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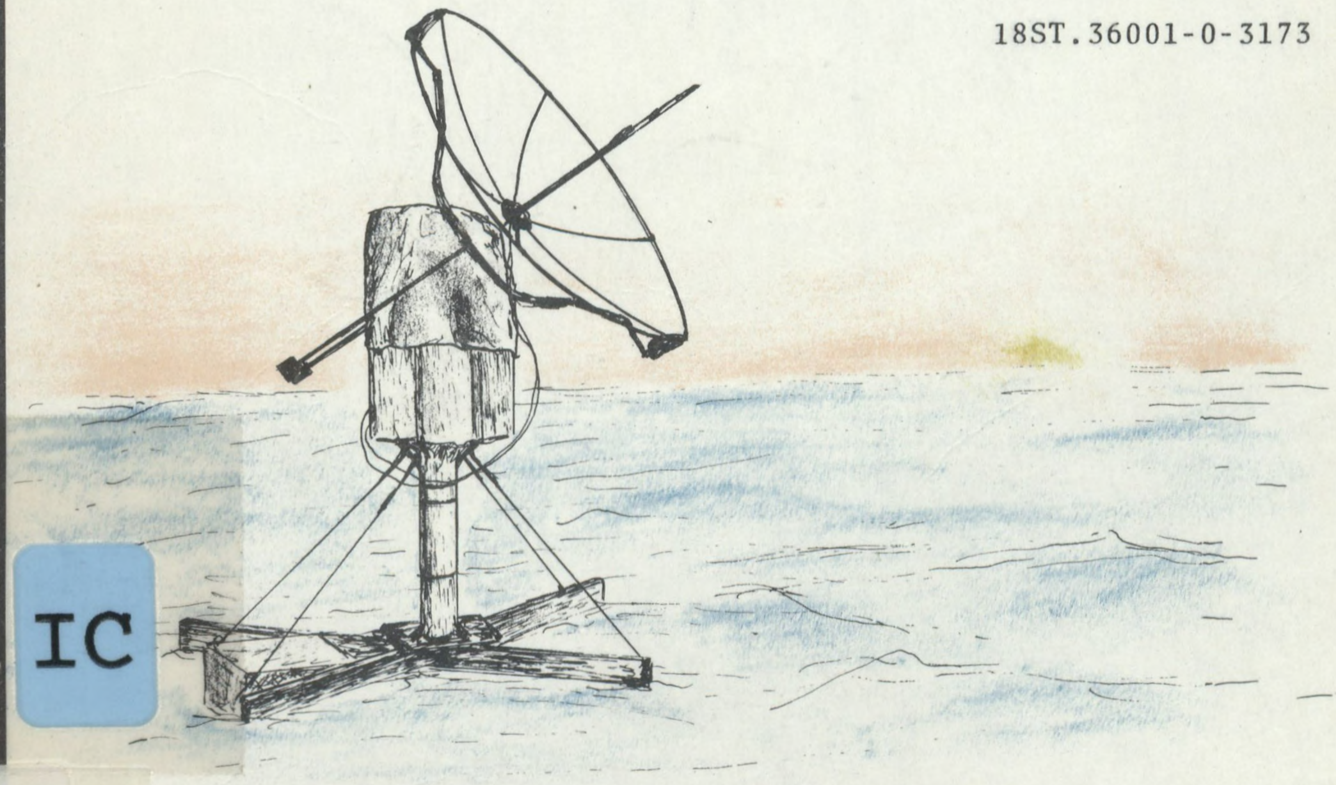
Centre for Radio Science

OPERATION OF AN EXPERIMENTAL MICROWAVE LINK BETWEEN OTTER LAKE, N.B. AND AYLESFORD, N.S.

A.R. Webster and W.I. Lam

Final Report

DSS Contract No.
18ST.36001-0-3173



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Operation of an Experimental Microwave Link between Otter Lake, N.B. and Aylesford, N.S.

A Final Report under

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University of Western Ontario

London, Canada

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Report prepared by: A.R. Webster

Introduction

A microwave diagnostic system designed to investigate anomalous propagation effects on terrestrial microwave systems, was operated on a path traversing the Bay of Fundy from Aylesford, N.S. (transmitter) to Otter Lake, N.B., (receiver) during the late summer/early fall of 1980: fig. 1 shows the geographical layout of the link. The equipment itself has been described in detail in previous reports (see report DSS Contract 03SU.36001-9-1599), and fig. 2 gives a brief summary of the main features. In essence, the system sweeps in frequency over a wide range (1 GHz), and amplitude and phase measurements derived from the signals received on two vertically spaced (3 m.) antennas allow the determination of several important properties of rays in single and multipath situations: these properties include amplitude, angle-of-arrival and relative delay between paths.

Additional measurements were made using a digital radio bit error rate system supplied by C.R.C. Some difficulties were experienced in the operation of this system, although it is believed that some useful data were recorded. These data are presently with C.R.C. and due to other pressures remain unprocessed. However, it is hoped that useful information will be available shortly to complement the analysis of data obtained from the diagnostic system.

At the present time the diagnostic system has been returned to the Bay of Fundy and is operating on a somewhat different experimental link in collaboration with Maritime Tel. and Tel. and New Brunswick Tel. This might be regarded as the second phase of these series of measurements and it is anticipated that the results of these two operational periods will provide considerable insight into the propagational properties in this difficult geographical area.

The Path Profile

Fig. 3 shows representative path profiles based on constant gradient with height in refractive index: the terrain profile refers to the height of the land surface above mean sea level and an additional height of perhaps 10 m. to allow for trees might be appropriate. The indicated antenna heights are those used by the diagnostic system and are comparable to the heights used in previous experimental digital radio measurements at the same sites. The angles quoted in fig. 3 refer to those expected at the Otter Lake site, the location of the diagnostic system receiver. The variation in angles (discounting possible terrain blockage), together with delay between reflected and direct path, all as a function of earth radius factor K are shown in fig. 4; it should be noted that the path length difference, and hence delay time, presented is phase path length rather than physical path length.

At the points A and B in fig. 3, a clearance of 10m and 20m respectively represents one half of one Fresnel zone so that these features would be expected to provide some degree of protection against the ray reflected from the sea, at least for low values of K. As the atmospheric refraction increases, the reflected ray will be raised to the point where it will clear the obstacles resulting in potential deep fading at K values equal to perhaps 5 or greater. Antenna discrimination is not likely to be of too much help since the angle of arrivals for the direct ray at K = 4/3, say, (the "normal" situation) and the reflected ray at K = 10, say (the abnormal situation), differ by only 0.1 deg or so. In fact, should the antennas be narrow beam and aligned at a quiet time when K = 4/3, then for K = 10, for example, the signal from the reflected ray is potentially greater than that from the direct ray due to the elevated angles of arrival.

The above is intended to provide a starting point only in the discussion of the sea reflection problem and is based on the simplifying assumption of constant gradient in refractive index. In fact, the refractive profile over the 300 m in height and 80 km in length involved would be expected to depart significantly from this simple picture due to the heavy influence of the sea on temperature and humidity. Nevertheless, a potential sea reflection problem does seem to exist for this link, which is borne out by some of the results to be presented here.

Experimental Results

Observations were made, with samples at 10 second intervals, over the period 4 September to 2 November, 1980, with an accumulation of some 50 MBytes of good data. An immediate impression was gained (from ancillary analog data) that a strong and persistent second path was present for a good proportion of the time, suggesting a reflection from the sea.

Fig. 5 shows 3 consecutive amplitude and phase records which have been fully processed to give the path parameters shown; here pattern synthesis has been employed to fit the experimental data. The angles shown have been corrected for a 7 mm difference (in a nominal 1.5 m) in waveguide lengths feeding the two mixers, discovered on subsequent careful measurement, resulting in a correction of 0.36 deg to the synthesized angles: this resolves an apparent discrepancy of about 0.4 deg in the derived angles and those predicted from ray-tracing as noted in an interim report. A comparison between experimentally determined parameters and those expected from ray-tracing (as in fig. 3), assuming a sea reflection, show good agreement for a constant refractivity gradient with K = 1.50, as may be seen in Table 1. It should be noted that a systematic uncertainty exists in absolute angle-of-arrival, due to an uncertainty of ± 0.5 cm or so in 300 cms in the vertical alignment of the receiving antennas; the <u>difference</u> in angle-of-arrival is somewhat more precise, being dependent only on the accuracy of phase measurement.

Table 1

Path parameters relating to fig. 5a; subscripts 1 and 2 refer to the direct and sea-reflected paths respectively

	θ_1^0	θ_2^0	$\Delta\theta_{21}^0$	ΔL, m
Experimental	-0.34±0.1	-0.59±0.1	-0.25±0.02	0.862
Ray Tracing (K = 1.50)	-0.265	-0.519	-0.251	0.866

The existence of a strong sea reflection, at least at the time indicated, seems to be established beyond doubt by fig. 5 and Table 1. The change in amplitudes in the two paths between sweeps is to be noted, however, and it is of interest to see what is the behaviour of the associated fading as a function of time. Fig. 6 shows 3 consecutive sweeps (amplitude only) at the turn of each hour for some 36 hours, and several points of interest emerge. First, significant changes sometimes occur between successive sweeps, suggesting fairly rapid changes, but most of the time such sweeps are quite similar. Second, if it is assumed that regular fading is the result of a sea reflection, then such a reflection is in fact absent as often as not. Third, evidence of extra paths, over and above the direct and the sea-reflected, appear from time to time (see, for example, 17.00 and 18.00 A.D.T. on 5 September). Such extra paths are almost certainly propagated entirely in the atmosphere rather than via a sea reflection. Fig. 7 attempts to summarise some of the information contained in fig. 6 and shows average fade depth and associated delay time between paths at times when a clear two path situation is indicated. The state of the tide in the Bay of Fundy might be expected to influence the sea reflection, providing greater clearance at high tide, and this seems to be partially borne out in fig. 7 where it may be seen that an apparent sea reflection occurs at two of the high tides. However, at that time the variation in sea level was "only" ± 3 m and the impression is gained from these and other records that the level of the sea plays only a secondary role in deciding whether or not a sea reflection is seen. Atmospheric conditions appear to be of much greater significance in this context.

As mentioned above, changes in propagation conditions occasionally occur quite quickly and this is well illustrated in fig. 8 where records spaced at 30 second intervals over a period of one hour are presented. From this it may be seen that significant changes occur within a period of a minute or two from time to time. For example, at about 16.31 A.D.T. a strong second path appears and then retreats within the space of 4 records, as presented, that is over a period of 1.5 minutes; a similar occurrence is witnessed at about 16.41 A.D.T. A somewhat longer interval for the same effect is seen at about 16.49 A.D.T. The appearance and disappearance of more complicated multipath, with similar time scales, is seen at about 16.59 and again at about 17.07 A.D.T. Figs. 9 and 10 present two of these intervals (16.31 and 17.07) at full resolution, that is 10 second sampling interval, in which the developments may be followed more closely. The former shows a relatively ordered progression, but the latter shows evidence of more rapid change from sweep to sweep.

The general impression created by figs. 6-10 is of a second path (probably sea reflected) whose influence waxes and wanes in times in the order of a minute or two, accompanied by the occasional appearance of extra rays (probably purely atmospheric) which causes more rapid change in the order of tens of seconds or even seconds.

Discussion

A substantial quantity of experimental data was accumulated during the observing period and while this is clearly desirable, it does present handling problems. Considerable time has been spent in developing automatic routines to extract the large amount of relevant information which is undoubtedly contained in the recorded data and much remains to be done. It is hoped that some information regarding the times of occurrence of errors in the previously mentioned digital radio system will become available in order to narrow down the search. A full digital radio system is operating concurrently with the present (August 1981) observations in the Bay of Fundy and this should facilitate matters considerably in the analysis of the recorded data. A look at the combined data from 1980 and 1981 should provide a substantial insight into the propagation phenomena which make the Bay of Fundy so difficult an operational area.

Much remains to be done, then, but some important features do seem to be emerging. It seems that for a good portion of the time, perhaps more than 50% (see fig. 6), all is quiet and single-path conditions, with no more than a trace of a second path, prevail. However, a second path reflected from the sea occurs on a significant number of occasions and this can result in quite deep fading. When present such fading can, and does, change in depth fairly quickly in times in the order of a few minutes. The delay time between reflected and direct rays changes more slowly, (over tens of minutes to hours) and seems to involve delay times in the range 2-6 nsec which is consistent with ray-tracing predictions. An interesting aid to the reader is provided by the fact that the numbers work out such that the delay between two paths in nsec is equal to the number of complete fading cycles in the amplitude record across the 1 GHz band.

On top of the regularly appearing reflected ray there appears, it seems, from time to time an additional path (or paths) which exhibit quite rapid changes and result in deep fades on occasion. At the present time, analysis has not proceeded sufficiently far to develop a "feel" for the amplitude and delays involved in these presumably atmospheric rays: this aspect will be given high priority in the continuing analysis.

Whether or not the sea-reflected ray would produce on its own unacceptable errors in a digital radio system is a question which demands a detailed knowledge of the actual equipment and modulation scheme; speculation on this point is perhaps beyond the scope of this report at the present time. However, it is perhaps noteworthy that the delay times involved (2-6 nsec) seem to be rather short. Whether or not the amplitude and phase distortion across the radio band would cause errors to arise is a question which might be answered readily by engineers intimate with the actual system involved. Fig. 11 shows these distortions for a delay time of 5 nsec and it may be seen that a phase shift approaching 180 deg (-90 deg to +90 deg) occurs at the amplitude minimum: a deep fade rapidly sweeping across the band might well cause upset within the modulation scheme.

It may be that neither the sea-reflected ray nor an atmospheric ray (which is bound to occur from time to time) would in itself produce grave difficulties, but that in combination the effects are more serious. The present measurements involving simultaneous operation of the diagnostic system and a digital radio should shed light on this aspect.

As a final note, although not part of the original contract proposal, a review of microwave angle of arrival for submission to C.C.I.R. (International Radio Consultative Committee) was requested by C.R.C. to be included as part of this contract. This was duly submitted to CNO/CCIR Study Group 5 and has been submitted, with minor editorial changes to C.C.I.R. in Geneva. A copy of the submission is included here as an Appendix.

LIST OF FIGURES

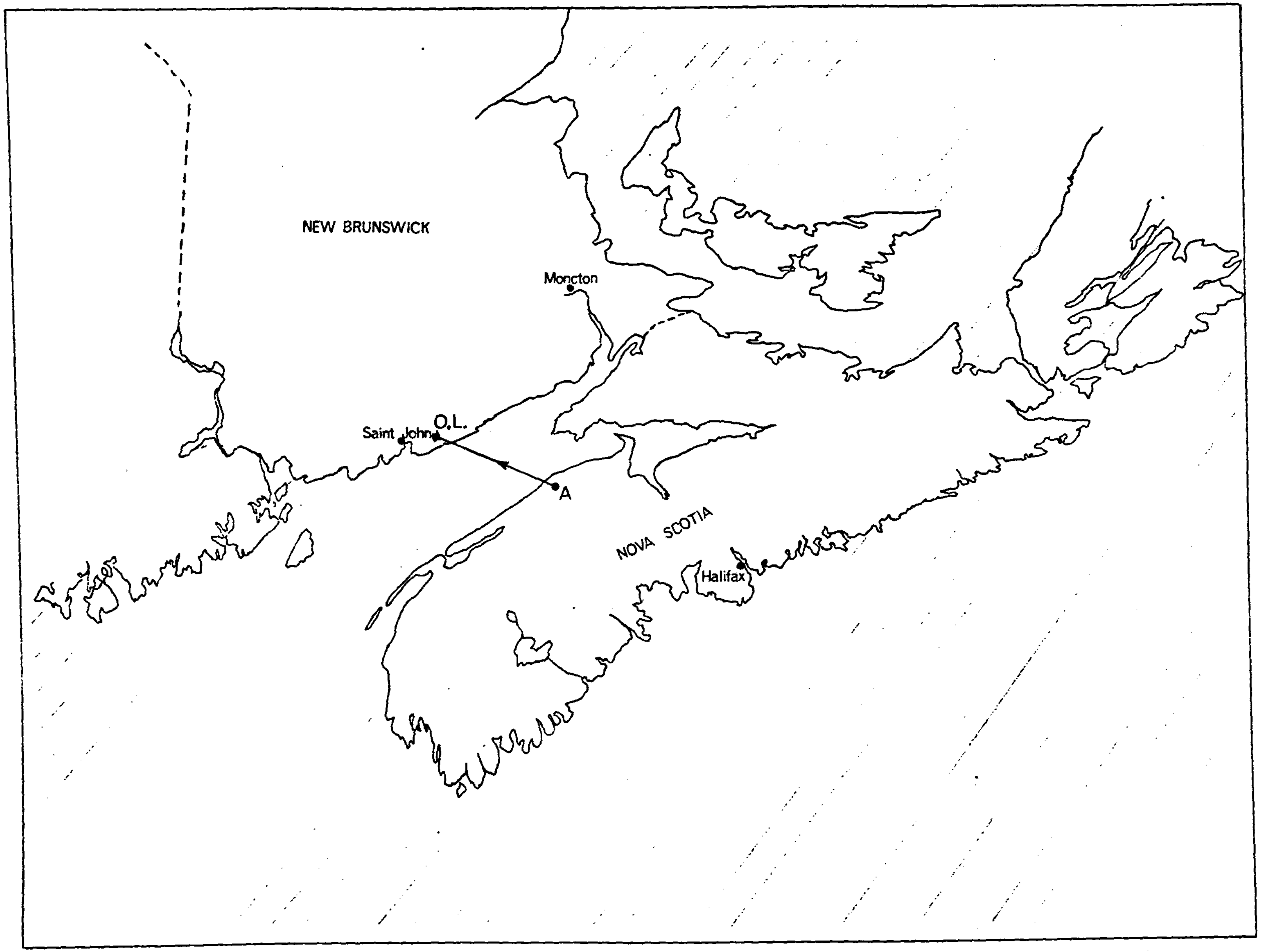


Fig. 1 The Bay of Fundy and microwave link (Aylesford-Otter Lake)

Transmit power:	2 W
Transmit antenna:	8' diameter paraboloid
Receive antenna:	2' diameter paraboloid vertically spaced 3 m
Frequency sweep:	9.500-10.508 GHz, 16 MHz steps, 64 steps total
Sweep time:	1.28 s
Repetition period:	10 s
Recording:	digital, 8 bit each, amplitude and phase
Path length:	80.25 km

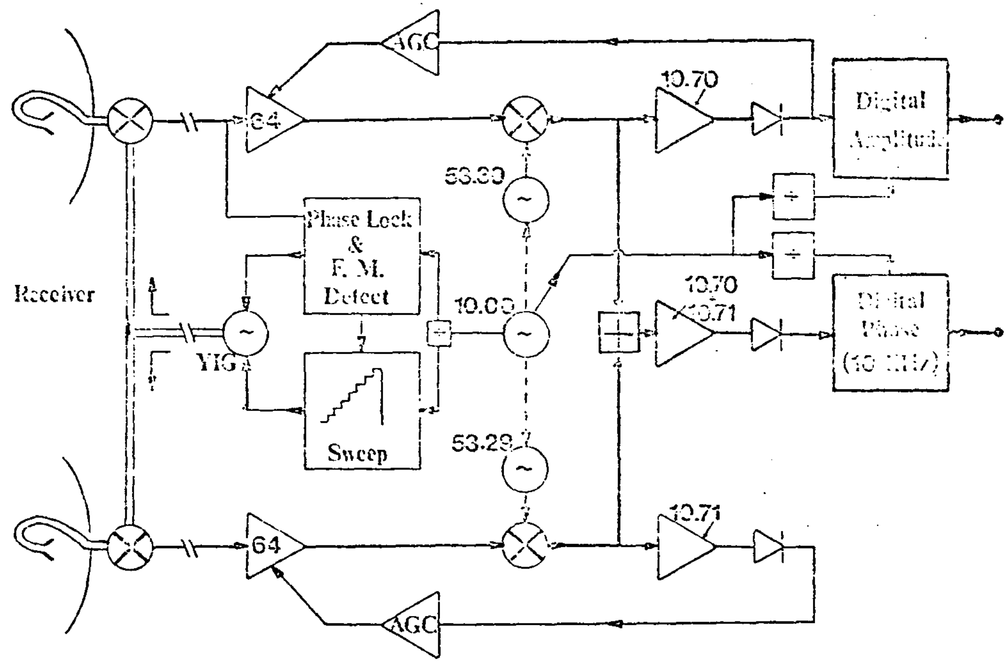


Fig. 2 Equipment details

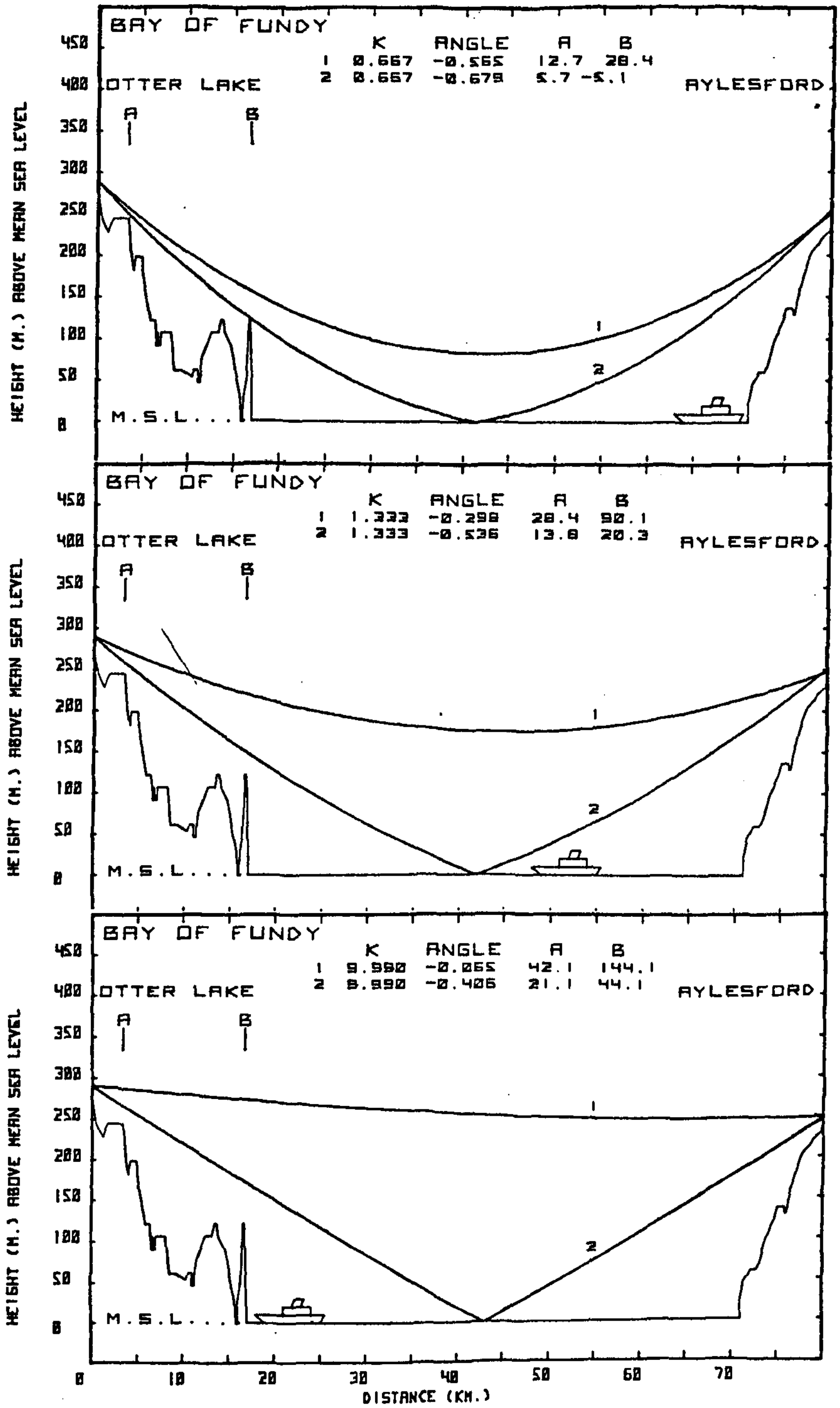


Fig. 3 Path profiles for different values earth radius factor, K; the angles are those seen at Otter Lake and the clearance at A and B, in m., is that above the land surface

