Investigation of Traveling Ionospheric Disturbances Using The Differential Doppler Data from the Apollo-Soyuz Mission

Polytechnic Institute of New York

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Principal Investigator

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Foreward

This Final Report fulfills the obligation of the Polytechnic Institute of New York under NASA Grant GAGW-51. The period of performance was March 1, 1980 to February 28, 1981. Dr. Stanley H. Gross was Principal Investigator. The program was joint with the Smithsonian Astrophysical Observatory (SAO) under a subcontract from the Polytechnic Institute of New York. Dr. Mario Grossi led the SAO effort. SAO was the source of the Doppler data from the Apollo-Soyuz mission.

Abstract

The ASTP Doppler data were recalibrated, analyzed and related to geophysical phenomena and found consistent. Spectra were computed for data intervals covering each hemisphere. As many as 14 such intervals were analyzed. Wave structure is seen in much of the data. The spectra for all those intervals are very similar in a number of respects. They all decrease with frequency, or with decreasing wavelength. Power law fits are reasonable and spectral indices are found to range from about -2.0 to about -3.5. Both large scale (thousands of kilometer) and medium scale (hundreds of kilometers) waves are evident. These spectra are very similar to spectra of in situ measurements of neutrals and ionization measured by Atmosphere Explorer C. There is just one data sample from AE-C from the only orbit for which measurements are available for the day of the ASTP flight. Unfortunately, a lack of receiver lock at this time produced no useful ASTP data for comparison. The nearest available data sample, about 50 minutes later, has a somewhat different spectral index and wave pools than the AE-C data. Its spectrum is made up of a different group of outstanding waves as well. ISIS-II data were briefly reviewed.

1. The Investigation

The purpose of the program was to study the Doppler data measured during the Apollo-Soyuz Test Program (ASTP)(Weiffenbach et al, 1977), on July 24, 1975 for information on traveling ionospheric disturbances (TID's) and to evaluate the experiment as a measuring scheme. The satellites were at an altitude of about 250 km, below the F peak in an orbit inclined approximately 50°. The Doppler technique, used between two spacecrafts, enables ionospheric measurements remote from the perturbing influence of the spacecrafts and their wakes. The differential Doppler measures the rate of change of the column content of ionization between the spacecrafts. It had also been planned to seek corroborative data from ground measurements to confirm the Doppler measurements and to deduce wave characteristics. Many of the efforts required to fulfill these purposes were completed. Some were not completed, requiring more time for searches and investigations. This report summarizes the accomplishments.

The tasks were divided between the Polytechnic Institute of New York and SAO. SAO was concerned with the proper calibration of the Doppler data, their reduction and processing, and the evaluation of the technique as an ionospheric measuring tool. The Polytechnic Institute of New York was concerned with the management of the effort, the interpretation of other measured data, if available, for corroboration, the study of ionospheric structure as detected by the measurements, and the use of the technique for detecting TID's.

SAO reduced and processed the data and identified a number of well-known ionospheric phenomena, including the equatorial anomaly, day-night transitions, medium-scale TID's and other features, providing confidence in the ability of the technique to measure the ionosphere. The results of their efforts were reported in a final report to the Polytechnic Institute of New York, which is attached to and becomes a part of this report.

Polytechnic's efforts are detailed in the remainder of this report. Initial emphasis was put on simulating the effects of TID's on ionograms for the purpose of analyzing real ionograms. This effort was primarily tutorial. Subsequent and major emphasis was on spectral analysis of the Doppler data via the MEM process (Ulryck and Bishop, 1975) for wave structure and its interpretation. A study was also made of Atmosphere Explorer (AE) data for the same day, July 24, 1975.

The only data were from one orbit of AE-C. Some ISIS-II data were also examined. Ground based ionograms were obtained by SAO. For the particular day of the ASTP these ionograms were found to be poor and of little use for the purpose.

