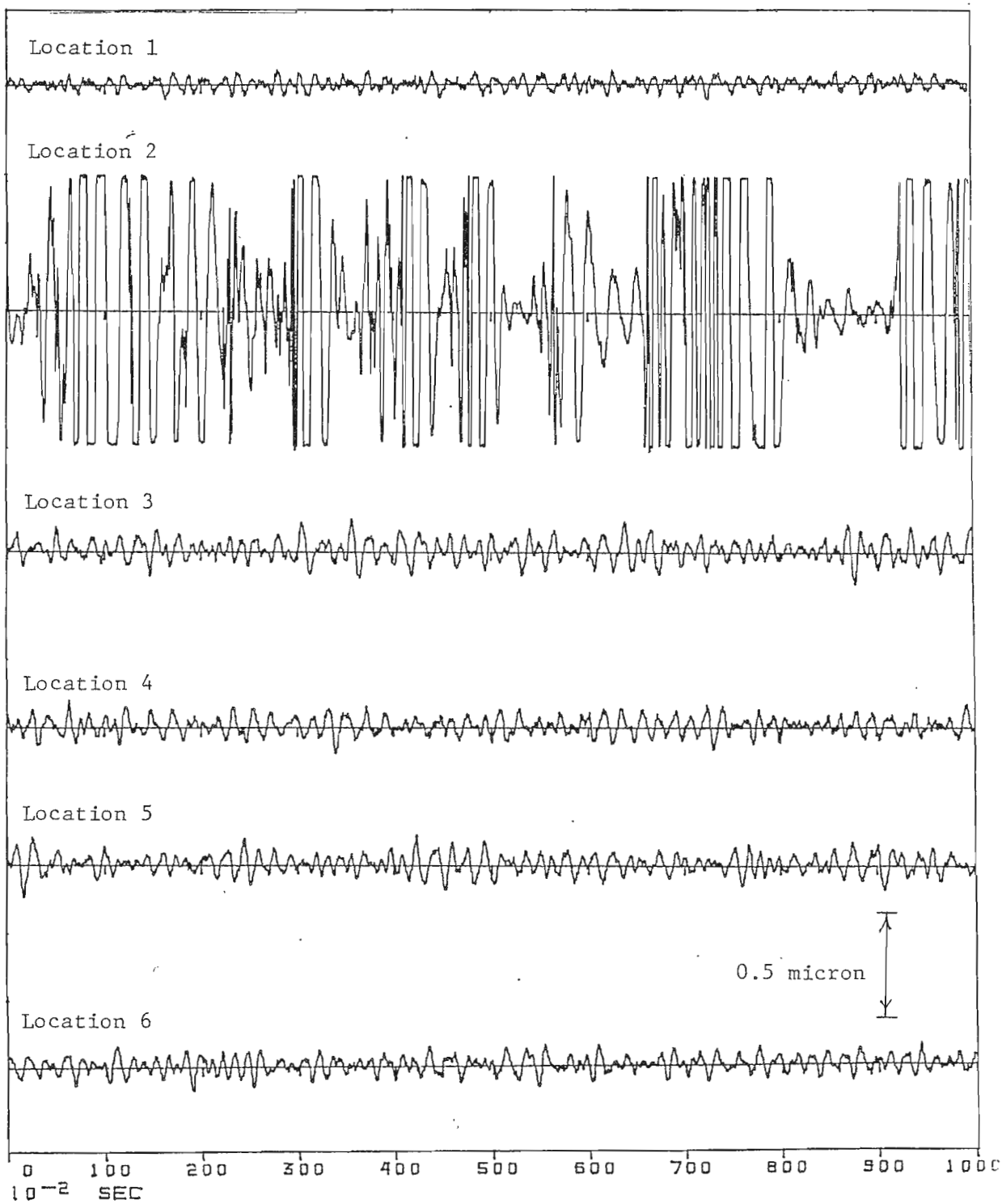

Fig. 31. Transient Displacement at 421 Minutes for Locations 1-6

near location 3 has been in operation since 7/28/88. Since that time the excitation has been observed only 4–5 times. If it reappears on a predictable schedule, instrumentation will be used to determine its location, the coupling mechanism, and possible action to eliminate or minimize it. An attempt to correlate its occurrence to surface groundwater level has been inconclusive.

The amplitude of the transient excitation is very high (≈1.2 micron, peak–to–peak) but it is of short duration and contains many frequencies. Therefore, the effect on a mechanical resonant system can be considered minimal. Nevertheless, we plan to monitor transient response at the APS site, but unless an unusual occurrence is observed, analysis will be minimal.

References

1. J. A. Jendrzejczyk, M. W. Wambsganss, and R. K. Smith, "Ambient Ground Motion Measurements at Argonne National Laboratory Over Extended Time Periods," LS–111, March 1988.

2. F. E. Richart, Jr., J. R. Hall, Jr., and R. D. Woods, "Vibrations of Soils and Foundations," pp. 244–247.