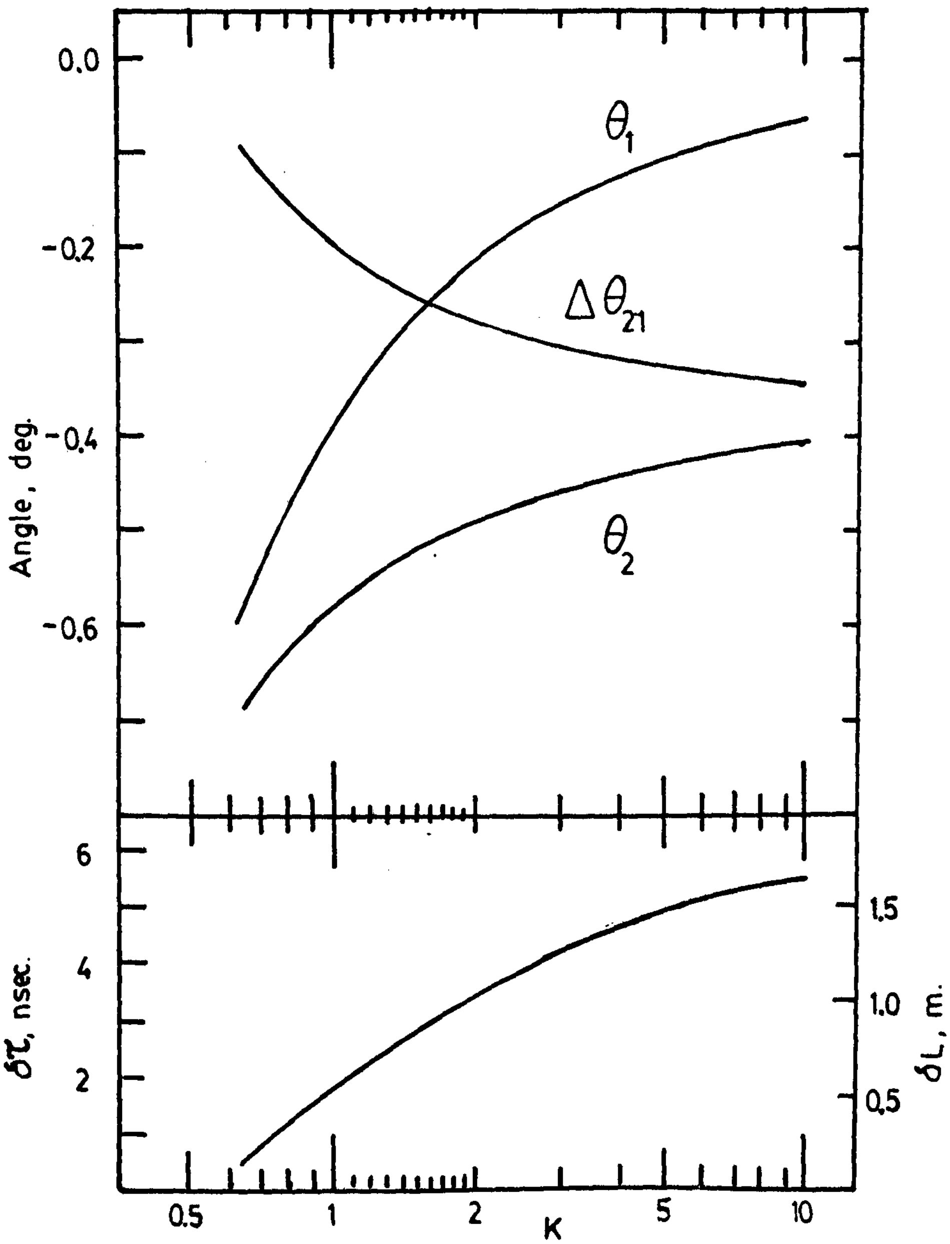


Fig. 4 Expected angles of arrival at Otter Lake of the direct (1) and sea reflected (2) rays, and the difference between these angles, together with path delay of the reflected relative to the direct ray, all versus earth radius factor K; derived from a ray-tracing routine as in fig. 3, and possible terrain blockage not taken into account

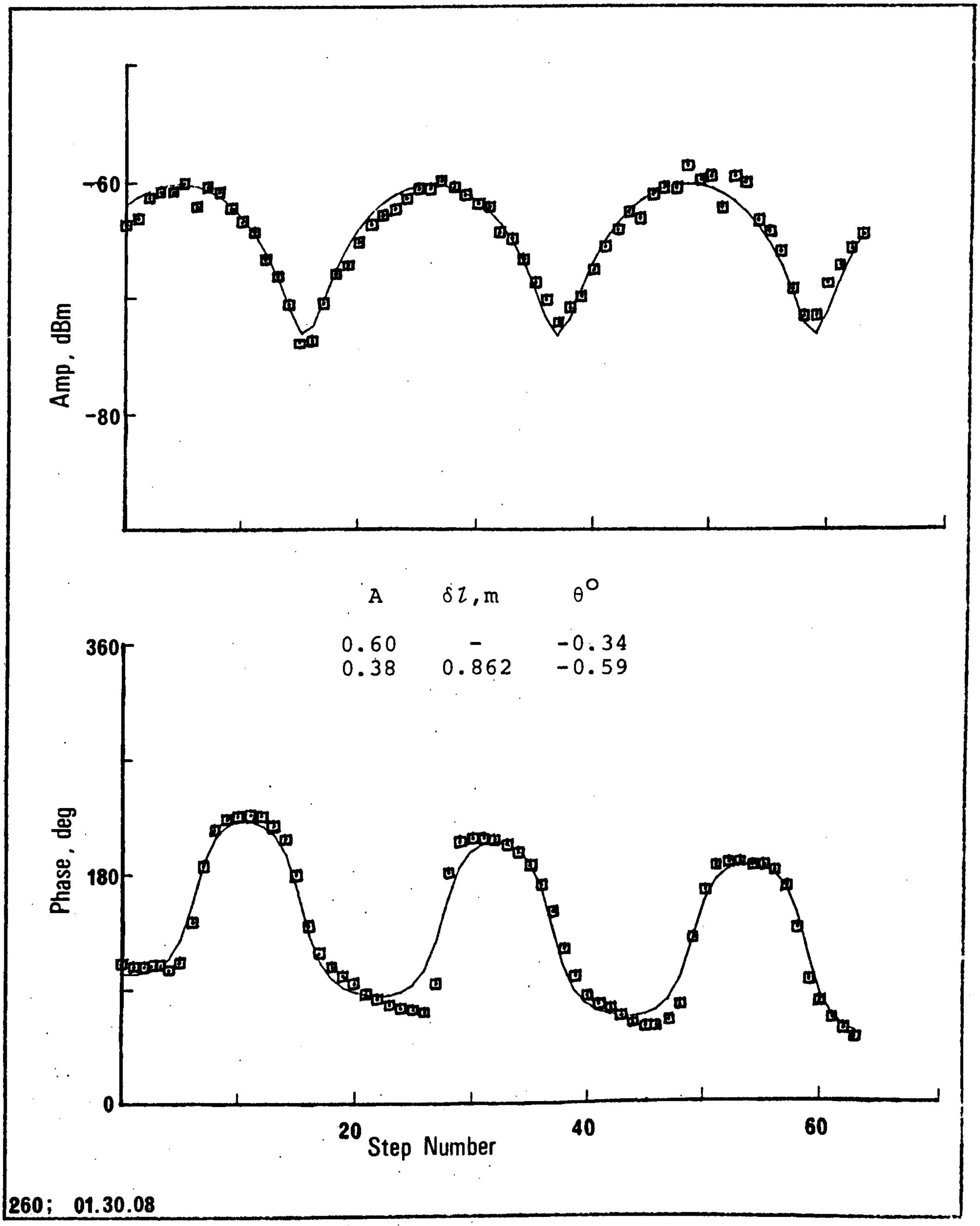


Fig. 5a Experimental and synthesized records (16 Sep.1980; day 260)

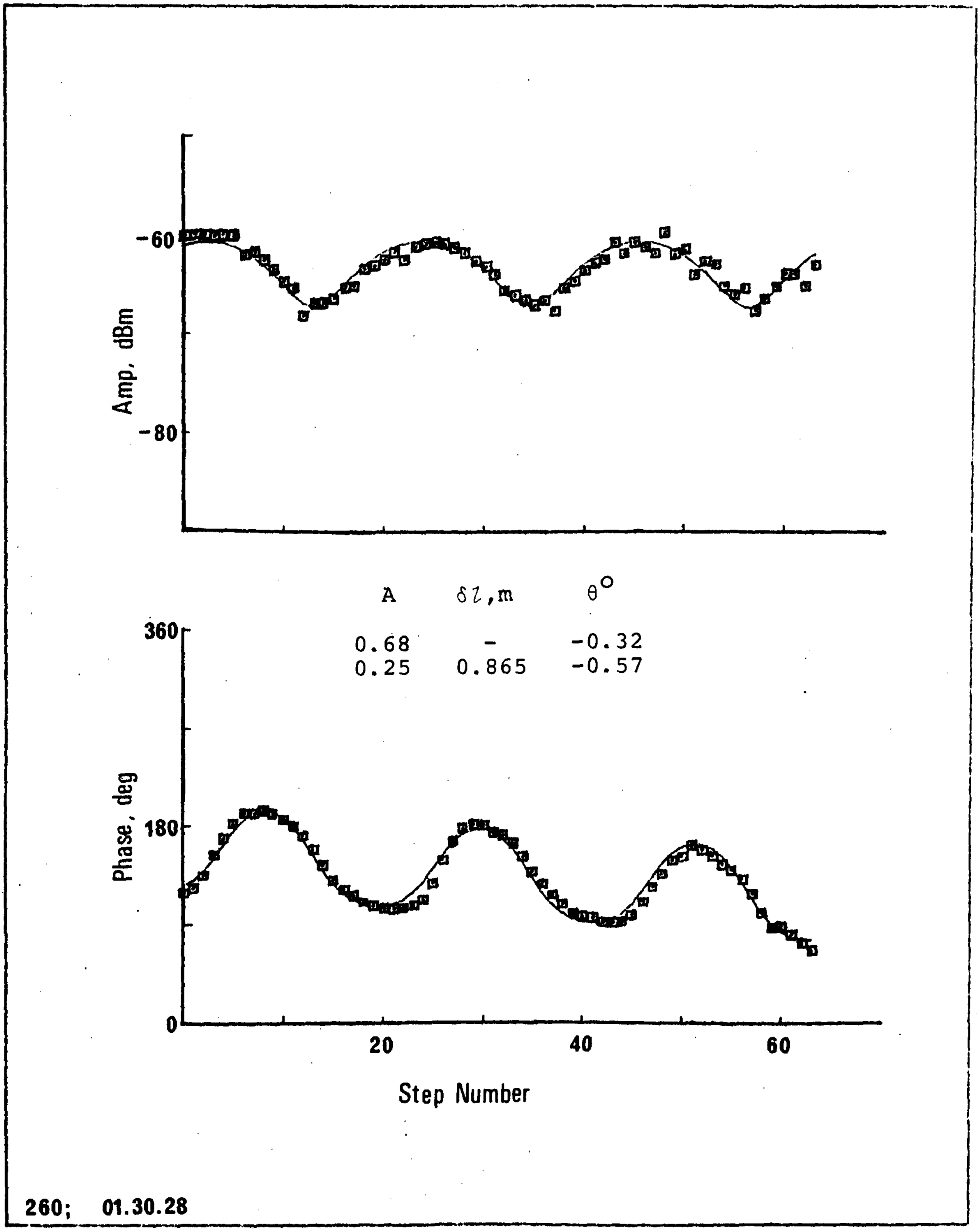


Fig. 5b Experimental and synthesized records

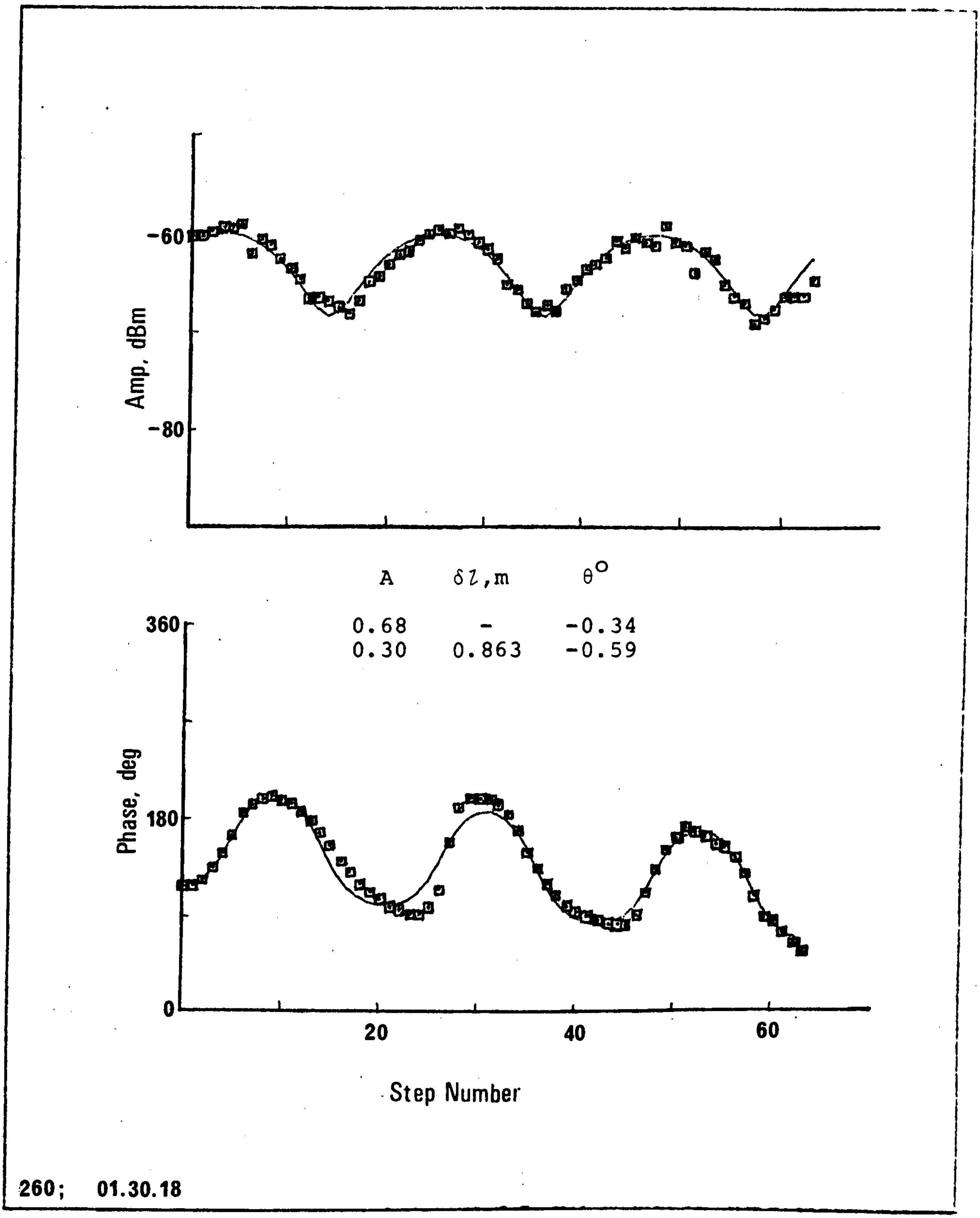
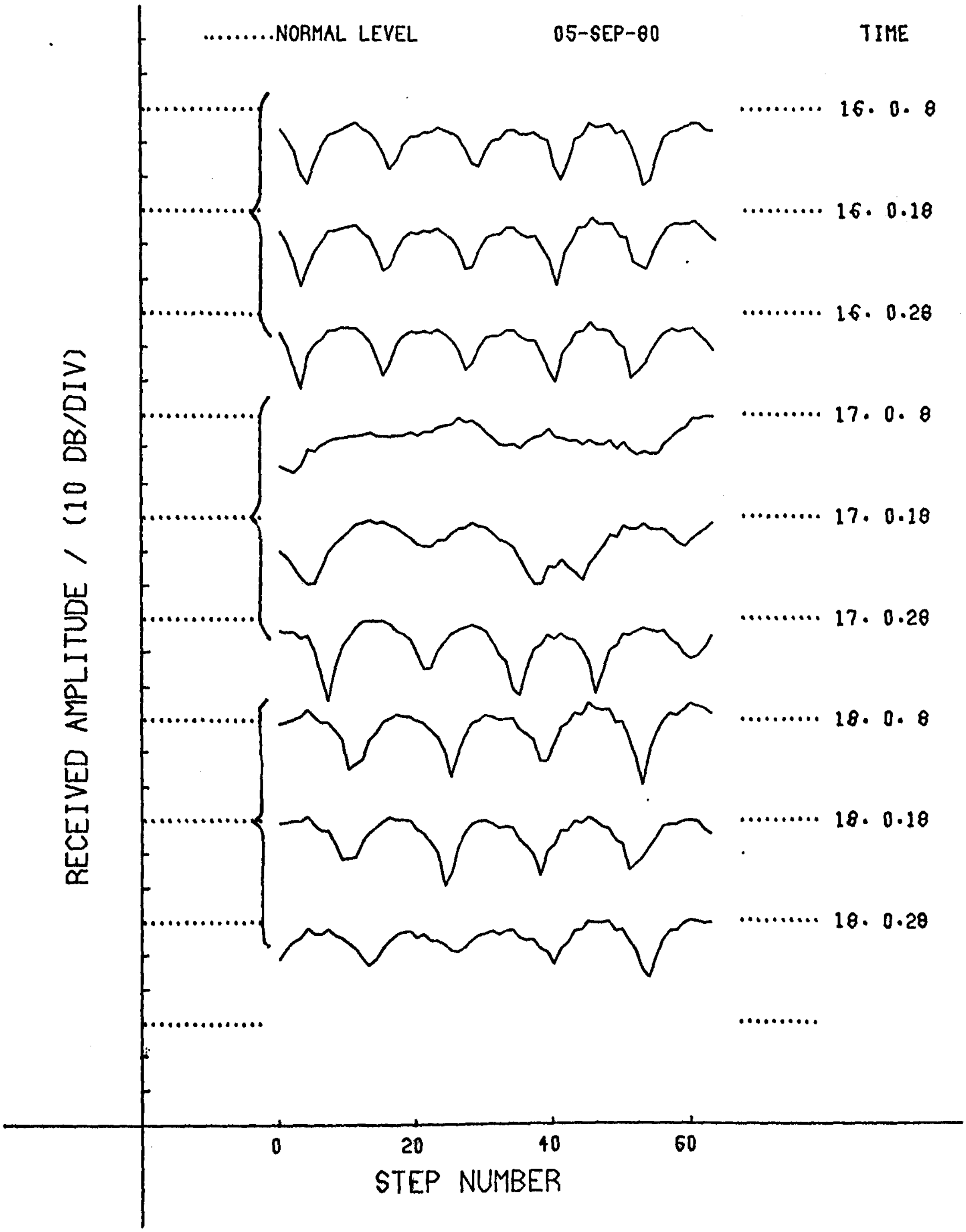


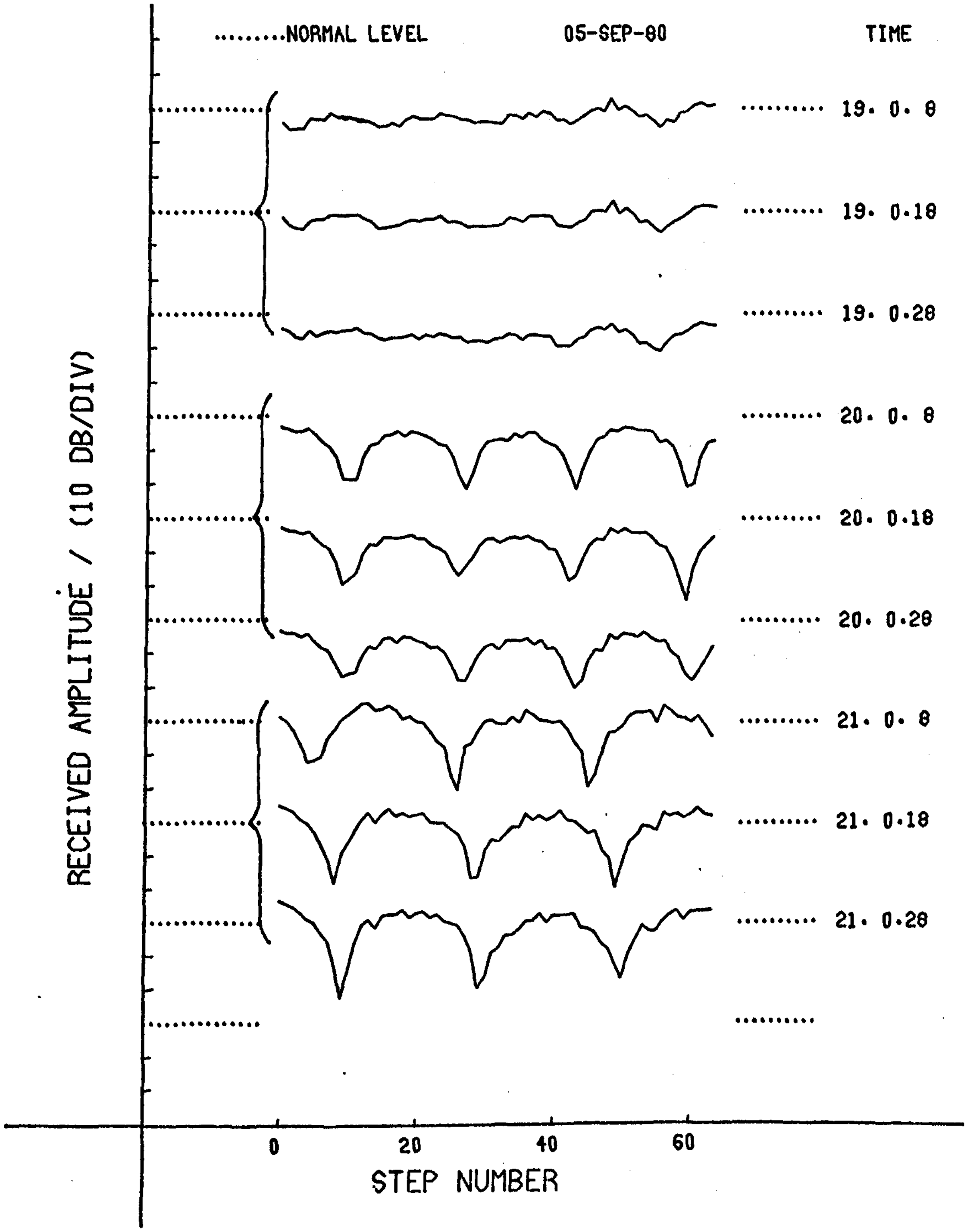
Fig. 5c Experimental and synthesized records