Spectral Analysis

Approximately 9 orbits of data were available from ASTP. A spectral analysis of all the data was made by SAO and shown in their attached report. Taking all the data together can be misleading from the standpoint of geophysics. Ideally, one would want to exam in data for various latitude bands. Because data are available in 10 second samples only, about 500 data points are available per orbit. Since one would like to have at least a few hundred data points in making a spectral analysis, the best one can do from the standpoint of geophysics is to analyze on a hemispheric basis. Thus, the data were divided into sixteen groups, each representing a hemisphere, and each consisting of about 256 data points.

An example of such a sample of data is shown in Figure 1 which shows Doppler shift in Hz vs. a normalized scale representing time. The normalized quantity varies from zero to 2, which corresponds to a time interval of 2560 seconds. The start of the data is at 22636 seconds (UT). This is for the northern (summer) hemisphere excursion of the spacecrafts in the longitude range 45°E to -150°W. Wavelike oscillations are evident in this sample of Doppler data. These oscillations have half periods from about 60 seconds to 200 seconds, corresponding to in-orbit distances of about 450 km to 1500 km for a satellite velocity of 7.8 km/sec. Smaller scale structure are also evident. The positive to negative Doppler extremes are no greater than about 2.5Hz.

The power spectrum of these data are shown in Figure 2 plotted as dots at discrete frequencies that are integral multiples of the fundamental frequency, $1/2560=3.906\times10^{-4}$ Hz, based on the duration of the record in Figure 1. The log of the spectral power is plotted against the integral number, or harmonic number, plotted on a logarithmic scale. The highest harmonic number is 128 which corresponds to the Nyquist frequency for 10 second samples, 0.05Hz. Thus the graph contains 128 dots, harmonic numbers or frequencies. The first dot is on the vertical axis and not visible. The first visible dot is the second harmonic.

A straight line is also drawn in the figure. This is a least squares fit to the data and demonstrates that a broad spectrum is involved, decreasing with frequency with a spectral index, AF in the figure for this case, equal to -2.4371.

The spectrum is seen to oscillate about the fit with a broad spectral range starting at harmonic 14 and continuing to harmonic 42 or 43, corresponding to the wavelength scale from 487 km to 1426 km. This range agrees with the periodicities seen in Figure 1.

A somewhat different sample of data is shown in Figure 3 plotted against the normalized time scale as in Figure 1. The time interval is the same, 2560 seconds, and the start is at 35916 seconds, UT. This sample is for southern hemispheric portion of the orbits in the longitude range 169°E to -27°W. Much less periodicities are evident in the figure than in Figure 1, much more small scale structure is evident. The larger periodicities, however, are typical of those seen in Figure 1.

The spectrum for the data in Figure 3 is shown in Figure 4 together with a power law fit. The spectral index of the fit AF= - 2.5494. Some peaks are observed in the spectra at the harmonics 7, 14, 17, 20, 27 and 71, corresponding to wavelengths of 2853 km, 1426 km, 1175 km, 998 km, 740 km and 281 km, respectively. In view of the nature of the Doppler data in Figure 3, it is not clear whether all these peaks are real or due to the peculiarities of the MEM procedure. Peaks at harmonics 14, 27 and 71 may be real, though not precise in frequency, due to the discrete nature of the spectra and inaccuracies in the MEM spectral estimate. There is a suggestion of nulls in the spectrum at about the 54th and 94th harmonic. The power in the spectrum of Figure 4 is comparable to that of Figure 2.

Other examples from both hemispheres are quite similar. Some are shown in Figures 5 through 8. Figure 5 and 7 are Doppler data. Each example of the data is followed by its spectrum in Figures 6 and 8. All data are plotted vs. a normalized time scale corresponding to 2560 seconds. The starting times for the data of Figures 5 and 7 are in seconds, UT, respectively, 25286 and 27936.