Fig. 6 Amplitude records across the 1 GHz band (9.5-10.5 GHz) over the period 16.00 A.D.T., 5 Sep.1980, to 03.00 A.D.T., 7 Sep.1980. Three consecutive records at the turn of the hour and 3 hours per section



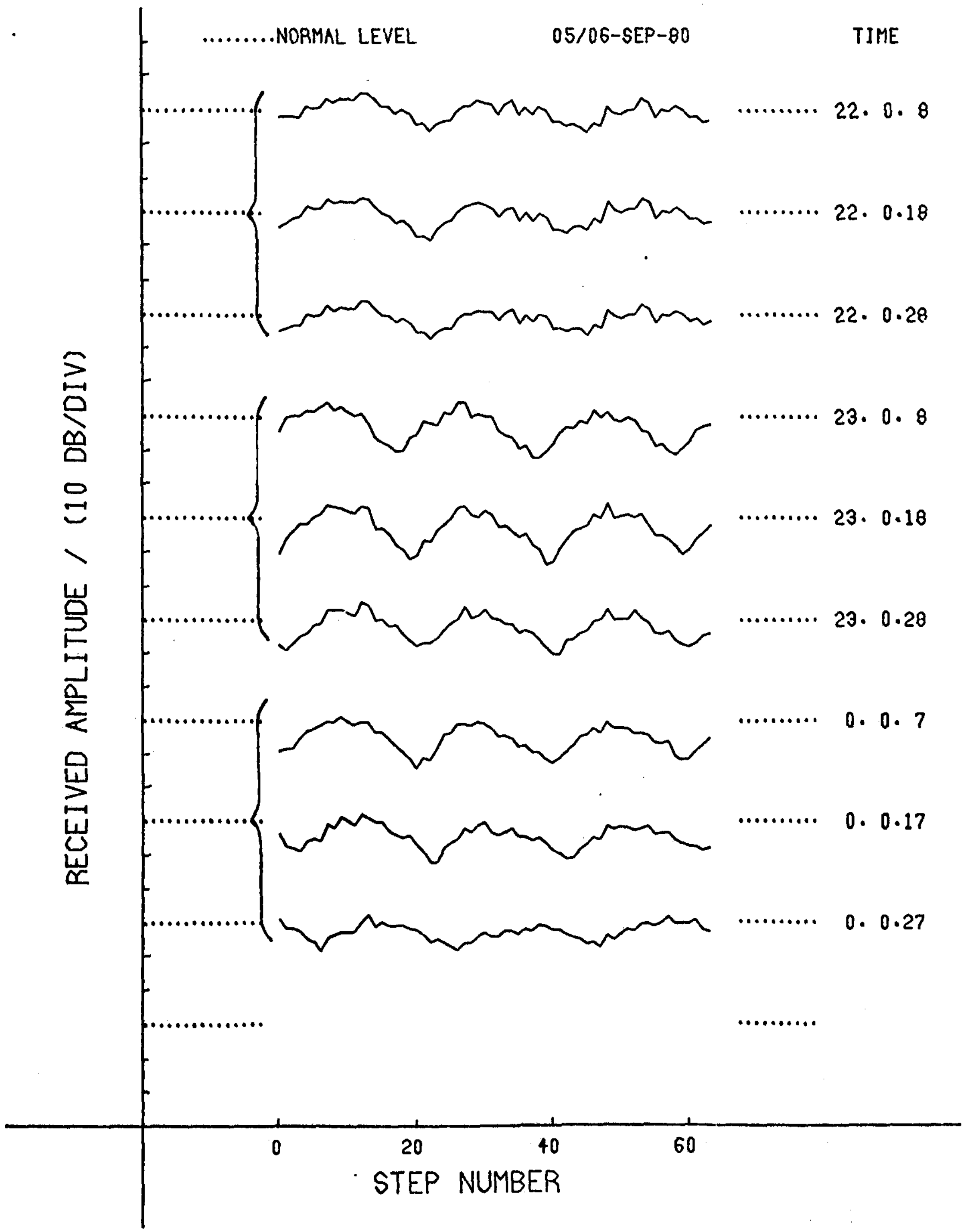
.........NORMAL LEVEL
05-SEP-80
TIME
16. 0. 8
16. 0.18
16. 0.28
17. 0. 8
17. 0.18
17. 0.28
18. 0. 8
18. 0.18
18. 0.28
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6a



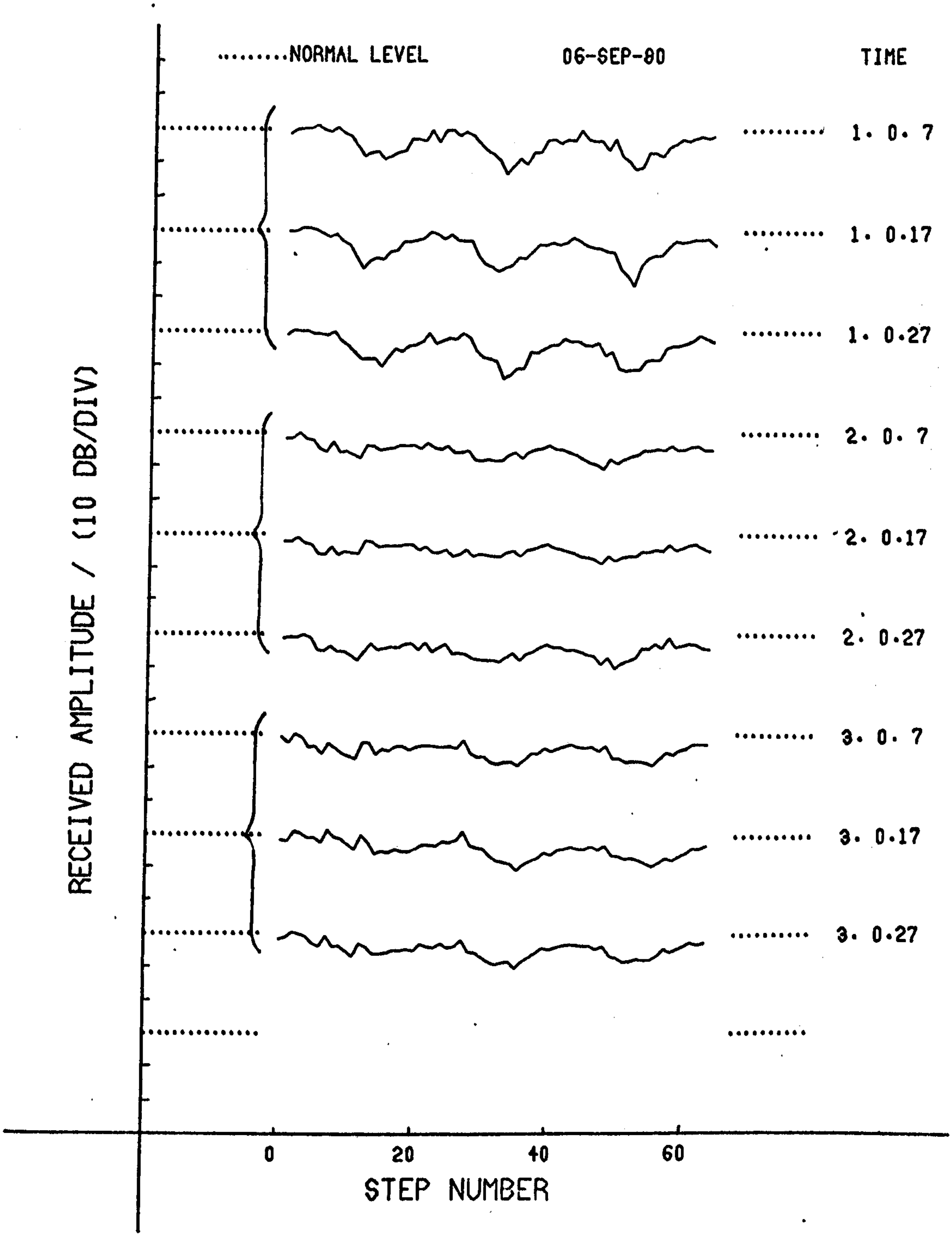
.........NORMAL LEVEL
05-SEP-80
TIME
19. 0. 8
19. 0.18
19. 0.28
20. 0. 8
20. 0.18
20. 0.28
21. 0. 8
21. 0.18
21. 0.28
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6b



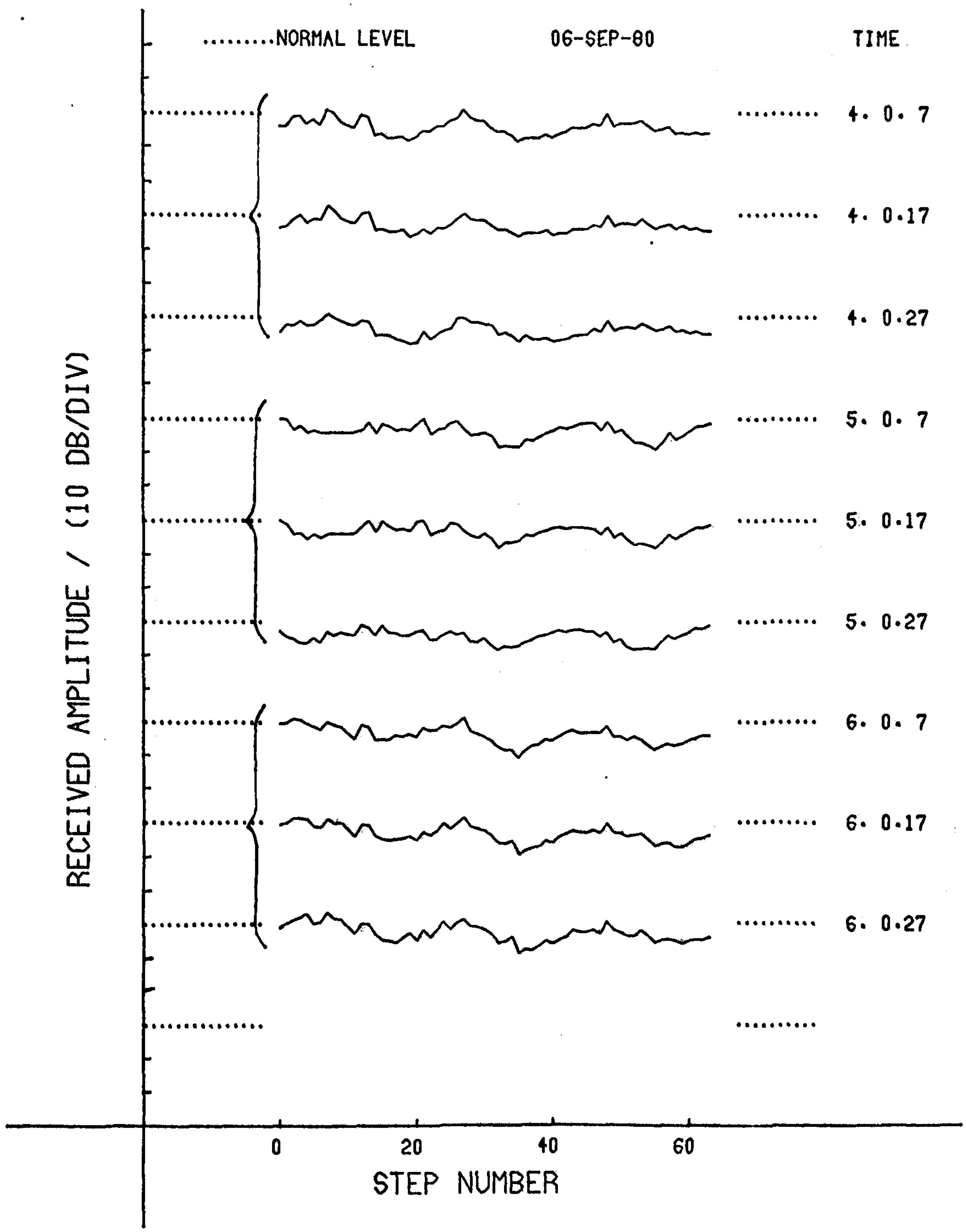
.........NORMAL LEVEL
05/06-SEP-80
TIME
22. 0. 8
22. 0.18
22. 0.28
23. 0. 8
23. 0.18
23. 0.28
0. 0. 7
0. 0.17
0. 0.27
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6c



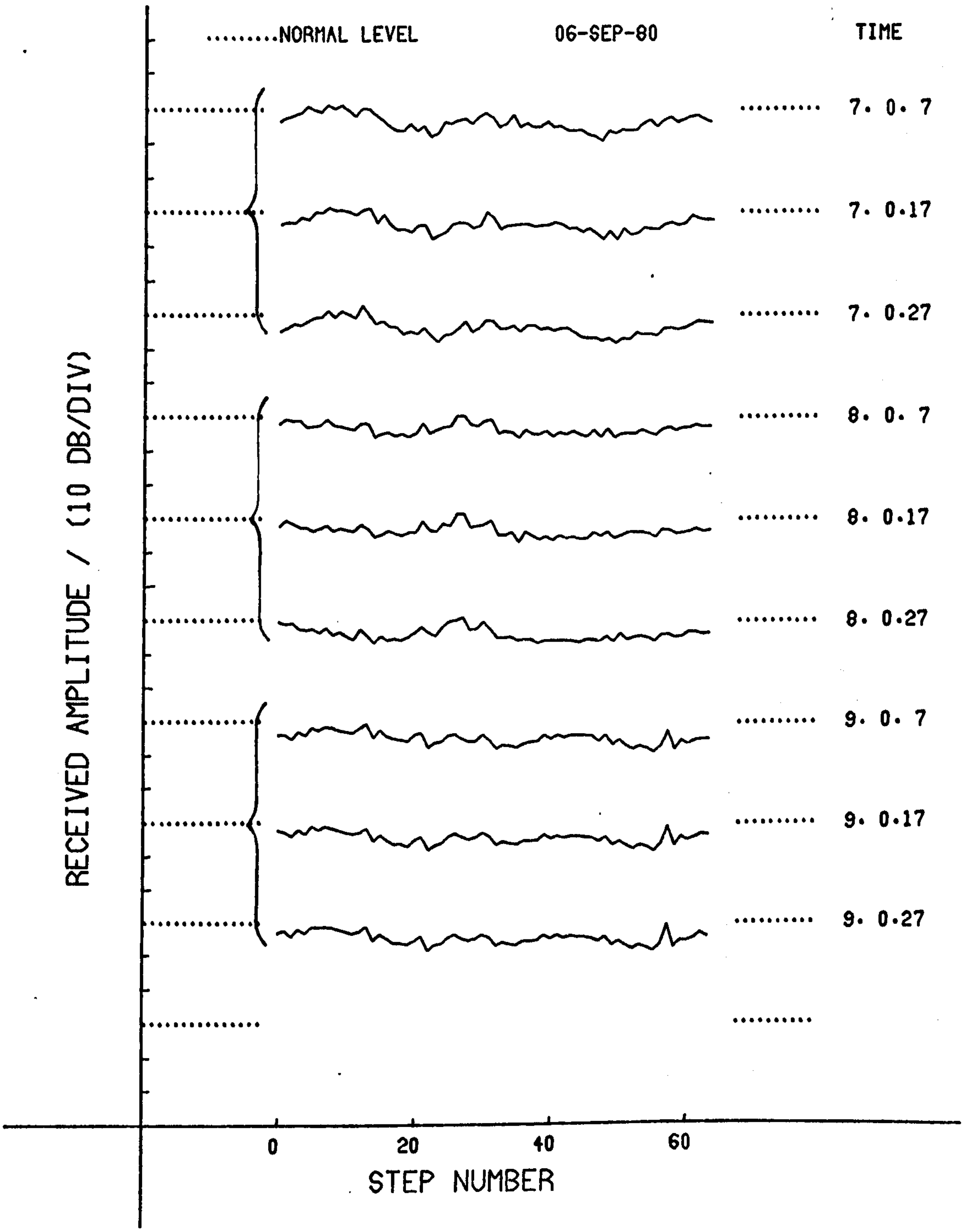
........NORMAL LEVEL
06-SEP-80
TIME
1. 0. 7
1. 0.17
1. 0.27
2. 0. 7
2. 0.17
2. 0.27
3. 0. 7
3. 0.17
3. 0.27
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6d



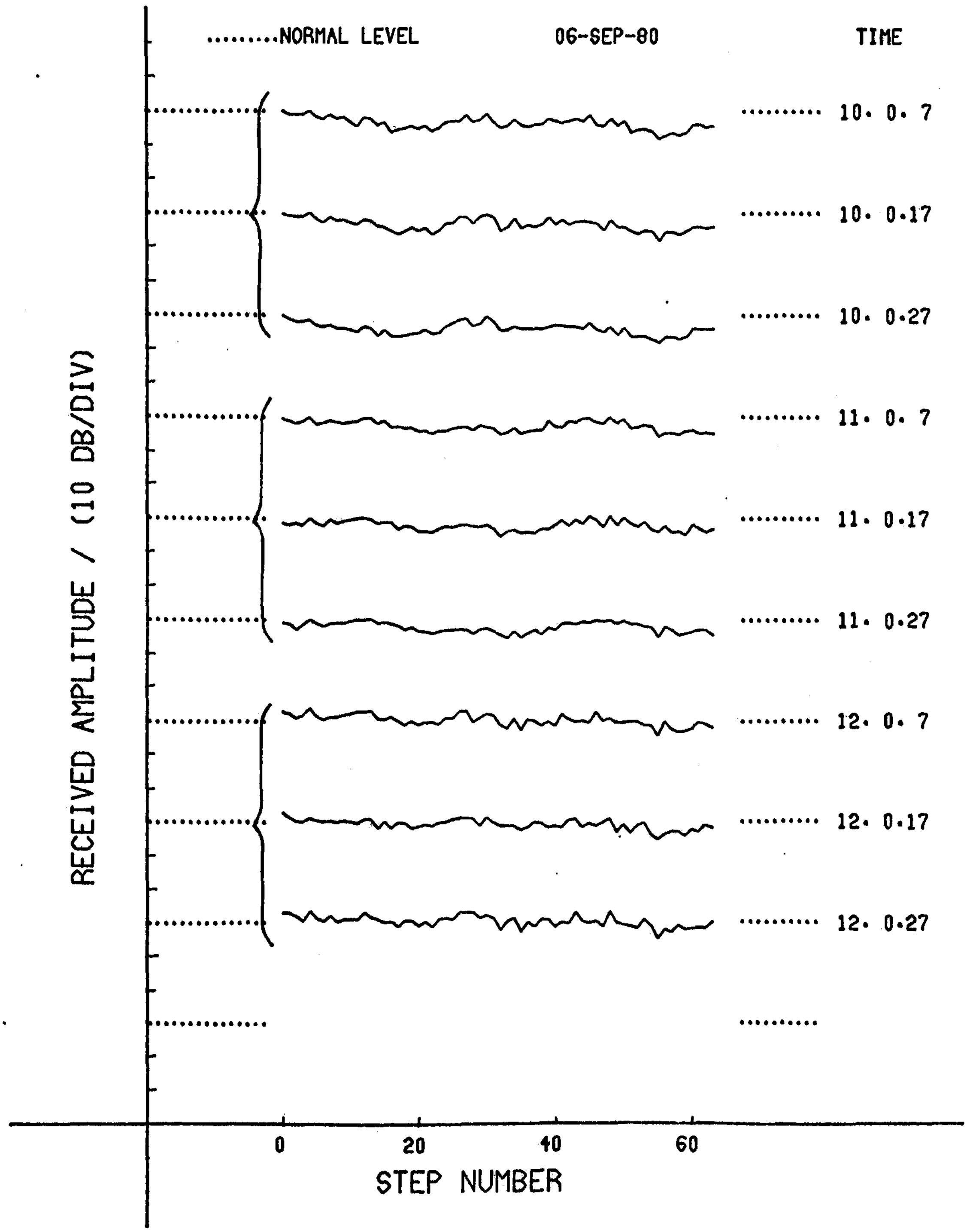
.........NORMAL LEVEL
06-SEP-80
TIME
4. 0. 7
4. 0.17
4. 0.27
5. 0. 7
5. 0.17
5. 0.27
6. 0. 7
6. 0.17
6. 0.27
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6e



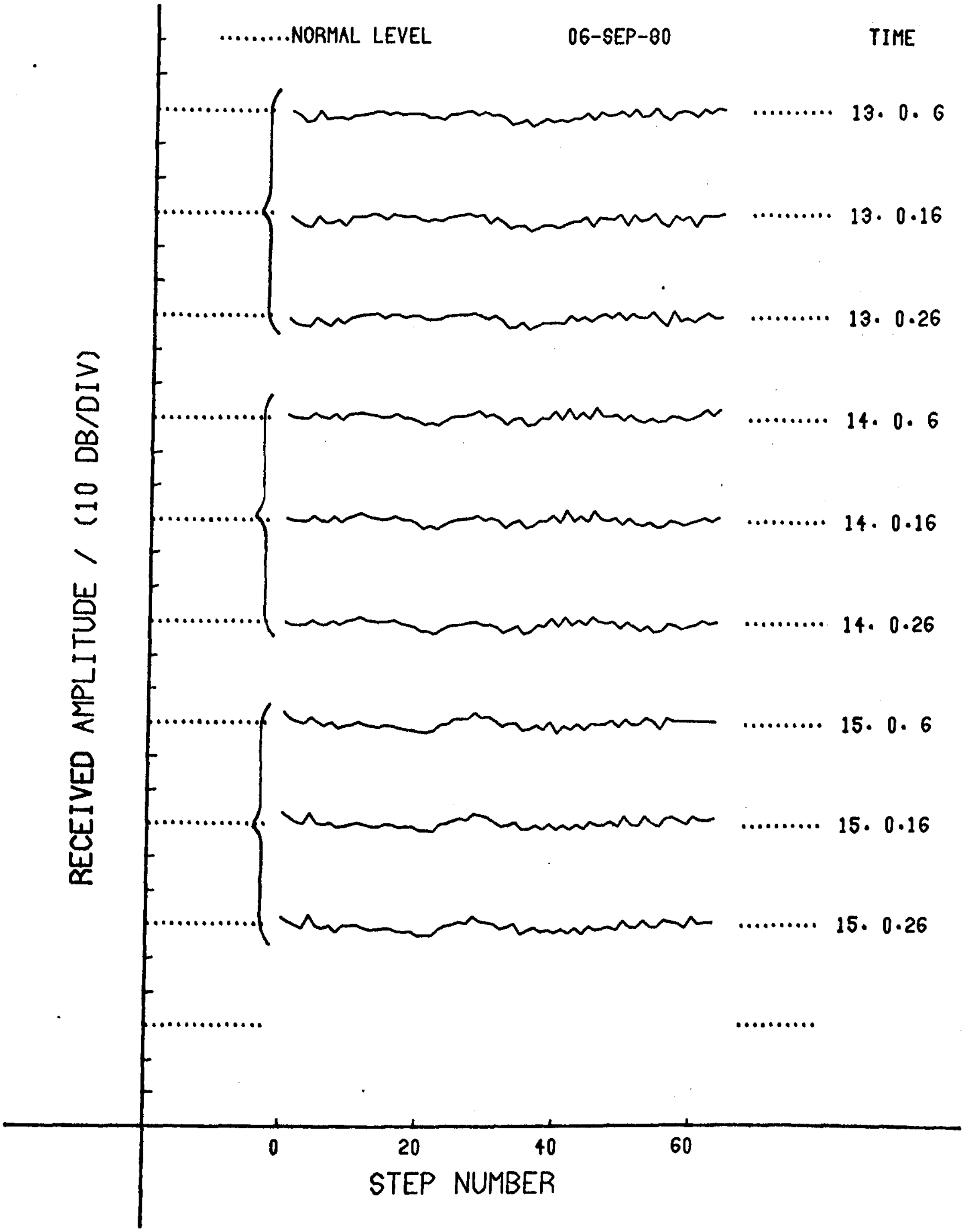
.........NORMAL LEVEL
06-SEP-80
TIME
7. 0. 7
7. 0.17
7. 0.27
8. 0. 7
8. 0.17
8. 0.27
9. 0. 7
9. 0.17
9. 0.27
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6f



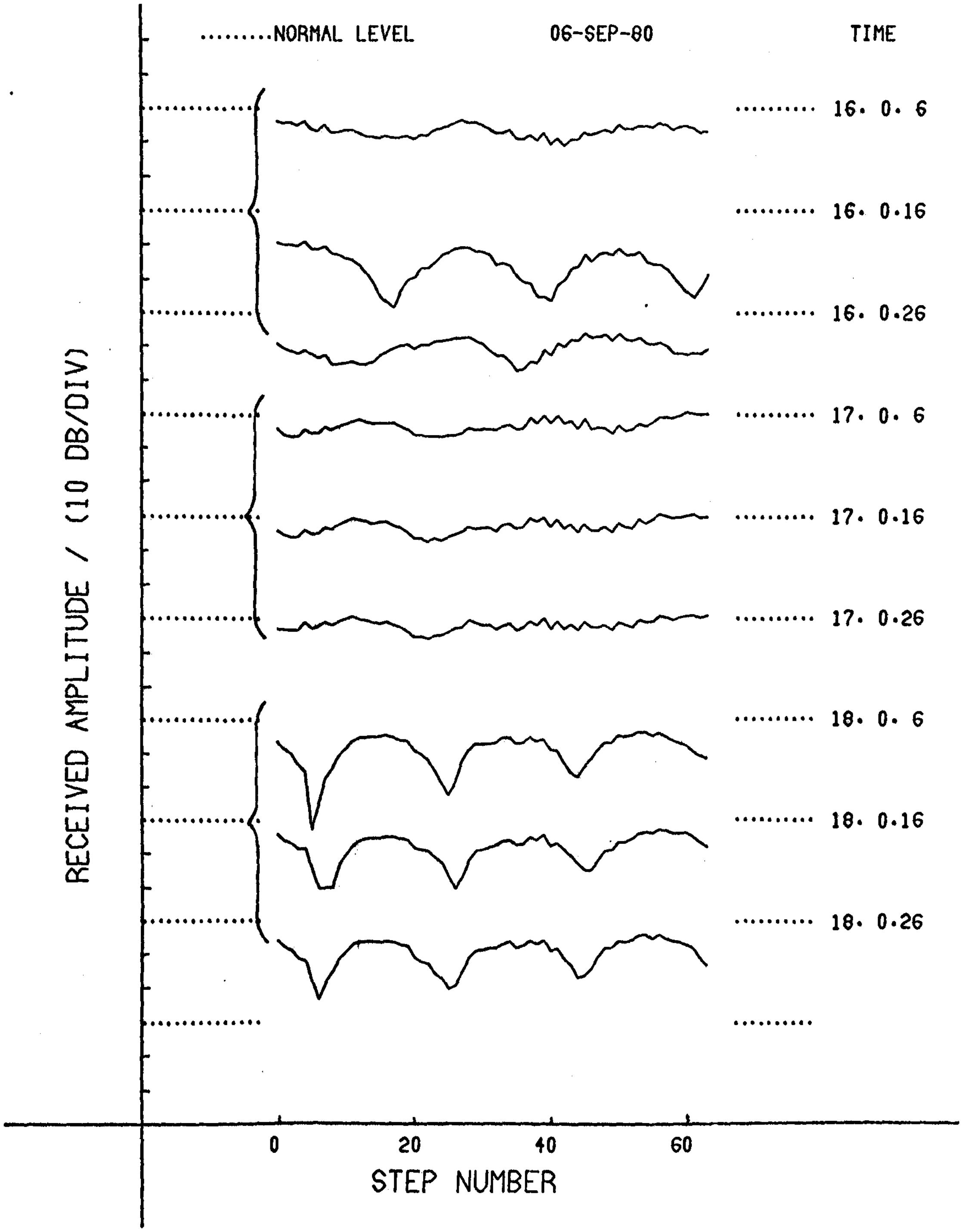
.........NORMAL LEVEL
06-SEP-80
TIME
10. 0. 7
10. 0.17
10. 0.27
11. 0. 7
11. 0.17
11. 0.27
12. 0. 7
12. 0.17
12. 0.27
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6g



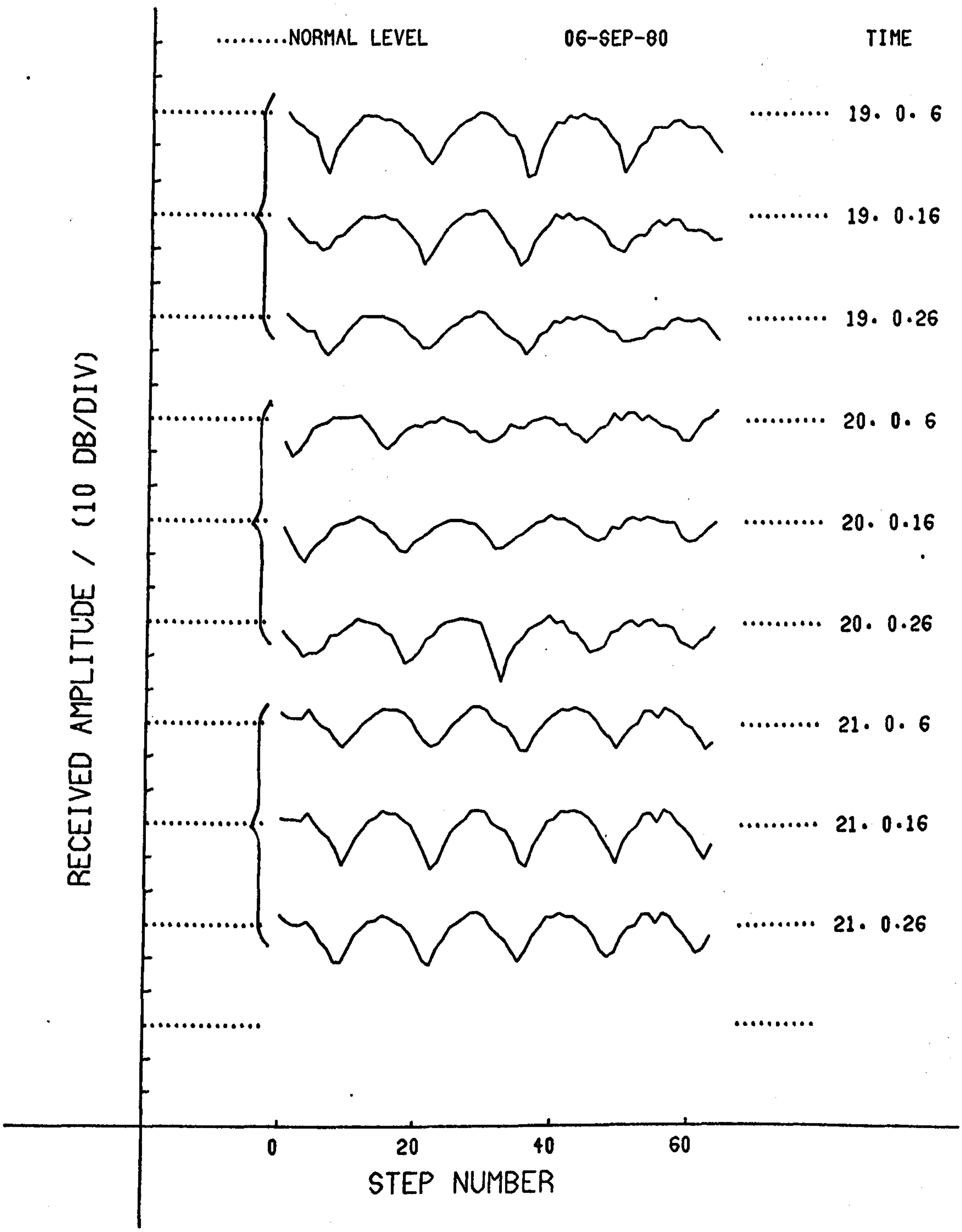
.........NORMAL LEVEL
06-SEP-80
TIME
13. 0. 6
13. 0.16
13. 0.26
14. 0. 6
14. 0.16
14. 0.26
15. 0. 6
15. 0.16
15. 0.26
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6h



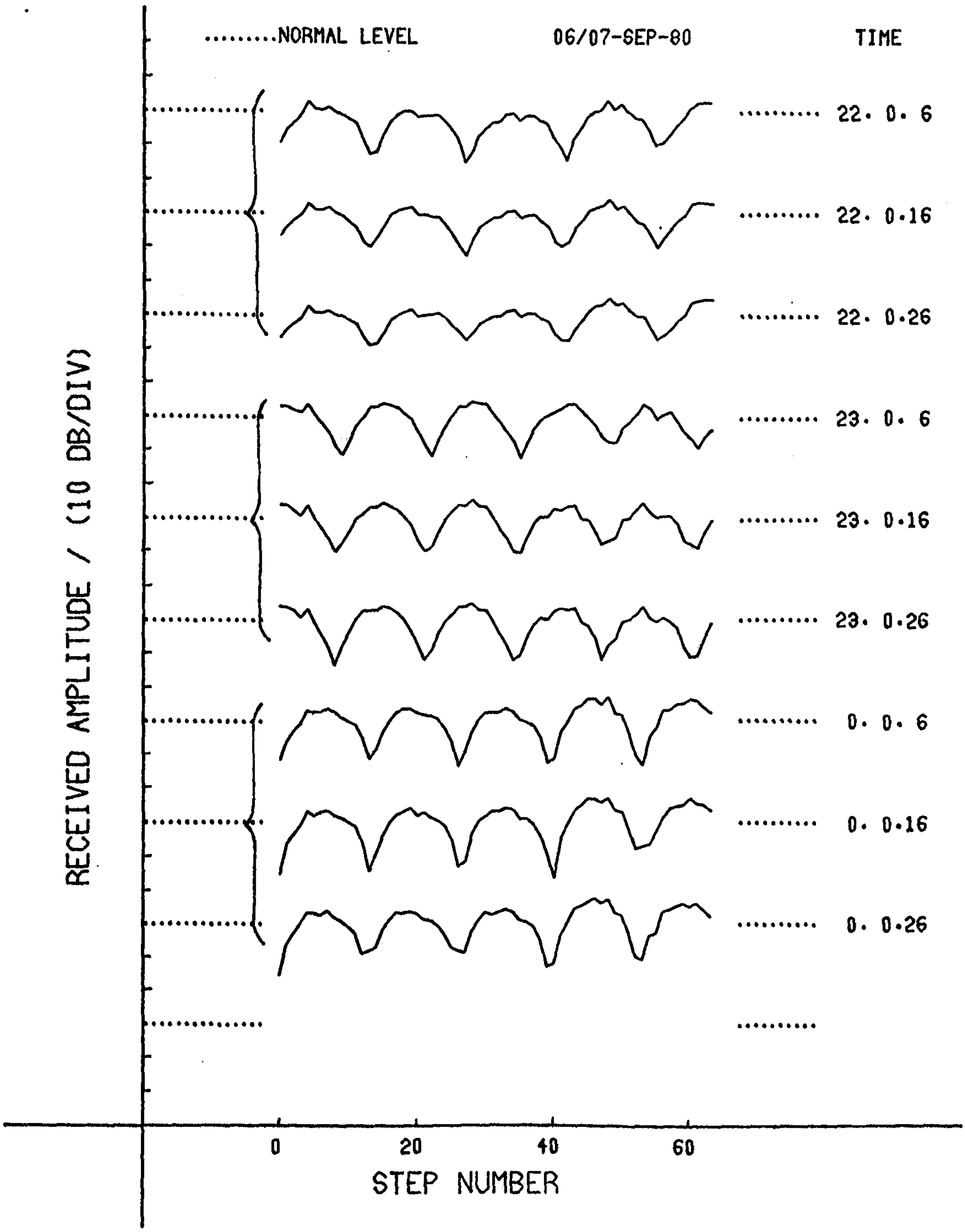
.........NORMAL LEVEL
06-SEP-80
TIME
16. 0. 6
16. 0.16
16. 0.26
17. 0. 6
17. 0.16
17. 0.26
18. 0. 6
18. 0.16
18. 0.26
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6i



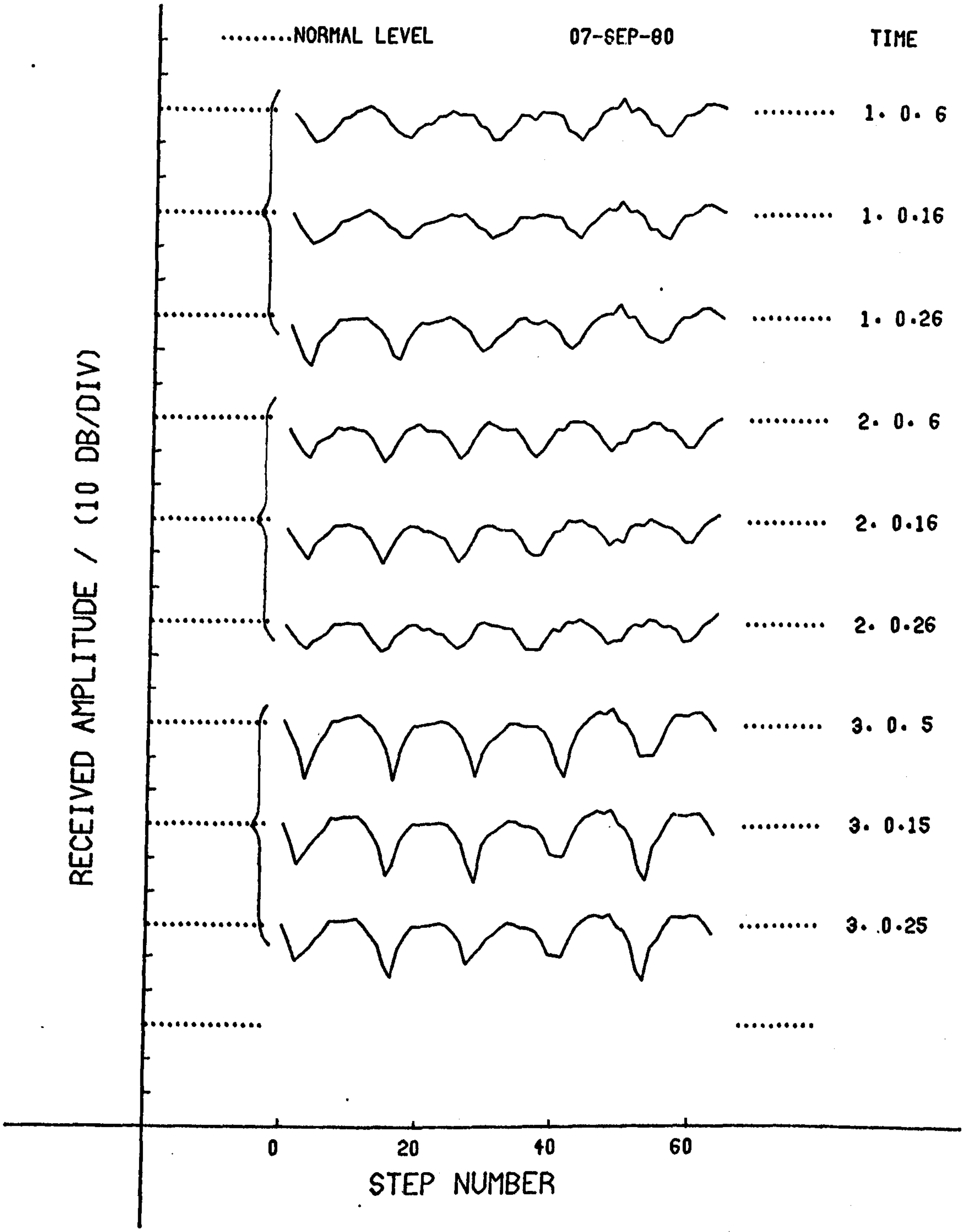
.........NORMAL LEVEL
06-SEP-80
TIME
19. 0. 6
19. 0.16
19. 0.26
20. 0. 6
20. 0.16
20. 0.26
21. 0. 6
21. 0.16
21. 0.26
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6j



.........NORMAL LEVEL
06/07-SEP-80
TIME
22. 0. 6
22. 0.16
22. 0.26
23. 0. 6
23. 0.16
23. 0.26
0. 0. 6
0. 0.16
0. 0.26
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6k



.........NORMAL LEVEL
07-SEP-80
TIME
1. 0. 6
1. 0.16
1. 0.26
2. 0. 6
2. 0.16
2. 0.26
3. 0. 5
3. 0.15
3. 0.25
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 6l

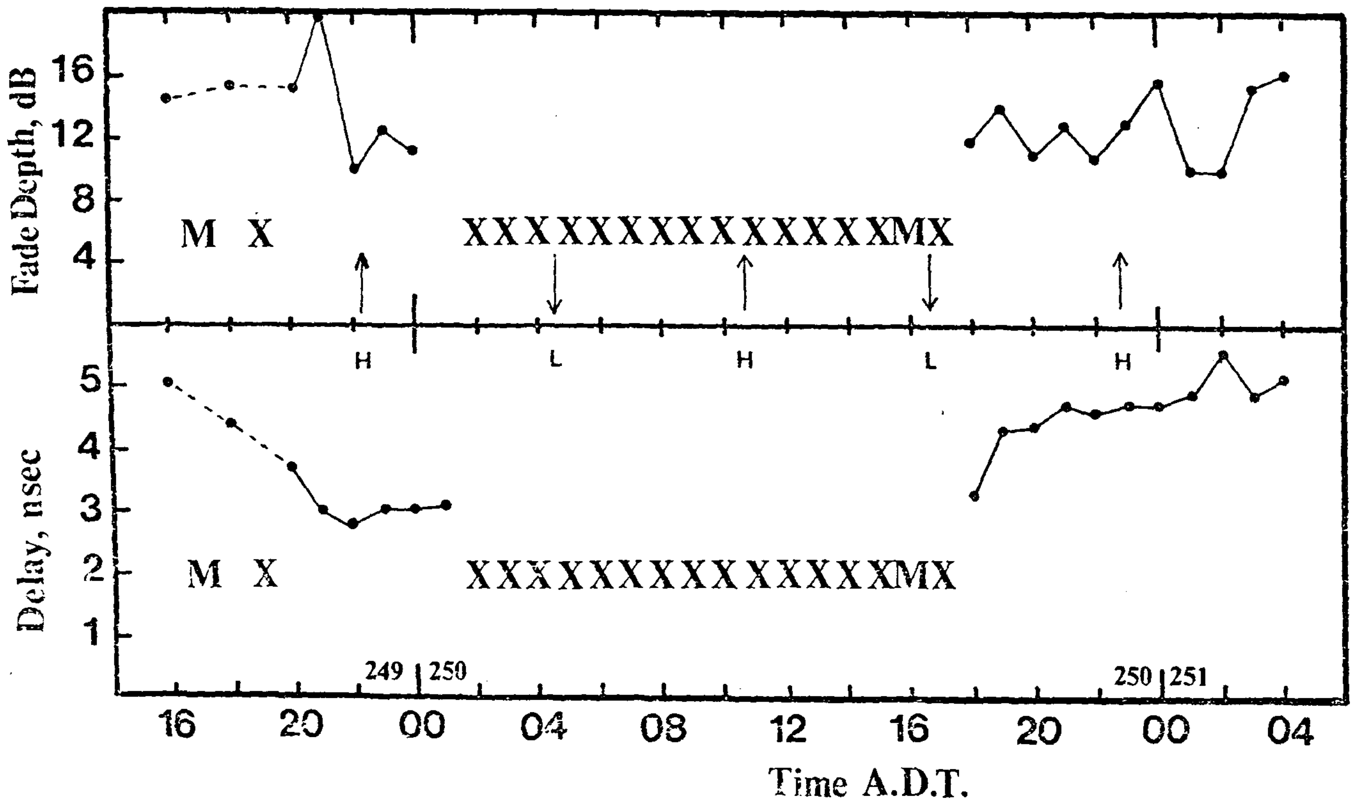


Fig. 7 A summary of fade depth and delay time taken from fig.6 when a clear two-path situation is indicated. X, little or no multipath; M, complicated multipath; H and L, high and low tide respectively at Saint John