Since the data samples are finite, the first 4 or 5 frequencies of their spectra are not reliable. The spectra are better estimates at higher frequencies. Therefore, power law fits based on all frequencies, as in Figures 2,4,6 and 8 are not valid. It can be seen in the figures that the fits are not representative of the spectral spread at the higher frequencies. The fit should be based on spectra starting from a higher frequency or harmonic, such as the tenth. The spectra were refitted this way. An example for the data of Figure 3 is shown in Figure 9. This is the same spectrum as in Figure 4, except that it starts from the tenth harmonic. The power law fit is much more representative of the spectrum. Its spectral index AF differs from that in Figure 4 and has a more negative value, -2.9972. The variance of the spectrum about the fit is given by EF and is 4.8064 in this case. Oscillations about the fit are more clearly seen in this figure. Two other examples are shown in Figure 10 and 11. The spectral index AF= - 2.3408 and variance EF=4.8183 in Figure 10, whereas the corresponding values are -2.0565 and 4.8595 for the spectrum in Figure 11. For ten cases studied in this fashion, the spectral index varied from -2.0565 (Figure 11) to -3.41067 with an average of -2.7148. The variance about the fits varied slightly from 4.8034 to 4.8721 with an average of 4.8356. The power levels of the spectra are within a factor of 2 of each other in most cases. In one case the power level is within a factor of 4 of the others. The magnetic activity conditions for the time of these measurements were relatively quiet. The magnetic index Ap ranged from 5 to 7 and from 1^+ to 2 for K_p. The AE index ranged from 53 to 475 over the period, but it is not clear whether there is any connection with this index. The uncorrected 10.7 cm solar flux F10.7 was 77 for the day.

It is evident that both large scale and medium scale spectral components are present in all the data analyzed. These may be gravity waves, the large scale possibly arising from auroral phenomena and the medium scale from local sources. The pattern persists, but no particular components stand out more than others in all the samples. The energy levels appear to be about the same, regardless of hemisphere.

Atmosphere Explorer

Only data from one orbit (8108) of AE-C on July 24, 1975 are available, and these only during the time from 45900 seconds (UT) to about 47050 seconds (UT). The altitude varied from about 303 km to about 317 km, putting it close to the

F peak or above, except in equatorial regions. The longitude range is from -151°W to -61°W. The satellite was entirely in the northern hemisphere during this time. ASTP Doppler data during two intervals that overlap the AE data were not useful due to a failure of receiver lock. These were from 43906 seconds (UT) to 46456 seconds (UT) and from 46566 seconds (UT) to 49116 seconds (UT). A comparison can only be made in the next interval for which data is useful, from 49226-51776 seconds (UT).

Figure 12 is a plot of electron density measured by the Cylindrical Electrostatic Probe, CEP, (Brace et al, 1973) on AE-C. Electron density relates to the Doppler shift, since the latter is proportional to the rate of change of column density of the electrons between the spacecraft. Wave structure is evident in the data. Figure 13 is a graph of nitrogen, helium and argon densities as measured by the neutral Atmosphere Temperature Experiment, NATE, (Spencer et al, 1973) on AE-C. Nitrogen is the upper curve. Helium is in the middle and Argon is at the bottom of the graph. There is some wave structure evident in these neutral densities. The measured ion and electron temperatures are shown in Figure 14. The electron temperature is the upper curve and is measured by CEP. The ion temperature is measured by the Retarding Potential Analyzer (RPA)(Hanson et al, 1973). Wave variations are very evident in these measurements.

Doppler data from ASTP are shown in Figure 15 plotted vs. the normalized time scale for the interval 49226 seconds (UT) to 51776 seconds (UT). These data are 2550 seconds in length and are for the northern hemisphere in the longitude range -68°W to +97°E. Considerable wave structure is evident. Periodicities of the order of 160 seconds and 126 seconds are evident, corresponding to wavelengths of about 1230 km and 986 km, respectively. Smaller structure are also evident. The spectrum of these data is shown in Figure 16. Peaks evident in the harmonic range 16 to 24, correspond to the periodicities seen in Figure 15. The slope of the spectral fit for harmonic 10 and above is -2.6322. Other higher frequency peaks are evident corresponding to wavelengths in the range about 250 km.

The spectrum of the AE-C measured electron density is shown in Figure 17. A considerable number of peaks are evident. Two lines are drawn on the figure. This graph is a plot of the log of power vs. log frequency in Hz. Other scales shown are the frequency, wavelength in kilometers and harmonic number. This spectrum is for AE-C data spaced roughly 1.5 seconds apart for 750 seconds starting at 46250 seconds (UT). The spectrum is estimated using the MEM procedure.