Fig. 8 Amplitude records across the 1 GHz band at 30 second intervals over the period 1630 A.D.T. to 1730 A.D.T., 5 Sep.1980; 5 minutes per section

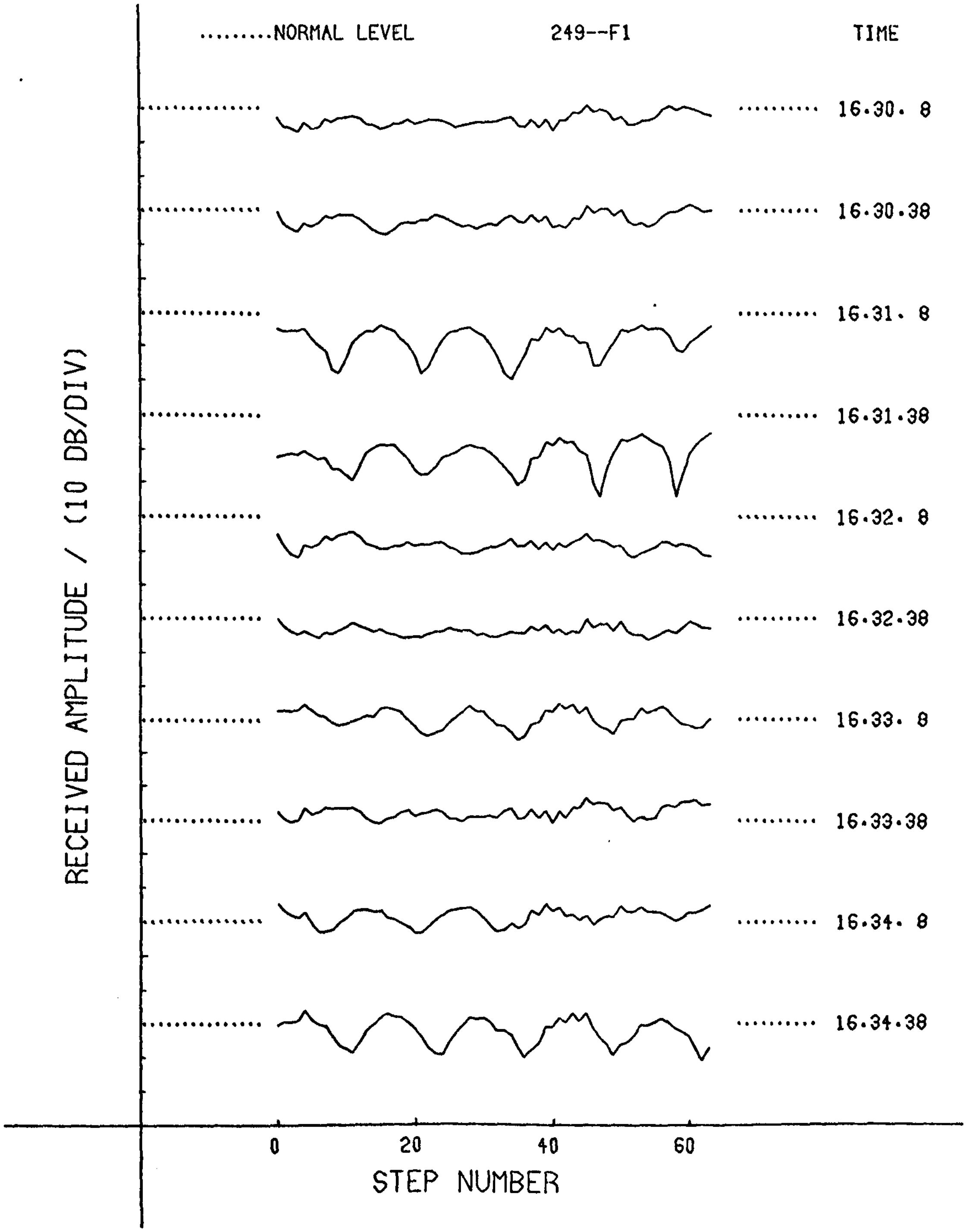

.........NORMAL LEVEL
249--F1
TIME
16.30. 8
16.30.38
16.31. 8
16.31.38
16.32. 8
16.32.38
16.33. 8
16.33.38
16.34. 8
16.34.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8a

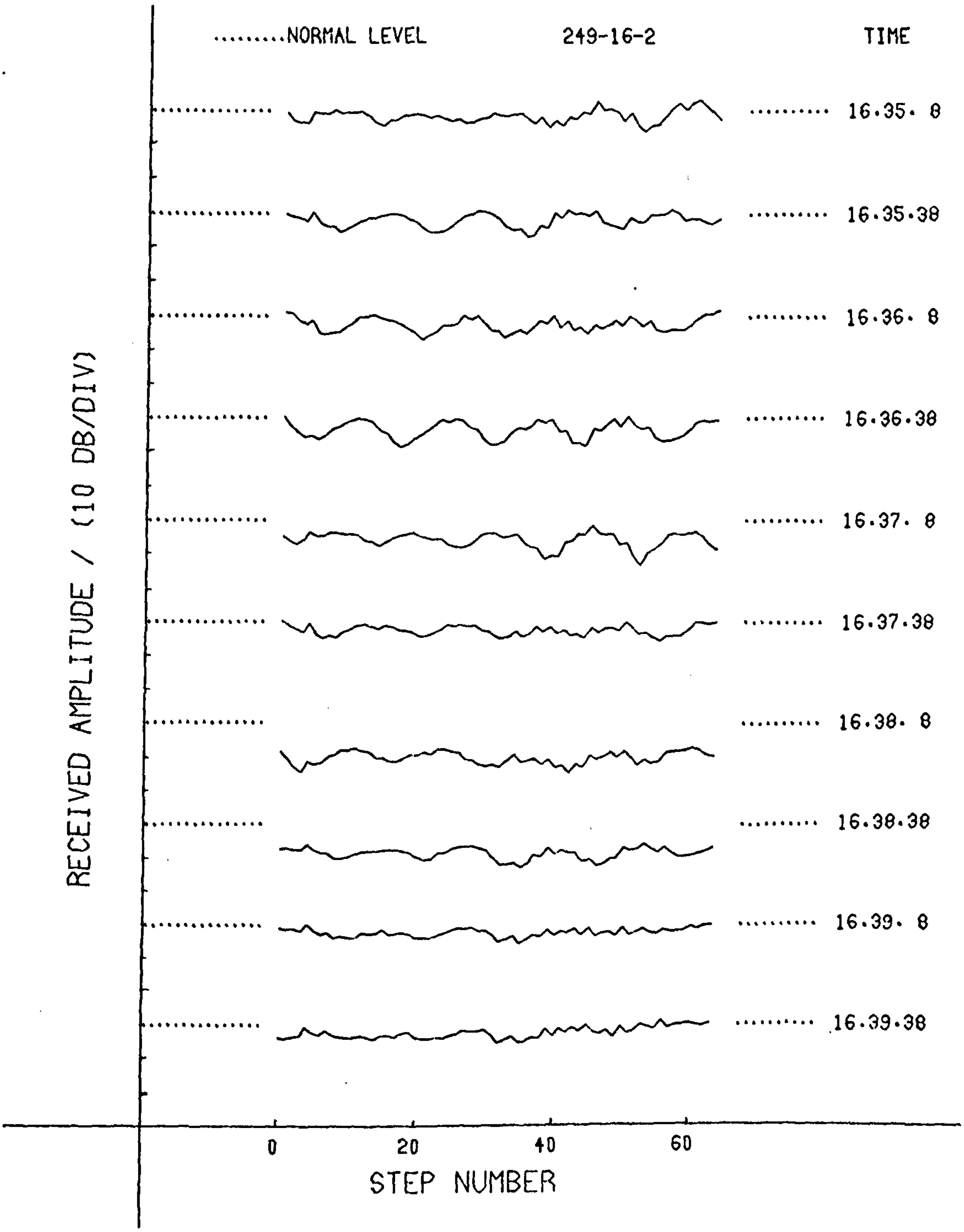
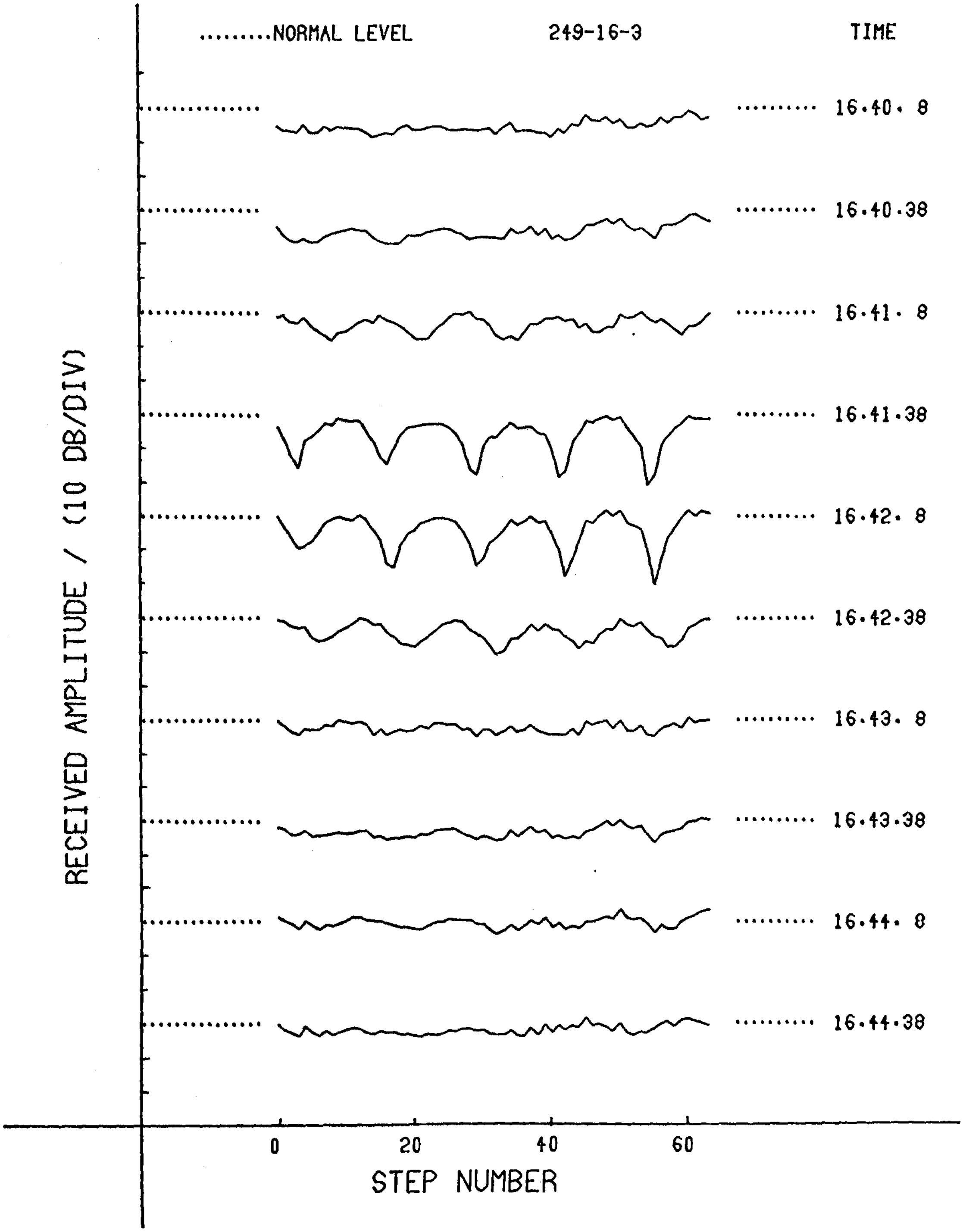
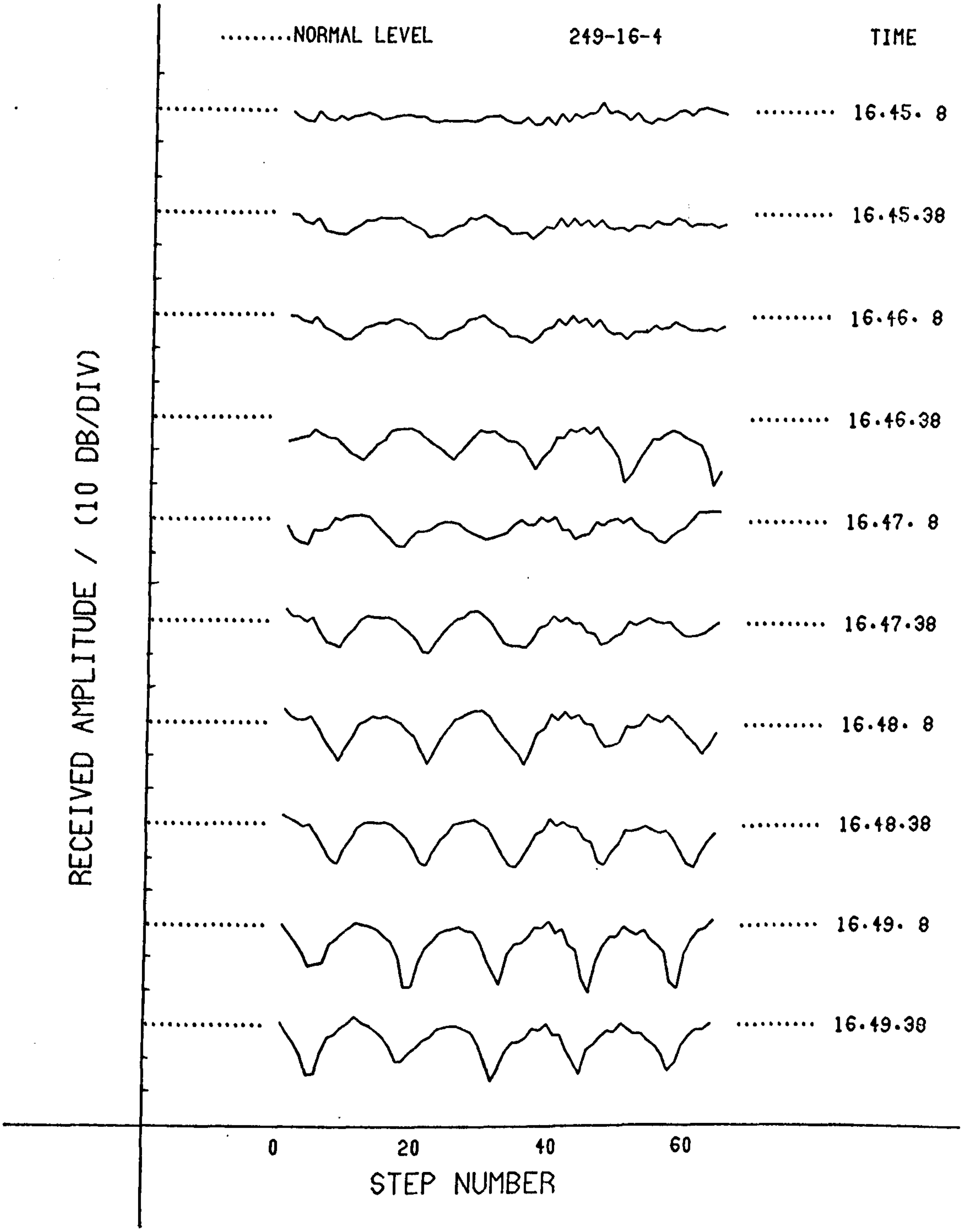

.........NORMAL LEVEL
249-16-2
TIME
16.35. 8
16.35.38
16.36. 8
16.36.38
16.37. 8
16.37.38
16.38. 8
16.38.38
16.39. 8
16.39.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8b



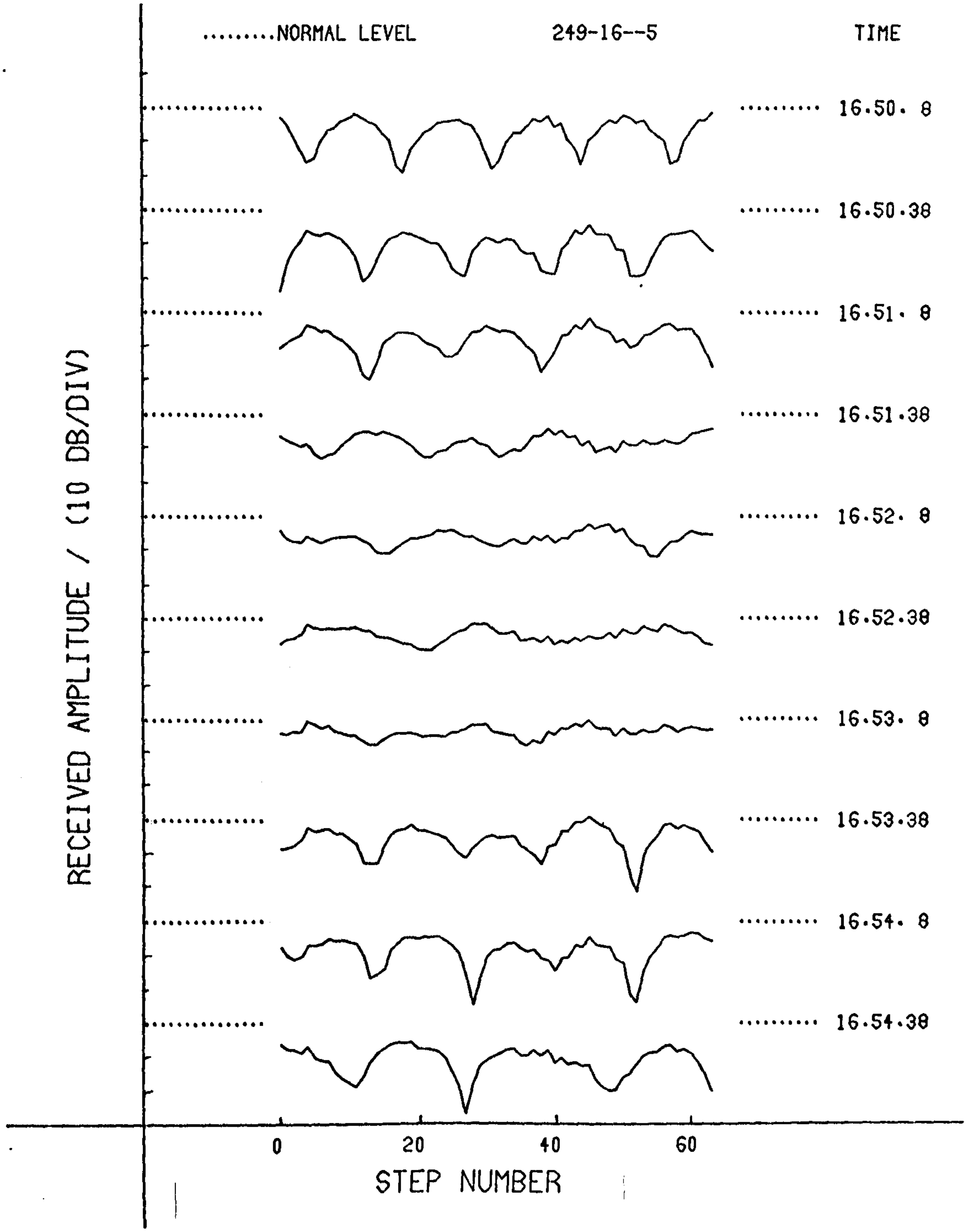
.........NORMAL LEVEL
249-16-3
TIME
16.40. 8
16.40.38
16.41. 8
16.41.38
16.42. 8
16.42.38
16.43. 8
16.43.38
16.44. 8
16.44.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8c



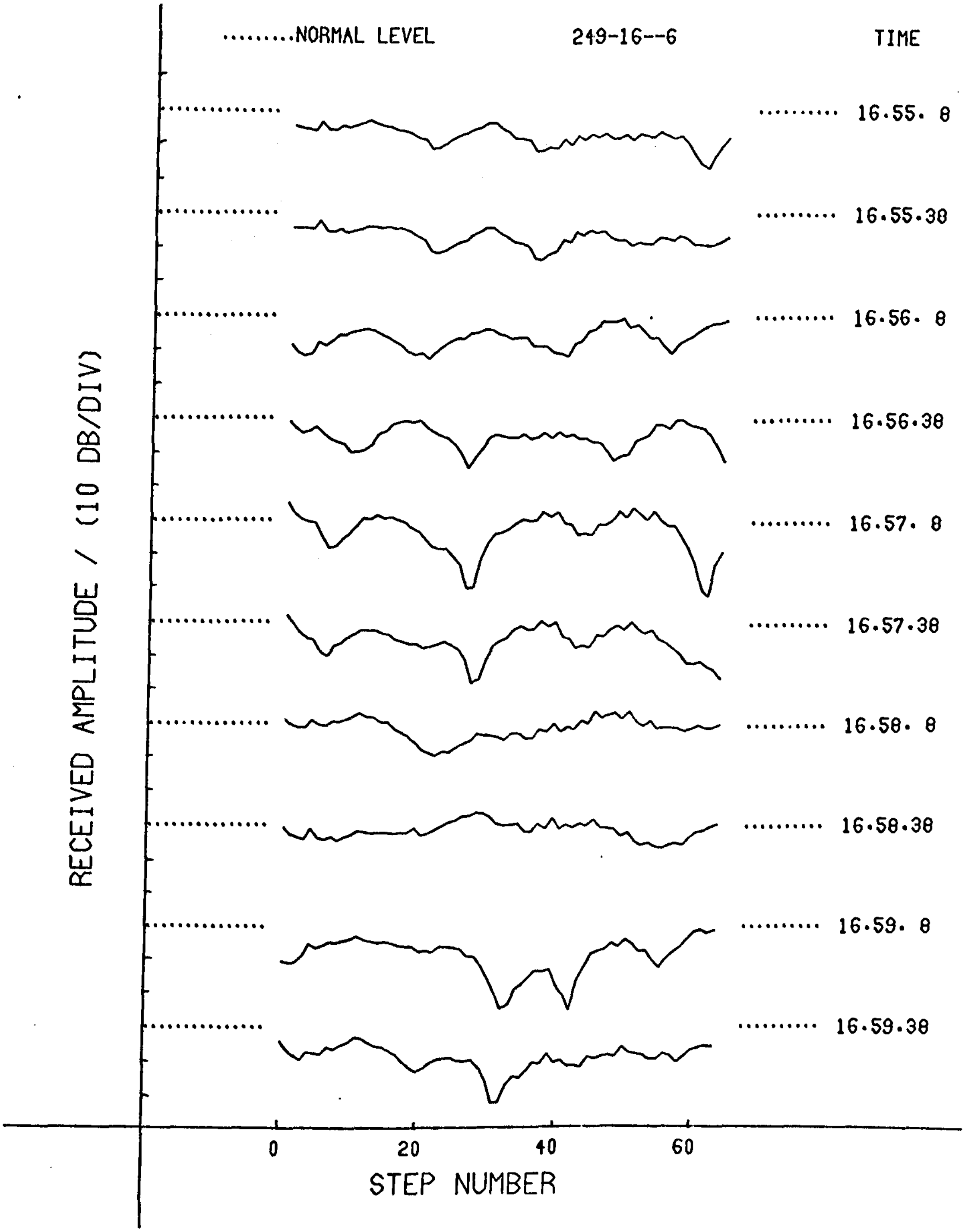
.........NORMAL LEVEL
249-16-4
TIME
16.45. 8
16.45.38
16.46. 8
16.46.38
16.47. 8
16.47.38
16.48. 8
16.48.38
16.49. 8
16.49.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8d



.........NORMAL LEVEL
249-16--5
TIME
16.50. 8
16.50.38
16.51. 8
16.51.38
16.52. 8
16.52.38
16.53. 8
16.53.38
16.54. 8
16.54.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8e



.........NORMAL LEVEL
249-16--6
TIME
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16.55.38
16.56. 8
16.56.38
16.57. 8
16.57.38
16.58. 8
16.58.38
16.59. 8
16.59.38
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0
20
40
60
STEP NUMBER

Fig. 8f

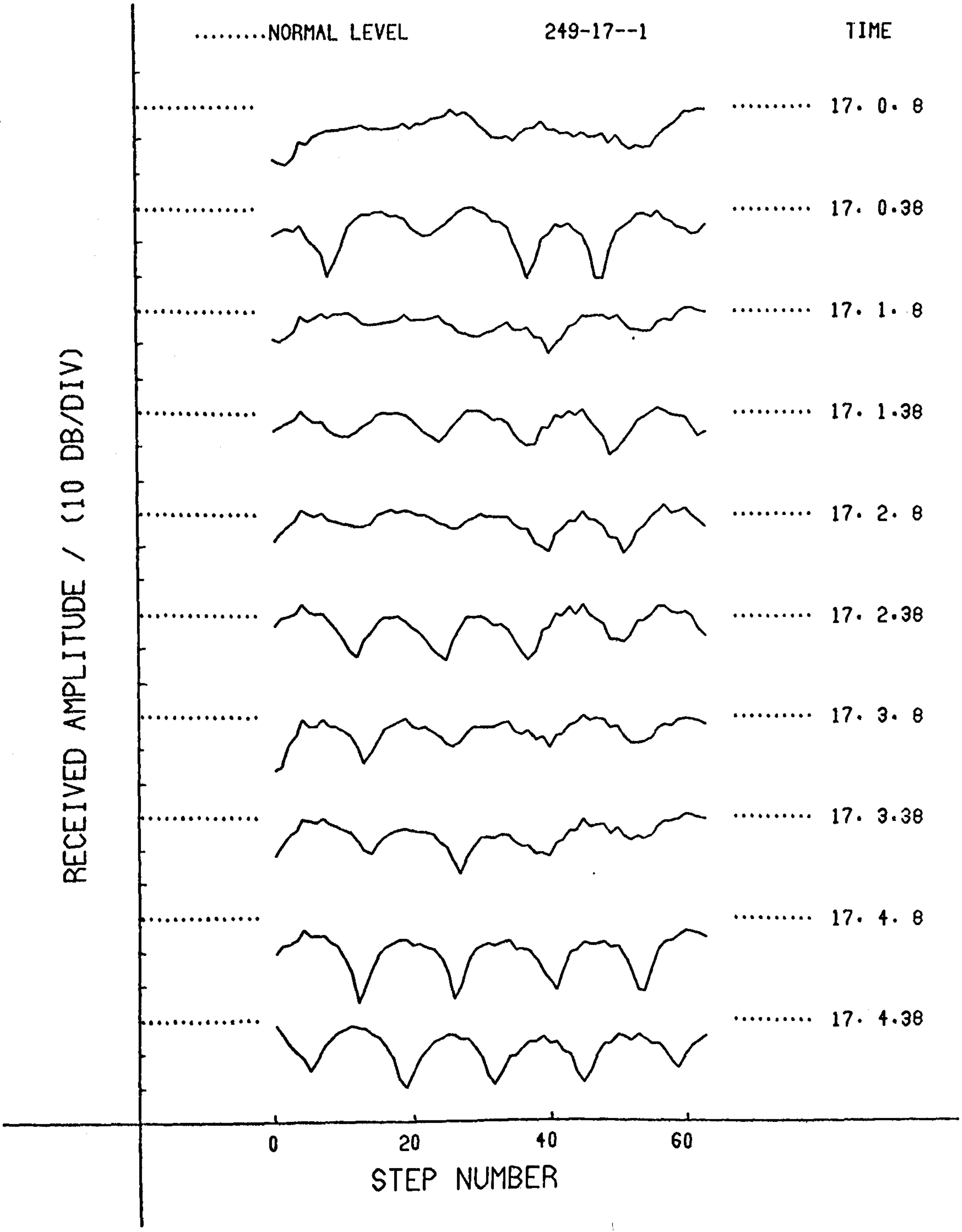
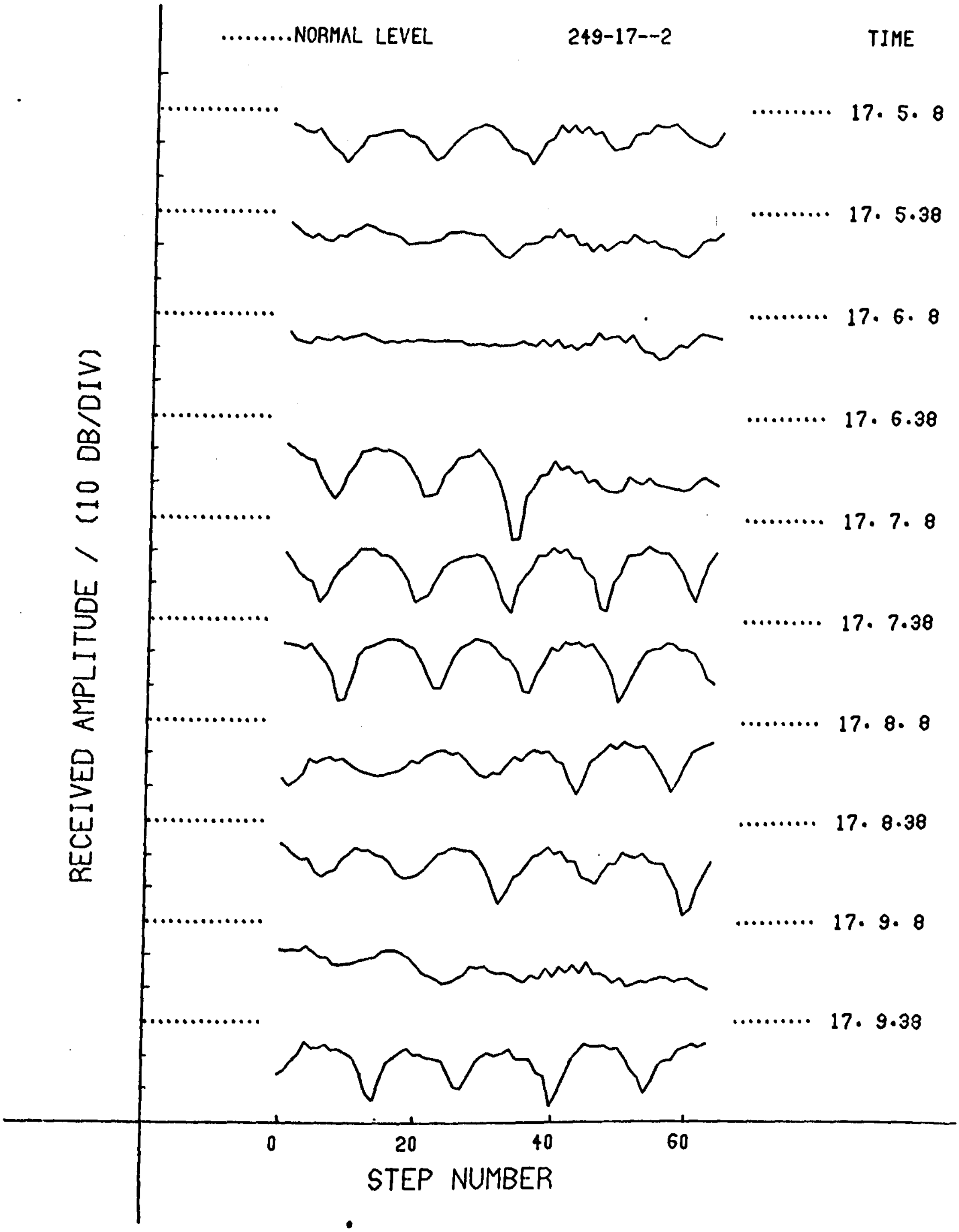
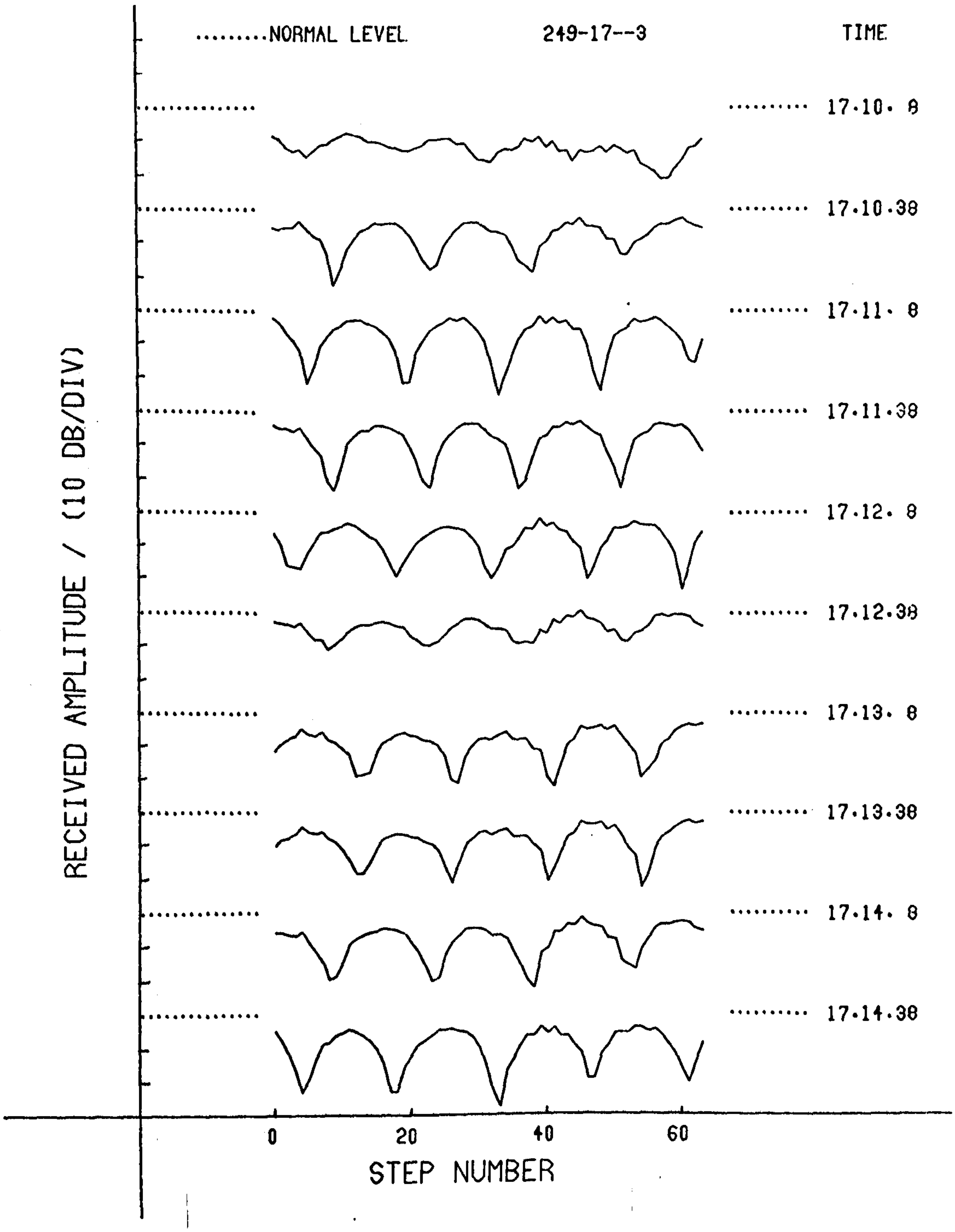

.........NORMAL LEVEL
249-17--1
TIME
17. 0. 8
17. 0.38
17. 1. 8
17. 1.38
17. 2. 8
17. 2.38
17. 3. 8
17. 3.38
17. 4. 8
17. 4.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8g



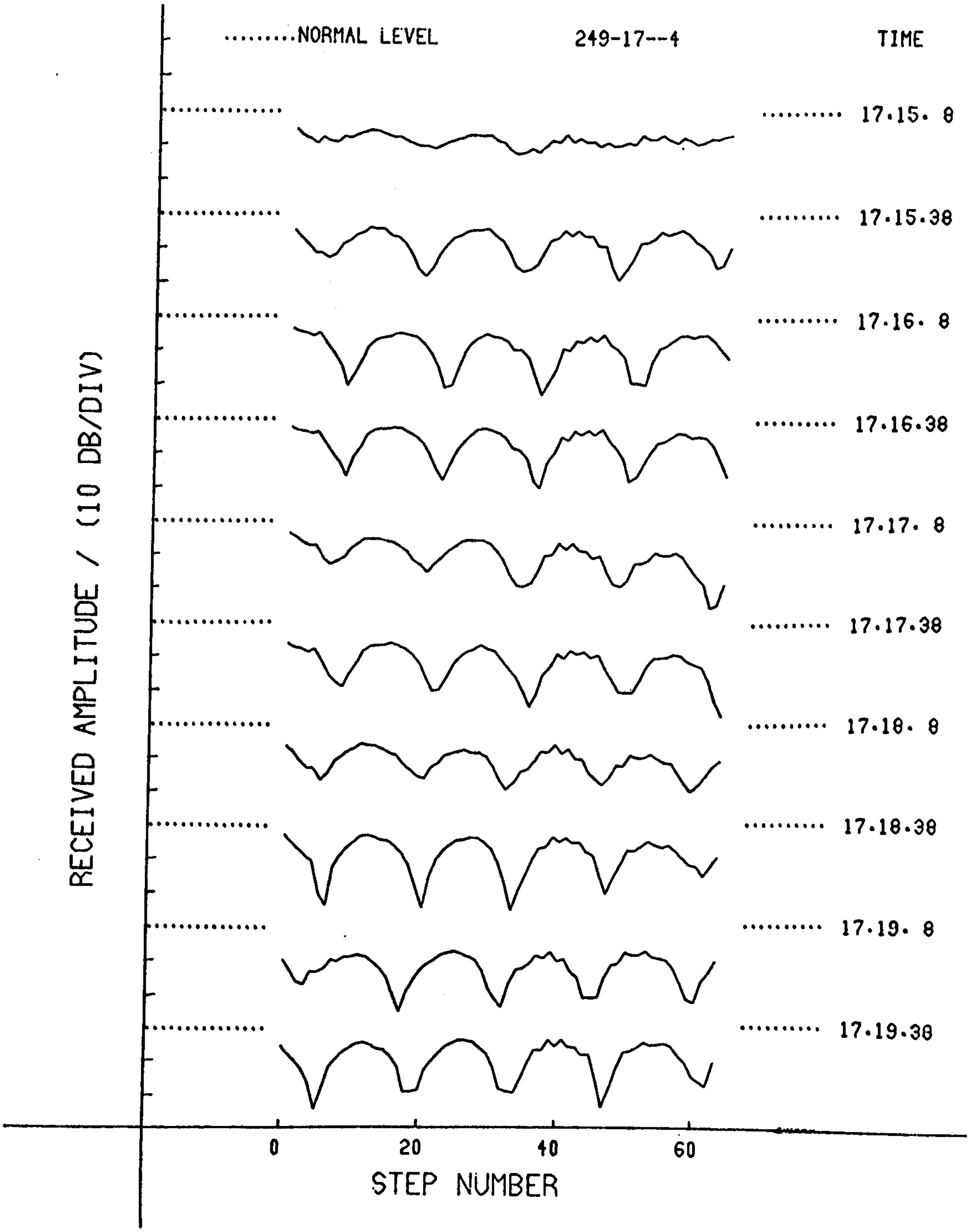
.........NORMAL LEVEL
249-17--2
TIME
17. 5. 8
17. 5.38
17. 6. 8
17. 6.38
17. 7. 8
17. 7.38
17. 8. 8
17. 8.38
17. 9. 8
17. 9.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8h



.........NORMAL LEVEL
249-17--3
TIME
17.10. 8
17.10.38
17.11. 8
17.11.38
17.12. 8
17.12.38
17.13. 8
17.13.38
17.14. 8
17.14.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8i


.........NORMAL LEVEL
249-17--4
TIME
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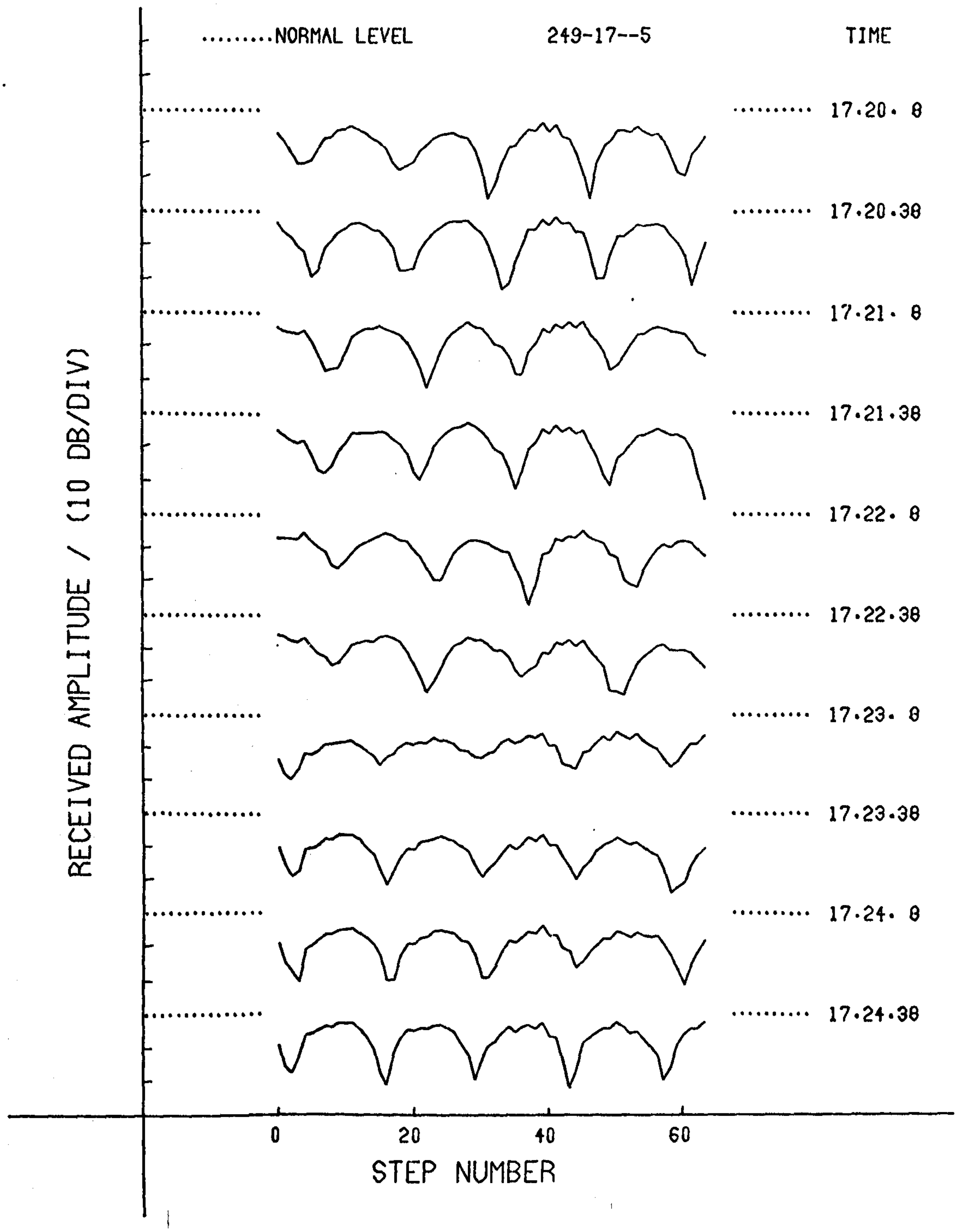
17.15.38
17.16. 8
17.16.38
17.17. 8
17.17.38
17.18. 8
17.18.38
17.19. 8
17.19.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8j