The two straight lines are least square fits for different frequency intervals. One has a spectral index of -.975 and is obtained for the frequency interval from 20.8 mHz to 130.2 mHz. This interval is approximately 80% of the frequency scale. The second fit has a spectral index of -1.85. It is obtained from the frequency interval from 20.8 mHz to 65.1 mHz, which is half the interval of the first. Which of the two fits is preferable is not certain. In any event this spectrum is flatter than that in Figure 16. This difference may be attributable to the difference in time and the differences in longitude. Peaks are evident in Figure 17 at wavelengths of 599 km, 300 km, 214 km, 146 km, 122 km, etc. These wavelengths seem to bear no relationship to those in Figure 16. Again the separation in time and longitude may be important. However, it is significant that the Doppler spectra and those of AE-C are similar in general features.

ISIS-II Data

ISIS-II (G.G.Shepherd et al, 1973) data for July 24, 1975 data were examined. Several orbits overlap in time with ASTP from orbit 19950 to 19958. The satellite was at an altitude of about 1400 km. Ionograms are of the topside of the ionosphere. Thouth ASTP was below the F-peak, it is of interest to relate the topside. Spread-F conditions indicative of structure are evident in the ionograms. The profiles were not reduced, and the record was only briefly examined. No positive connections were possible with such limited effort. More analysis is needed.

Staff

Computer facilities of the Polytechnic Institute of New York were used during the program. One student was engaged in programming and analysis as part of a project effort.

Papers

A paper by R.D.Estes and M.D.Grossi of SAO has been prepared based on SAO work. It has been submitted to GPL for publication. Another paper by S.H.Gross, C. Friedman and M.D.Grossi is in preparation based on the Polytechnic spectral work.

Recommendations

The program should be continued to seek corroborative data from ground facilities to deduce the wave characteristics. This technique should be more fully utilized for ionospheric measurements when two or more spacecraft are available, as may be possible with Shuttle launched equipment.

References

Brace, L.H., R.F.Theis and A.Dalgarno (1973) - The Cylindrical Electrostatic Probes for Atmosphere Explorer-C, -D, and -E. J.Geophys.Res.8,341-348.

Hanson, W.B., D.R.Zuccaro, C.R.Lippencott and S.Sanatani (1973) - The Retarding Potential Analyzer on Atmosphere Explorer. J.Geophys.Res.8,333-339

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Spencer, N.W., H.B.Niemann and G.R.Carignan (1973) -The Neutral-Atmosphere Temperature Instrument. J.Geophys. Res.8, 287-296

Ulryck, T.J., and T.N.Bishop (1975), Maximum Entropy Spectral Analysis and Autoregressive Decomposition. Rev.Geophys.Sp.Phys. 13,183-200.

Weiffenbach, G.C., M.D.Grossi, and P.W.Shores (1977), Doppler Tracking Experiment MA-089, Summary Science Report, Apollo-Soyuz Test Project, Volumne I, pp.137-175.