.........NORMAL LEVEL
249-17--5
TIME
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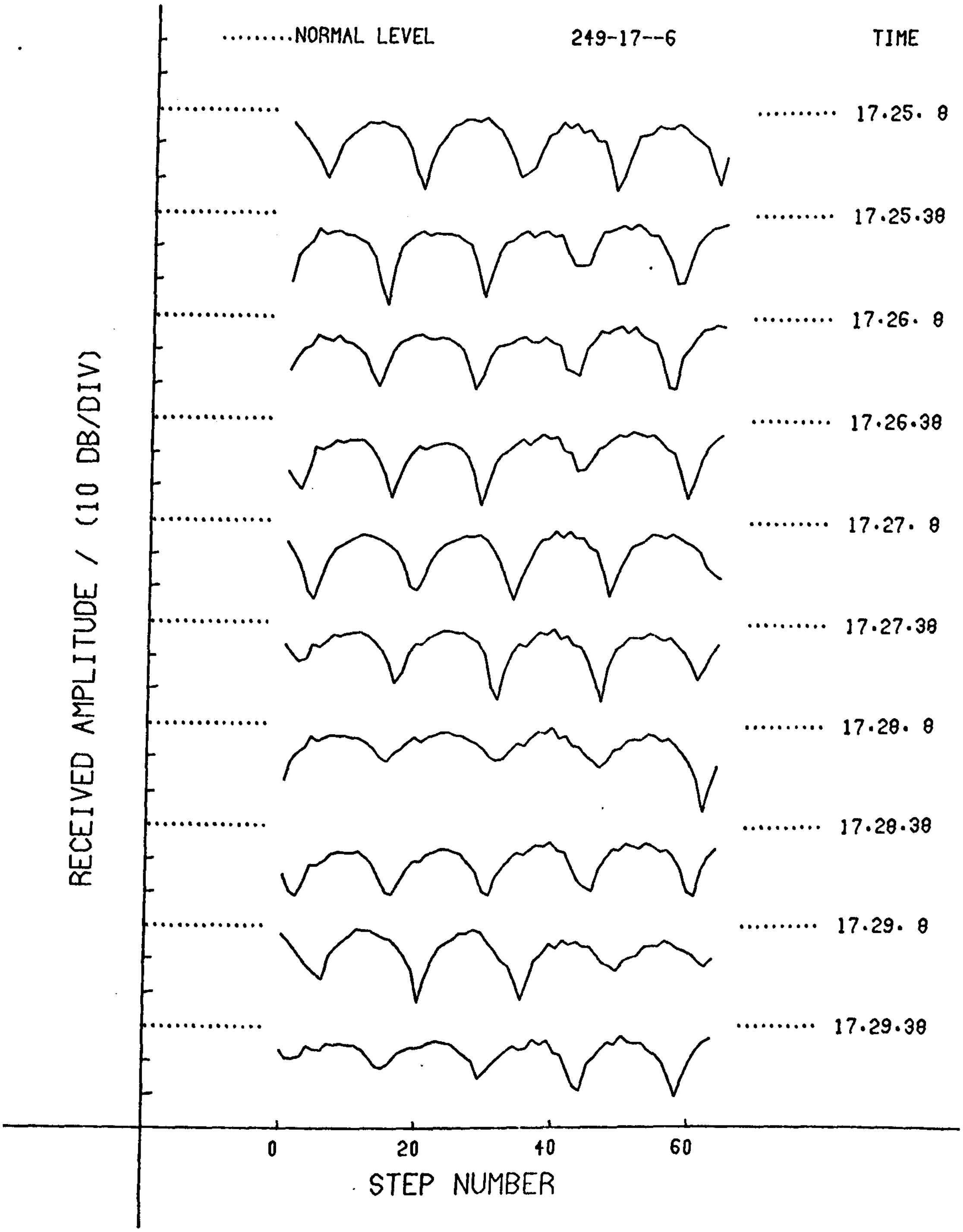
17.20.38
17.21. 8
17.21.38
17.22. 8
17.22.38
17.23. 8
17.23.38
17.24. 8
17.24.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8k



.........NORMAL LEVEL
249-17--6
TIME
17.25. 8
17.25.38
17.26. 8
17.26.38
17.27. 8
17.27.38
17.28. 8
17.28.38
17.29. 8
17.29.38
RECEIVED AMPLITUDE / (10 DB/DIV)
0
20
40
60
STEP NUMBER

Fig. 8Z

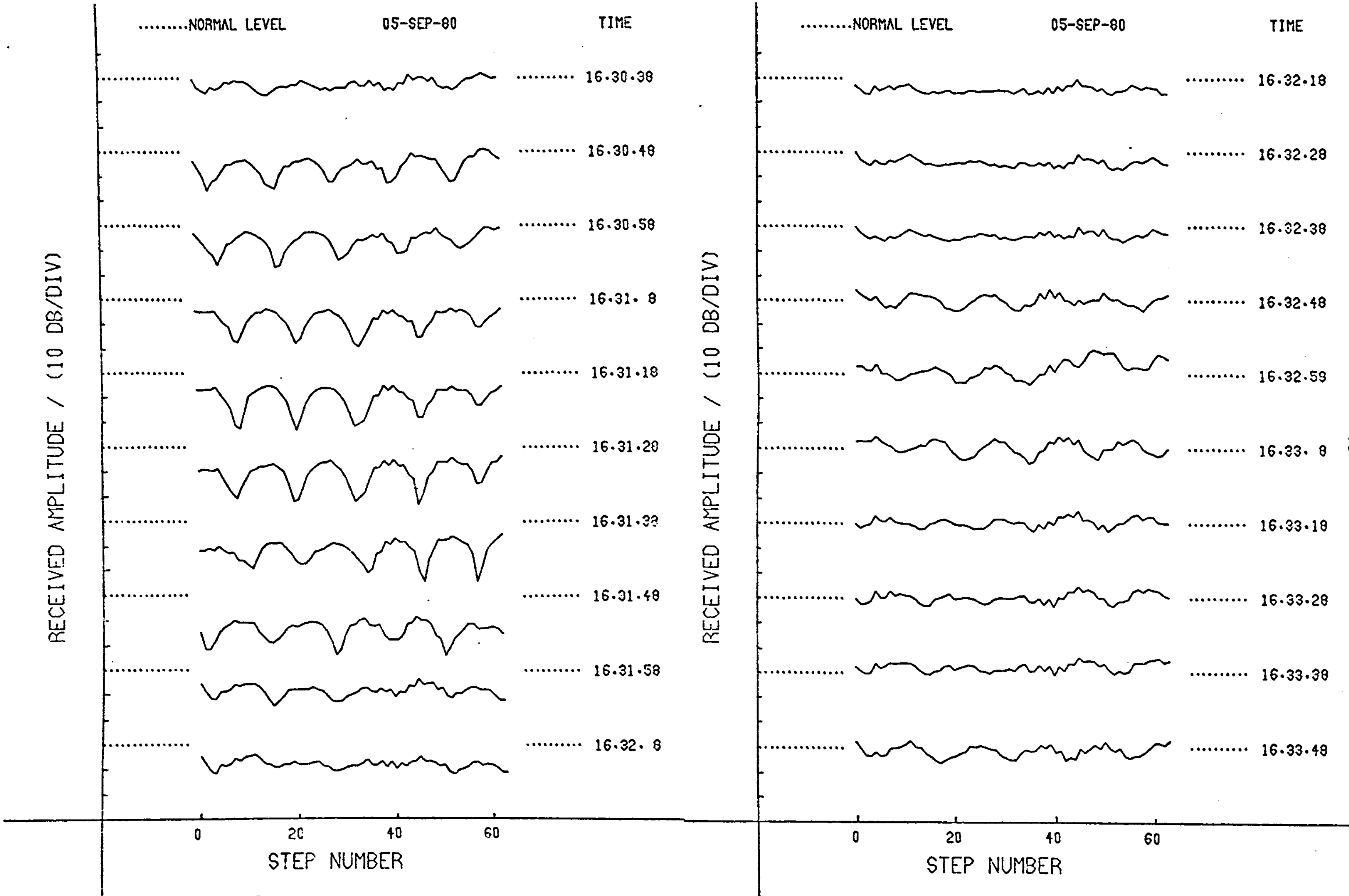


Fig. 9 Consecutive sweeps (amplitude) at the indicated times

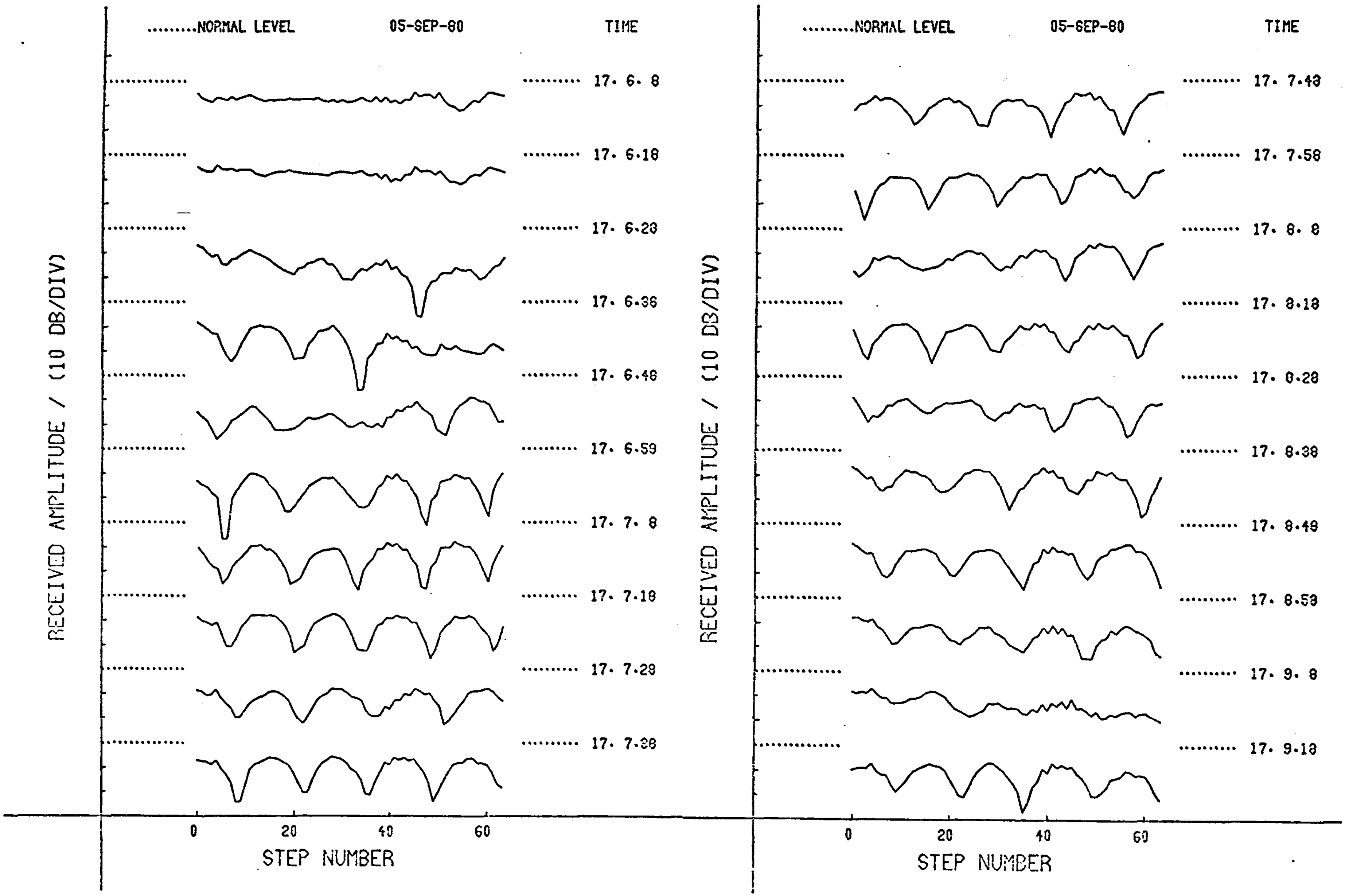


Fig. 10 Consecutive sweeps (amplitude) at the indicated times

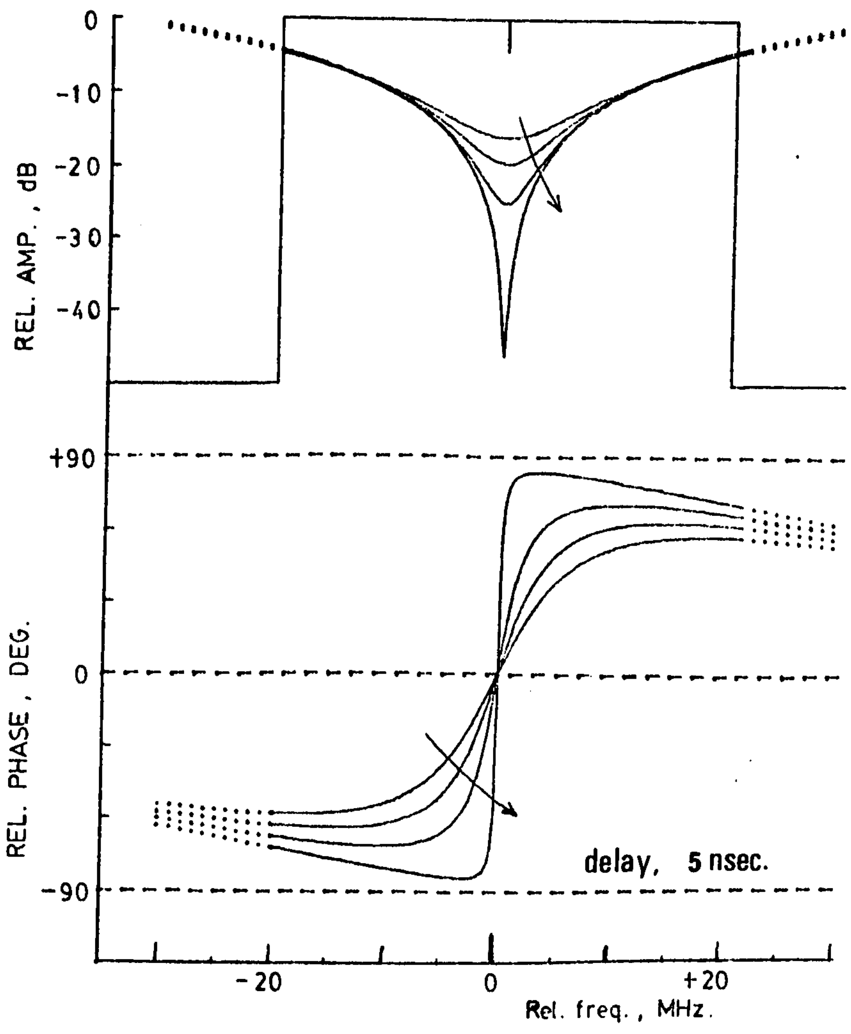


Fig. 11 Illustrating the amplitude and phase distortion, relative to that which would be obtained from a single path, associated with a two-path fade. The arrows indicate increasing fade depth and an ideal 40 MHz band is indicated

APPENDIX

Submission to C.C.I.R. concerning microwave angles-of-arrival

Documents

C.C.I.R. Study Groups

Period 1978-1982

Received:

Original: English

Subject: Report 338-3

CANADA

PROPAGATION DATA REQUIRED FOR LINE-OF-SIGHT RADIO RELAY SYSTEMS

Variations in Angle-of-Arrival on Terrestrial Microwave Links

1. Introduction

In collaboration with the Communications Research Centre, the Centre for Radio Science, University of Western Ontario, has conducted experiments aimed at the investigation of anomalous propagation on terrestrial microwave links. This work has been funded largely by a series of D.S.S. contracts.

Results obtained from experimental observations in South-Western Ontario are presented which relate to movements in received angle-of-arrival on a typical microwave link as operated by Ontario Hydro, and whose cooperation in these measurements is greatly appreciated. A discussion of the problems encountered as a result of such movements is included with a view to modification of the CCIR Report 338-3.

2. Experimental Measurements

The microwave diagnostic system used in the measurements described here is designed to provide accurate estimates of path delay (± 0.01 m) and component angle-of-arrival (± 0.05 deg) under multipath conditions, and angle-of-arrival during periods of single path propagation with similar precision. Based on a frequency swept interferometer, the system is described in detail in Webster and Ueno [1980]. The measurements presented here involved a sweep in frequency in the range 8.5-9.5 GHz and samples of amplitude and phase were taken over a 1 second interval every 20 seconds (unless otherwise stated); the path length was about 35 km. with antennas at a height of about 50 m. above ground at each end.

Under single path conditions, typical observed movements in angle-of-arrival are shown in figs 1 and 2. In the first of these, different sampling rates are used to illustrate the oscillatory nature of some of the perturbations and to exclude the possibility of aliasing. Fig. 2 shows similar variations together with a signal amplitude from the independent Ontario Hydro communications system; it is seen that the angle-of-arrival changes show reasonable correlation with amplitude fluctuations suggesting mild antenna decoupling. These examples of angle-of-arrival movements are not uncommon occurrences and such changes over a total range of about 0.6 deg. seem to be almost routine. A more extreme example is shown in fig. 3 where a sudden change of almost 1 deg. in AOA is seen to occur, and which coincides with fluctuations in the communication link amplitude. However, it should be noted that, here, the diagnostic system sampled only every 30 mins so that while all records taken indicated single path propagation, the possibility of multipath conditions in the intervening periods cannot be excluded.

When multipath does occur, experimental records similar to those presented in figure 4 are obtained from which the path parameters listed are derived by pattern synthesis. The difference in AOA for the two paths (~ 0.4 deg) is typical and extreme values of individual path AOA over a range of about 1 deg. have been observed.

Observations such as the above are discussed at greater length in Webster and Ueno [1980], Webster and Lam [1980], and Webster and Lam [1981].

3. Discussion

3.1 Single-path propagation

For a given refractive index gradient with height, it may be shown readily that over distances normally associated with terrestrial microwave links, the resultant angle-of-arrival varies almost directly with path length. Further, for a given change in (uniform) gradient, the specific change in angle-of-arrival (that is change in AOA/path length in km)

$$\Delta\theta_s = -2.86\times10^{-5}\Delta\left(\frac{dM}{dh}\right) \;°/\text{km}$$

where M is the often used modified refractive (dM/dh is in N units/km). It is useful at this point to gain some feel for anticipated changes in angle-of-arrival during single path propagation on the somewhat simplistic assumption that dM/dh is uniform over the height range of interest but that its magnitude varies in accordance with published measured values. Using data from GTE Lenkurt (1975) and Segal and Barrington (1978), representative values are given in table 1 for the range of Δ(dM/dh) and $\Delta\theta_s$ (relative to the median values). Ranges encompassing the expected AOA for 95% and 99.8% of the time for dry inland and humid coastal regions are considered.

Table 1

Anticipated range of angle-of-arrival for 95% and 99.8% of the time

	Median	95%		99.8%	
	$\frac{dM}{dh}$	$\Delta\left(\frac{dM}{dh}\right)$	$\Delta\theta_s$ °/km x 10^3	$\Delta\left(\frac{dM}{dh}\right)$	$\Delta\theta_s$ °/km x 10^3
Inland	+120	-50 → +50	+1.43 → -1.43	-80 → +70	+2.29 → -2.00
Coastal	+100	-85 → +80	+2.43 → -2.29	-240 → +160	+6.86 → -4.58

These numbers are translated into ranges of angle-of-arrival for typical links of length 35 km and 80 km in fig. 5. Beamwidths of commonly used parabolic antennas (between half-power points) as a function of frequency are shown in fig. 6. It may be seen, using figs 5 and 6, that long, high-frequency, links using high gain antennas in humid coastal regions are likely to experience considerable difficulty with antennna decoupling, whereas systems at the other extreme (relatively low-frequency, short path length over dry inland terrain) should be relatively free of such bothersome effects, even if "big dishes" are used. In between these two situations, whether or not problems arise might be dependent upon such matters as accuracy of original alignment (particularly if the antennas are aligned by chance under somewhat anomalous conditions). It might be remarked that the above ranges are based upon the stated simplifying assumptions and it might not be surprising to find that perturbations exceeding these by perhaps a factor of 2 occur in practice. Such an increase might entail disproportionate consequences since if a given change produces a loss of 3 dB, doubling that change is likely to produce signal attenuations exceeding the system fade margin.

Experimental evidence tends to support the above simple picture of angle-of-arrival under single path conditions. Using what appears to be best described as an inland link, of length 55 km, Bell [1967] reports no changes exceeding $\pm$ 0.12 deg in a year's observations [this translates into a specific change in AOA of min extreme values $\pm$ 2.18 x 10^{-3} deg/km. see Table 1]. On the other hand, the results shown here indicate a fluctuation range of perhaps 0.7 deg at the 99.8% level which give roughly $\Delta\theta_s$ in the range $\pm$ 10 x 10^{-3} deg km]. The climate in South-Western Ontario is heavily influenced by the proximity of the Great Lakes and is best described as a "modified coastal"; the word "modified" is used in recognition of the fact that air/water temperature relationships are somewhat different from those experienced on a true coastline.

Data collected in Japan [Ikegami et al, 1968] shows significant changes in angle-of-arrival ranging from about ± 0.4 to -0.1 deg over a 29 km path [$\Delta\theta_s$ = +14 to -3.5 x 10^{-3} deg/km]. The authors do not give exact path details, but it appears that it is within a few kilometers of the sea. Substantial seasonal variation is indicated in these measurements. Sharpless [1946] reports upward movements of up to 0.46 deg on a 38 km [$\Delta\theta_s$ = +12 x 10^{-3} deg/km], again on a path influenced by the sea. Later measurements in the same area [Crawford and Sharpless, 1946] show angles which give $\Delta\theta_s$ in the range +5.5 to -2 x 10^{-3} deg/km. Two of these papers [Ikegami et al, and Crawford and Sharpless] present data illustrating good correlation between angle-of-arrival and modified refractive index gradient dM/dh.

3.2 Multi-path Propagation

The angle-of-arrival of each component during multi-path conditions is not related to path length in such a simple way as as above (if at all) since the effects are usually dictated by antenna vertical positions in relation to to the height of atmospheric refractivity perturbations, although it should be noted that for a given refractivity profile a minimum path length exists below which only single path propagation is possible.

Several authors have presented AOA data obtained under multi-path conditions. In measurements made in the same geographic area (coastal), results are presented by Crawford and Sharpless [1946] and Crawford and Jakes [1952] which show a high degree of variability. Individual path AOAs up to 0.75 deg above normal are reported with separations between components ranging from about 0.7 deg down to unresolvable. Rapid changes with time were also observed. Similar results are presented by Webster and Ueno [1980] with angles of arrival up to 0.7 deg above normal, component separation of 0.4 degree and evidence of values changing with time. As with single path changes, very large excursions seem to be predominantly in the direction of higher than normal.

All of the above is concerned with movements in angle-of-arrival in the vertical plane. Changes in the horizontal plane would be expected to be much less due to slower changes in refractive index: this is supported by experimental measurements [Sharpless, 1946] indicating changes to be less than + 0.1 deg.

4. Conclusions

It seems that substantial change in angle-of-arrival are to be expected in terrestrial microwave communications and that for single path propagation the following should be noted:

(a) The range in angle-of-arrival is approximately proportional to path length.

(b) The effect is more pronounced in coastal regions than inland, with specific change in AOA (deg/km) of about $\pm 2 \times 10^{-3}$ for the latter and up to + 14 to -5×10^{-3} for coastal operations.

(c) Extreme departures from normal seem to be predominantly upwards (although this may be partially a product of terrain obstruction with angles lower than normal).

(d) In the interest of high received signal levels, larger antennas tend to be used on longer paths, which essentially "squares" the problem of antenna decoupling and is to be regarded as somewhat undesirable. Effective elliptical apertures may be of help here.