67-68, 71-32

Northern Hemisphere

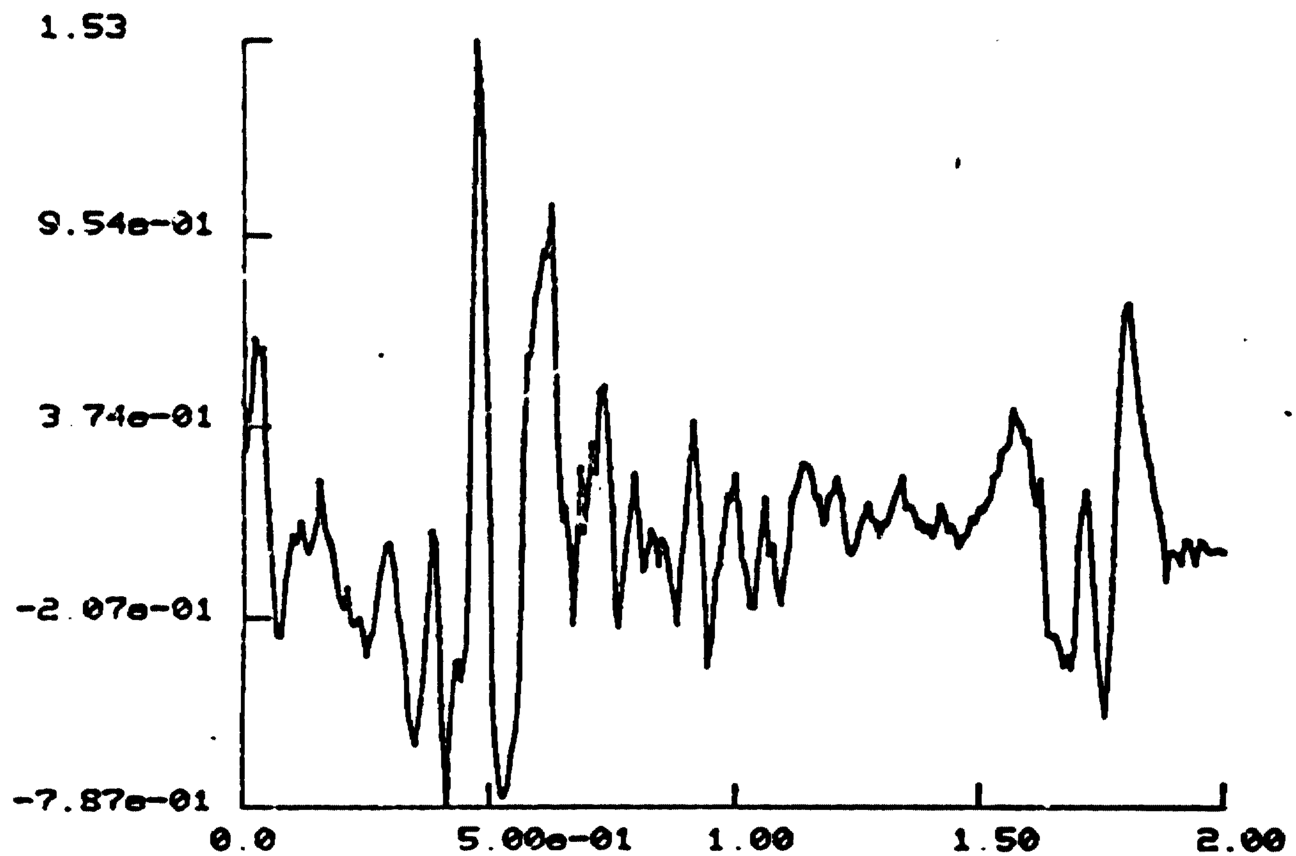


Figure 1. Differential Doppler data vs. relative time. The abseissa range from 0 to 2 corresponds to 2560 seconds. The ordinate is the Doppler shift in Hz. The time at the start of the figure is 22636 seconds (UT). The data are for the northern hemisphere.

Figure 2. Discrete spectrum of the Doppler data in Figure 1 obtained by the MEM. The spectrum is given by the dots. The abscissa, a log scale, is the harmonic number which is the frequency f, divided by the frequency f_T, associated with the total time sample; $f_T=1/2560$. The plot is to the Nyquist frequency for which the harmonic number =128. The ordinate is the logarithm of the spectral power. The straight line is a least squares fit to the spectrum. The longitude and latitude of the satellites at the beginning and end of the data are indicated. The frame and word identify the location of the data in the original data stream. The time span (UT) of the data is also given. The order of the MEM used was 85. AF is the slope or spectral index of the fit. BF is the constant which together with the slope describes the equation of the line. EF is the variance of the data (dots) about the line.

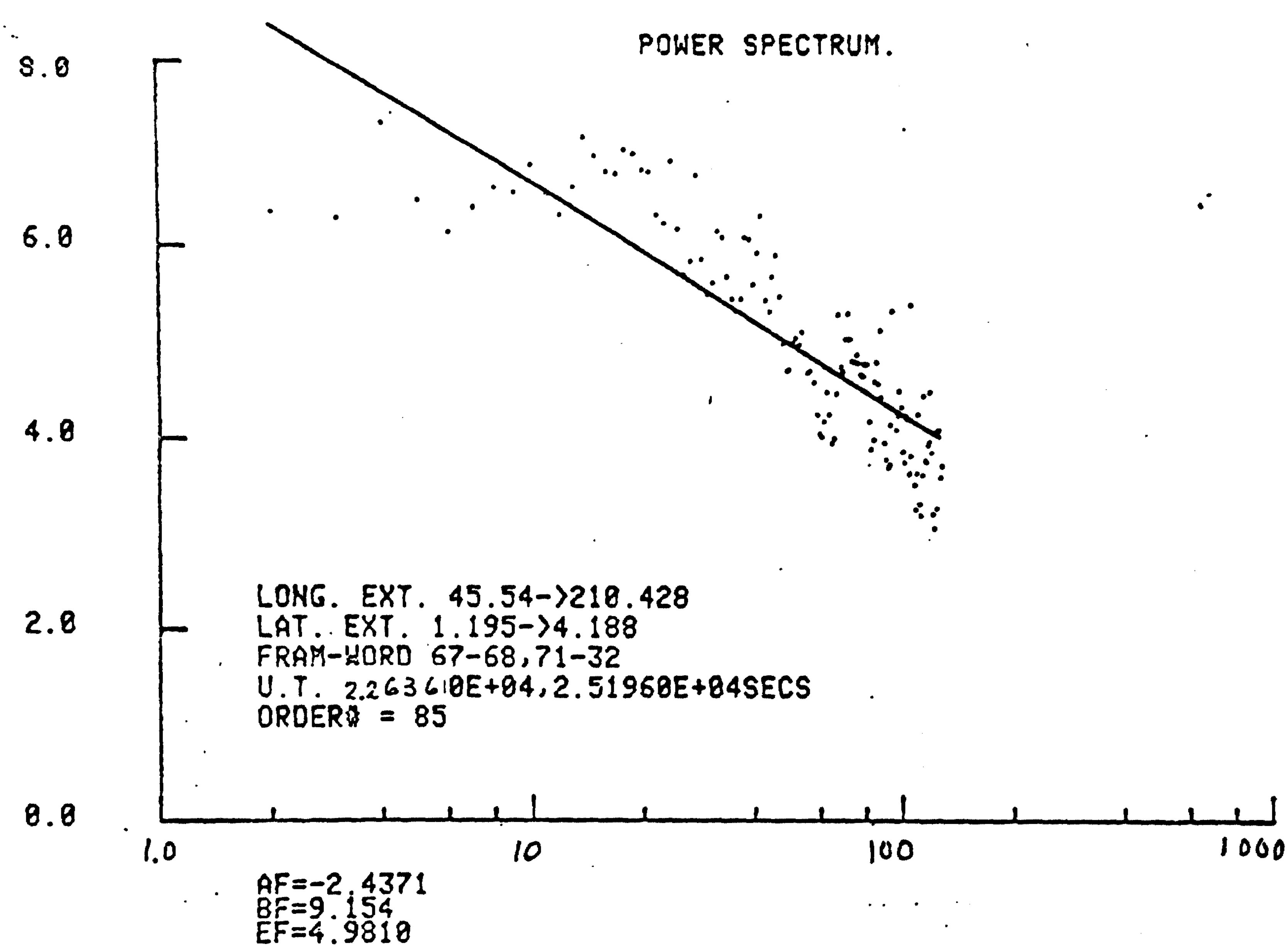

POWER SPECTRUM.
8.0
6.0
4.0
2.0
0.0
1.0
10
100
1000
LONG. EXT. 45.54->210.428
LAT. EXT. 1.195->4.188
FRAM-WORD 67-68,71-32
U.T. 2.26361OE+04,2.51960E+04SECS
ORDER# = 85
AF=-2.4371
BF=9.154
EF=4.9810