During periods of multi-path propagation, the expected range of angles-of-arrival seems to be not dissimilar to that under single path conditions, a point of some interest if antenna discrimination is contemplated in attempting to reduce multi-path effects.

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IKEGAMI, F., Akiyama, T., Aoyagi, S. and Yoshida, H. [March, 1968]. Variation of radio refractive index in the lower atmosphere, I.E.E.E. Trans. Ant. Propagat., AP-16, 194-210.

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SHARPLESS, W.M., [1946], Measurement of the angle-of-arrival of microwaves, Proc. I.R.E., 838-845

WEBSTER, A.R. and Ueno, T. [1980], Tropospheric microwave propagation - an X-band diagnostic system, I.E.E.E. Trans. Ant. Propagat., AP-28, 693-699.

WEBSTER, A.R. and Lam, W.I. [1980], Microwave angle-of-arrival measurements under anomalous tropospheric propagation conditions, pre-prints URSI Commission-F Symposium, Lennoxville, Canada.

WEBSTER, A.R. and Lam, W.I. [1981], Microwave angle-of-arrival measurements under anomalous tropospheric propagation conditions. To be published, Ann. de Telecomm.

ANNEX

Suggested modification to CCIR Report 338-3

(a) Replace section 3 with the following:

3. Variation in angle-of-arrival

3.1 Single path propagation

Variations in angle-of-arrival in the vertical plane, caused by changes in refractive index gradient with height, are observed, with the magnitude of the changes being approximately proportional to the path length. The expected range of angle-of-arrival is wider in humid coastal regions than in dry inland areas.

Measurements made on an inland path of length 55 km and at a frequency of 11 GHz showed no variations greater than ± 0.12 deg during a period of 1 year [Bell, 1967]. Measurements in the Federal Republic of Germany on a path of length 70 km at a frequency of 0.515 GHz show approximately the same order of variation.

Observations in more humid coastal regions show significantly higher variations. Ikegami et al [1968] measured changes ranging from + 0.4 to -0.1 degrees on a 29 km path with marked seasonal dependence. Sharpless [1946] and Crawford and Sharpless [1946] using different paths (but in the same geographic area) report similar proportionate deviations. Webster and Ueno [1980] and Webster and Lam [1981] operating near the Great Lakes present ranges of about ± 0.4 deg on a 35 km path at a frequency of 9 GHz and note an oscillatory nature for the fluctuations on occasion.

Direct observation of mild antenna decoupling due to angle-of-arrival movements are shown by Webster and Lam [1980] and similar effects have been observed in the U.S.S.R. where the narrow beam widths employed are thought to be responsible for slow variations in signal strength. This is consistent with descriptions presented elsewhere.[see Dougherty, 1968]

Since, under given conditions, the deviation in angle-of-arrival is expected to be proportional to path length, a useful parameter might be defined, namely, specific change in angle-of-arrival (that is, change in degrees/path length in km). Theoretical and experimental evidence suggests that, as a guide, the range of specific change in angle-of-arrival covering 99.8% of the time be taken as ± 2×10^{-3} deg/km for inland paths and + 14 to -5×10^{-3} deg/km for coastal regions: the larger upward movements in the latter case should be noted.

3.2 Multi-path propagation

Deviations from the normal angle-of-arrival vary widely under multi-path conditions and do not exhibit a strong dependence on path length. Crawford and Sharpless [1946] and Crawford and Jakes [1952], in measurements in the same geographic area, find a high degree of variability, with individual paths elevated up to 0.75 deg above normal and component separations from 0.7 deg down to unresolvable. Rapid changes with time were also noted. Similar results are presented by Webster and Ueno [1980] who note elevated angles-of-arrival up to 0.7 deg and component separations in the order of 0.4 deg; variability with time in these angles is also observed. Very large excursions seem to be predominantly in an upward direction.

(b) As an alternative, the section labelled 3.2 above might be inserted after para. 1 in section 4.1.

(c) Include in the list of references:

Crawford, A.B. and Sharpless, W.M. [1946], Further observations of the angle-of-arrival of microwaves. Proc. I.R.E. 845-848.

Sharpless, W.M., [1946], Measurement of the angle-of-arrival of microwaves, Proc. I.R.E., 838-845.

Webster, A.R. and Ueno, T. [1980], Tropospheric microwave propagation - an X-Band diagnostic system, I.E.E.E. Trans. Ant. Propagat., AP-28, 693-699.

Webster, A.R. and Lam, W.I. [1981], Microwave angle-of-arrival measurements under anomalous tropospheric propagation conditions. To be published, Ann. de Telecomm.

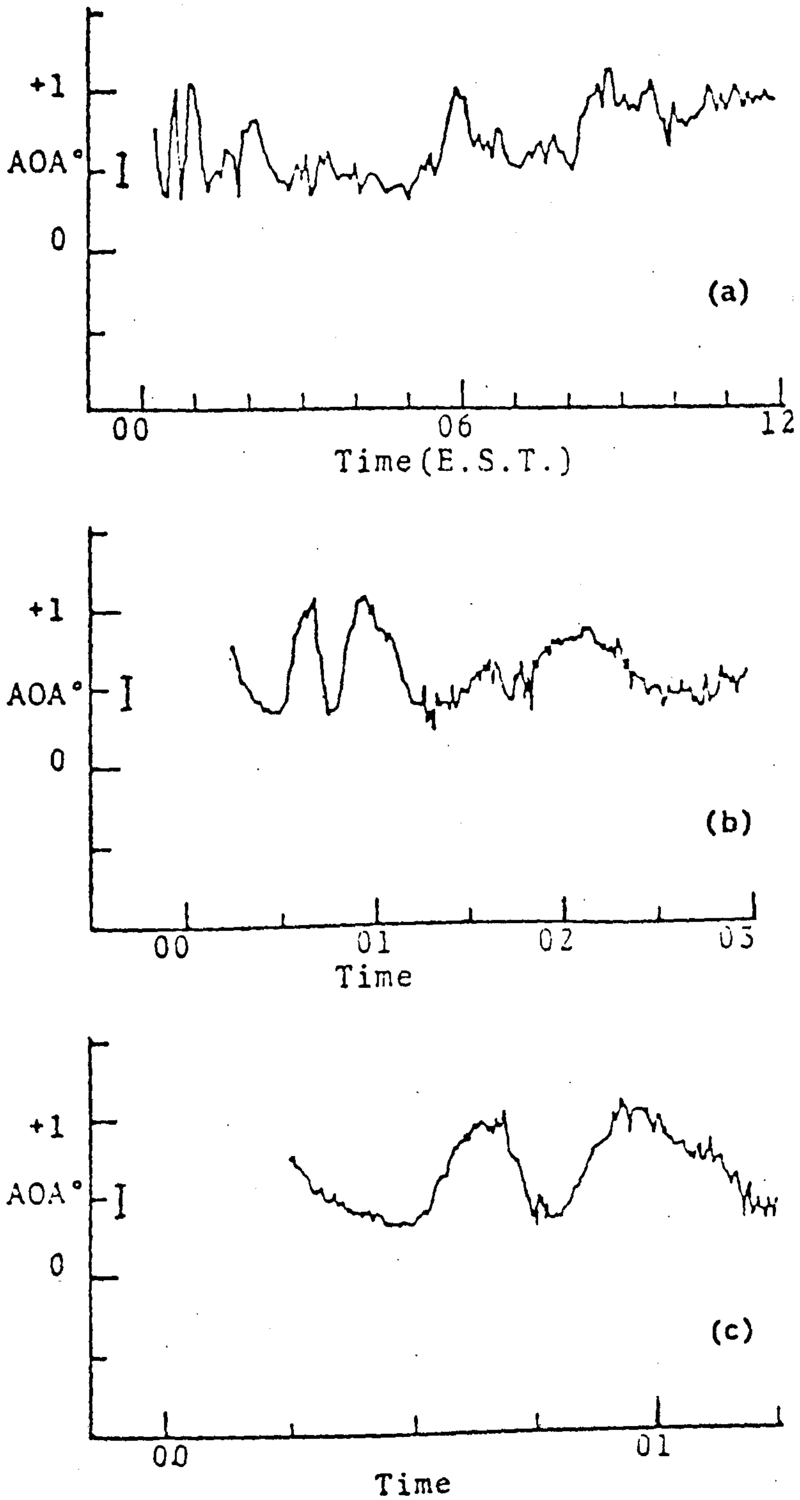


Fig. 1 Observed angle-of-arrival (AOA) for September 10, 1979 sampled at intervals of (a) 5 minutes, (b) 1 minute and (c) 20 seconds.

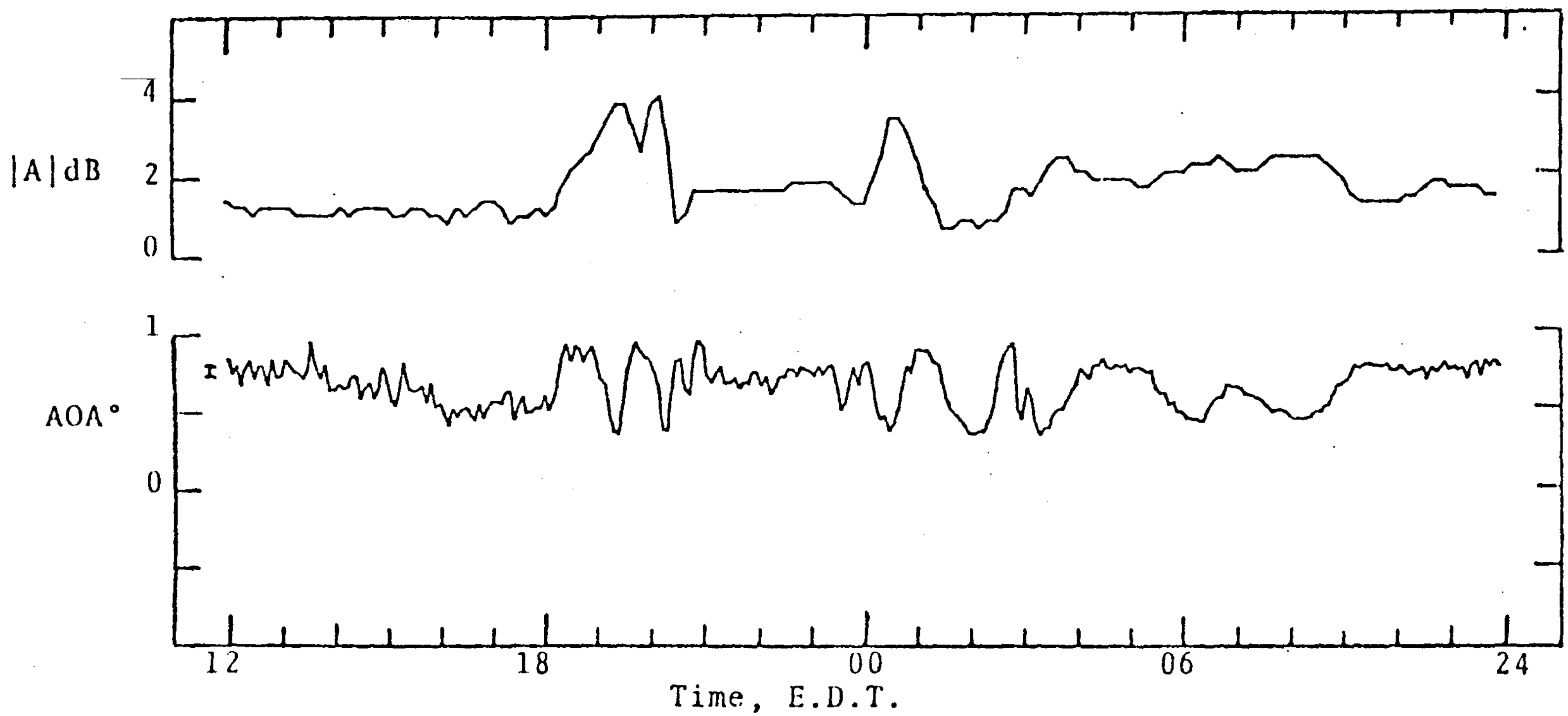


Fig. 2 Communications link relative amplitude (|A|) and diagnostic system angle of arrival (AOA) for August 22/23, 1979.

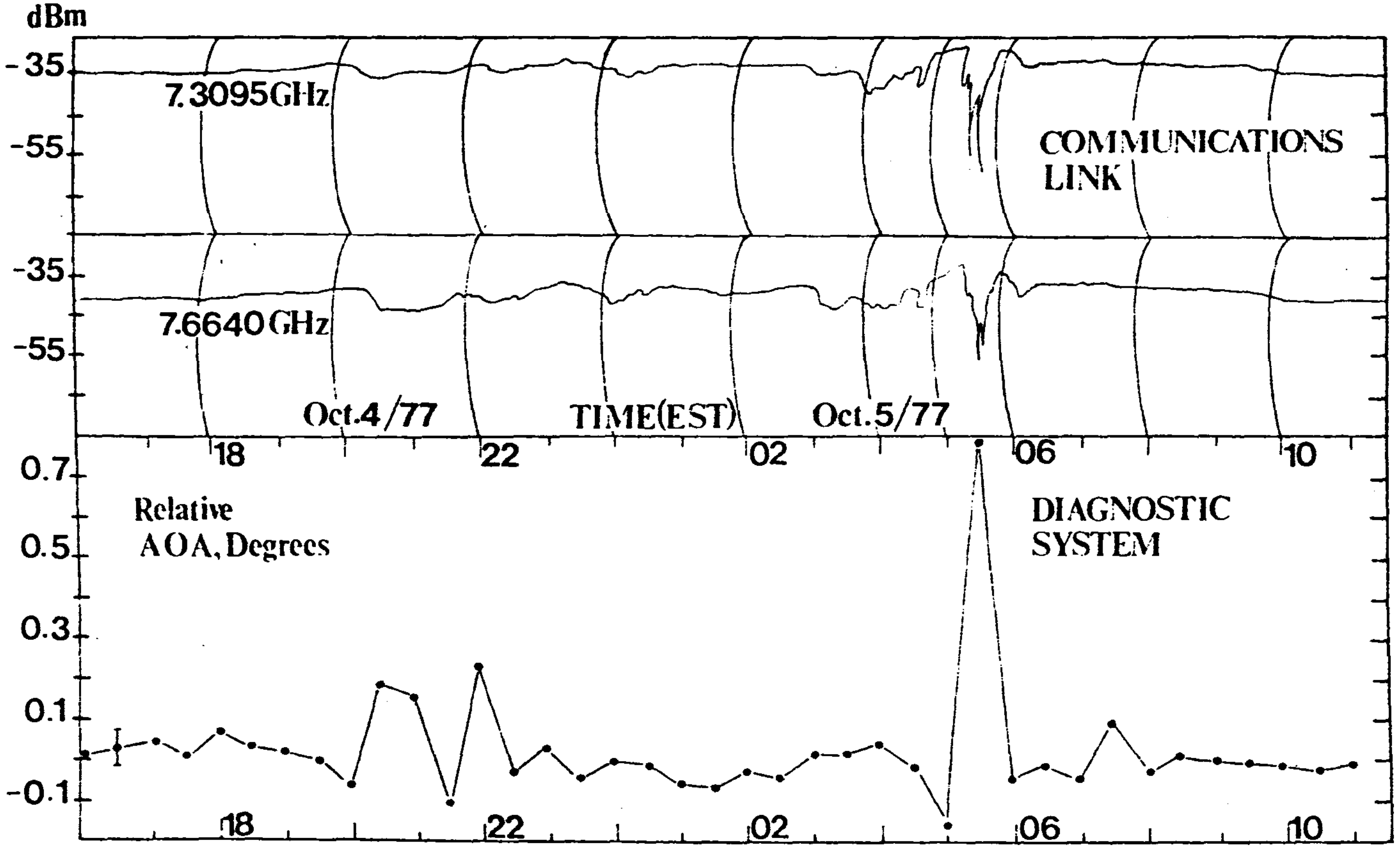
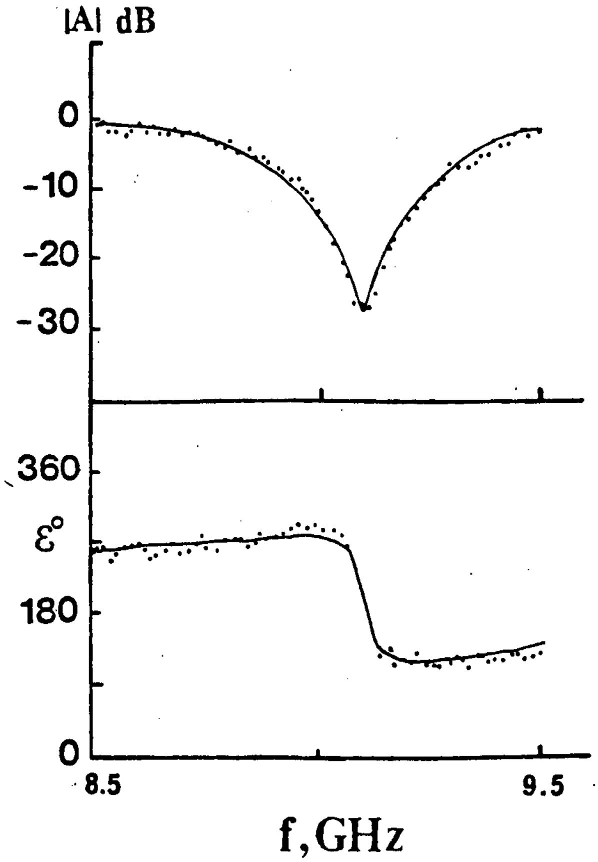


Fig. 3 Communications link amplitude and diagnostic system angle-of-arrival for October 4/5, 1977



$A_0 = 0.50, \theta_0 = 0.70^\circ$

$A_1 = 0.45, \theta_1 = 0.33^\circ, \delta l_1 = -0.247\text{m}$

Fig. 4 A typical two path record of diagnostic system amplitude and phase: dots, experimental; full line, synthesized.

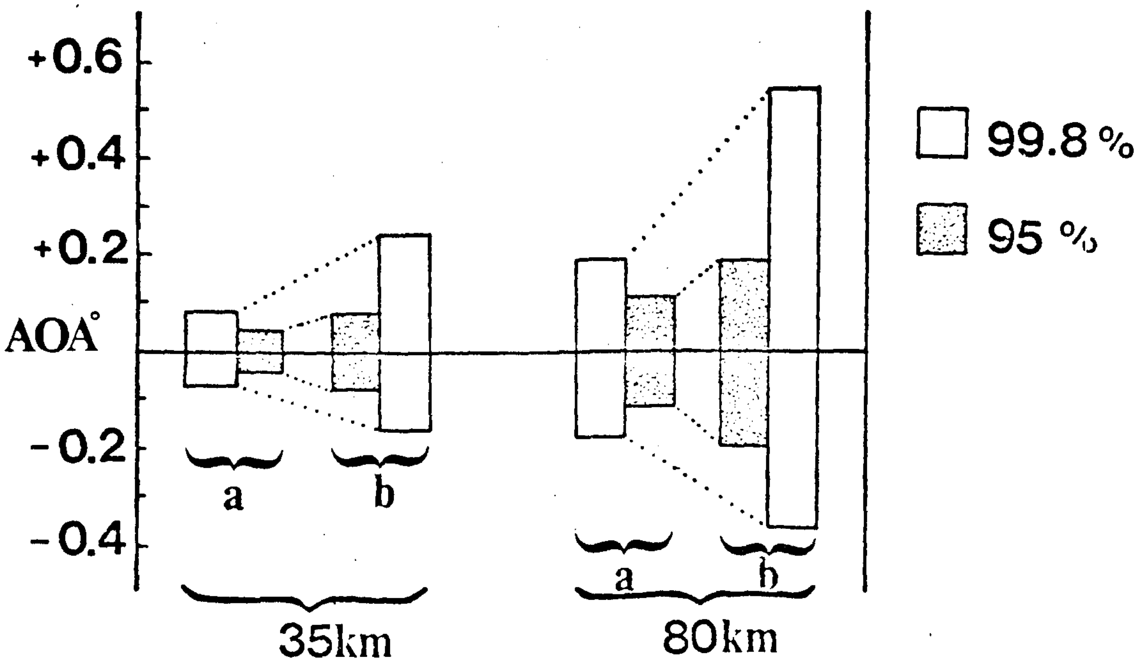


Fig. 5 Expected range of angle-of-arrival for (a) inland and (b) coastal microwave links for 95% and 99.8% of the time; path lengths as indicated

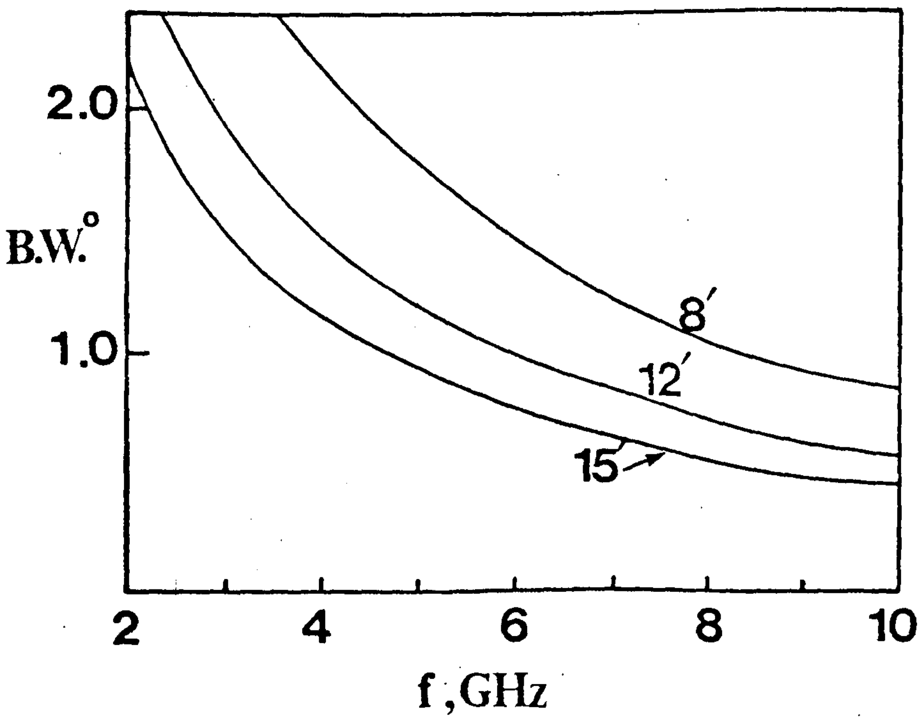


Fig. 6 Beam-width (between 3 dB points) for 8, 12 and 15' paraboloids as a function of frequency

DATE DUE
DATE DE RETOUR