Fig. 2

Southern Hemisphere

66-09, 89-95

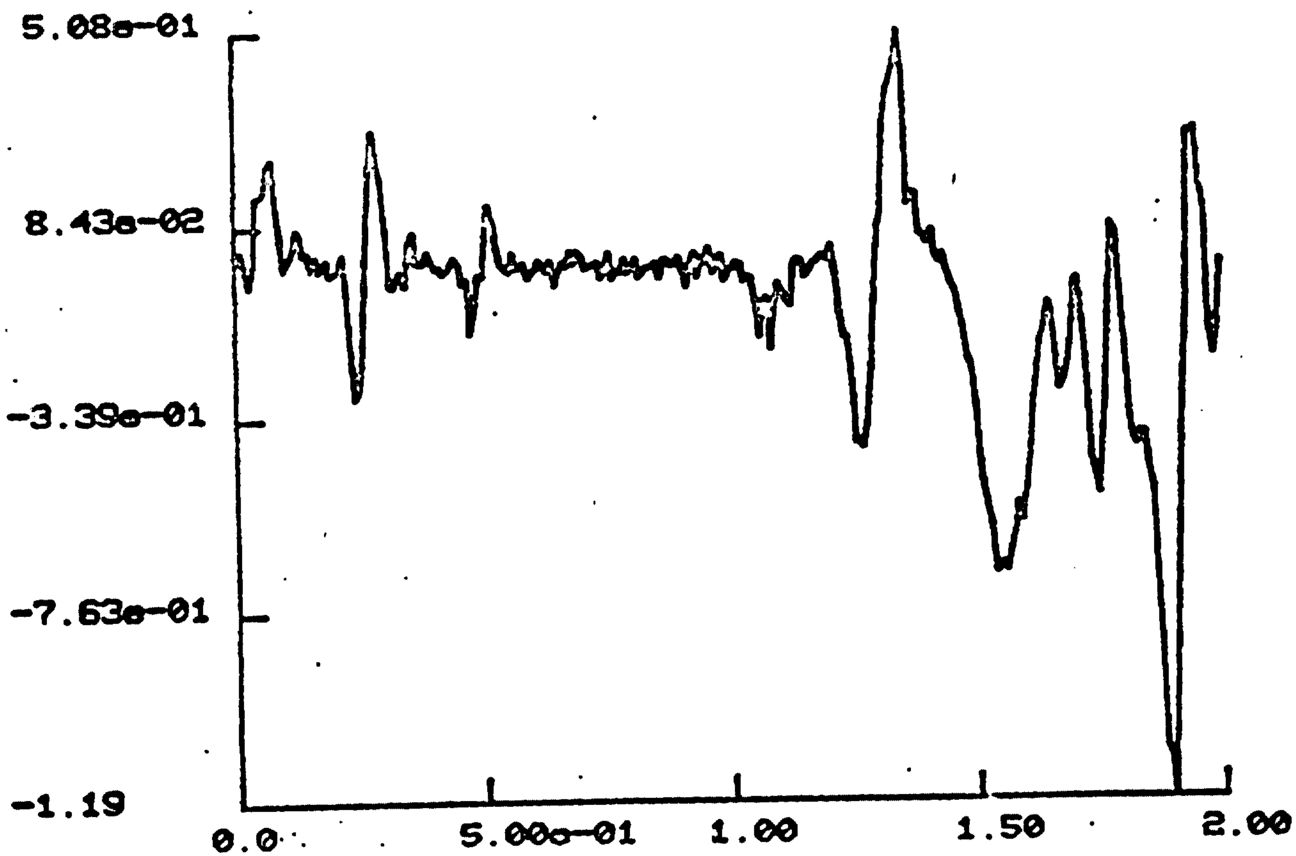


Figure 3. Another example of Doppler data as in Figure 1. This is for the southern hemisphere. The time span is 2560 seconds. The longitude, latitude, universal time information for this sample are given in the body of Figure 4.

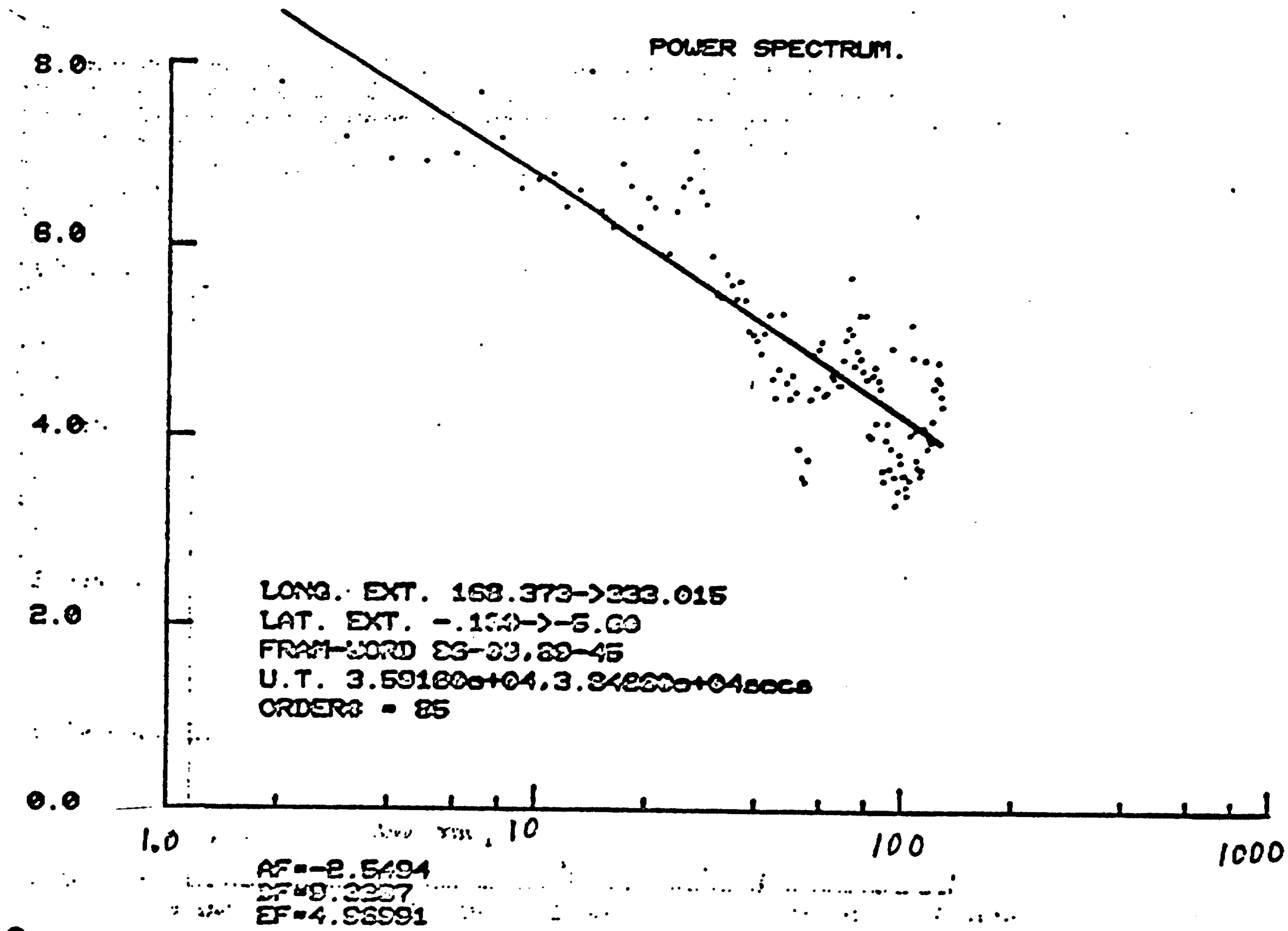


Figure 4. The spectrum of the data in Figure 3. All other items are as in Figure 2, but for the applicable data.

71-41, 75.4

Southern Hemisphere

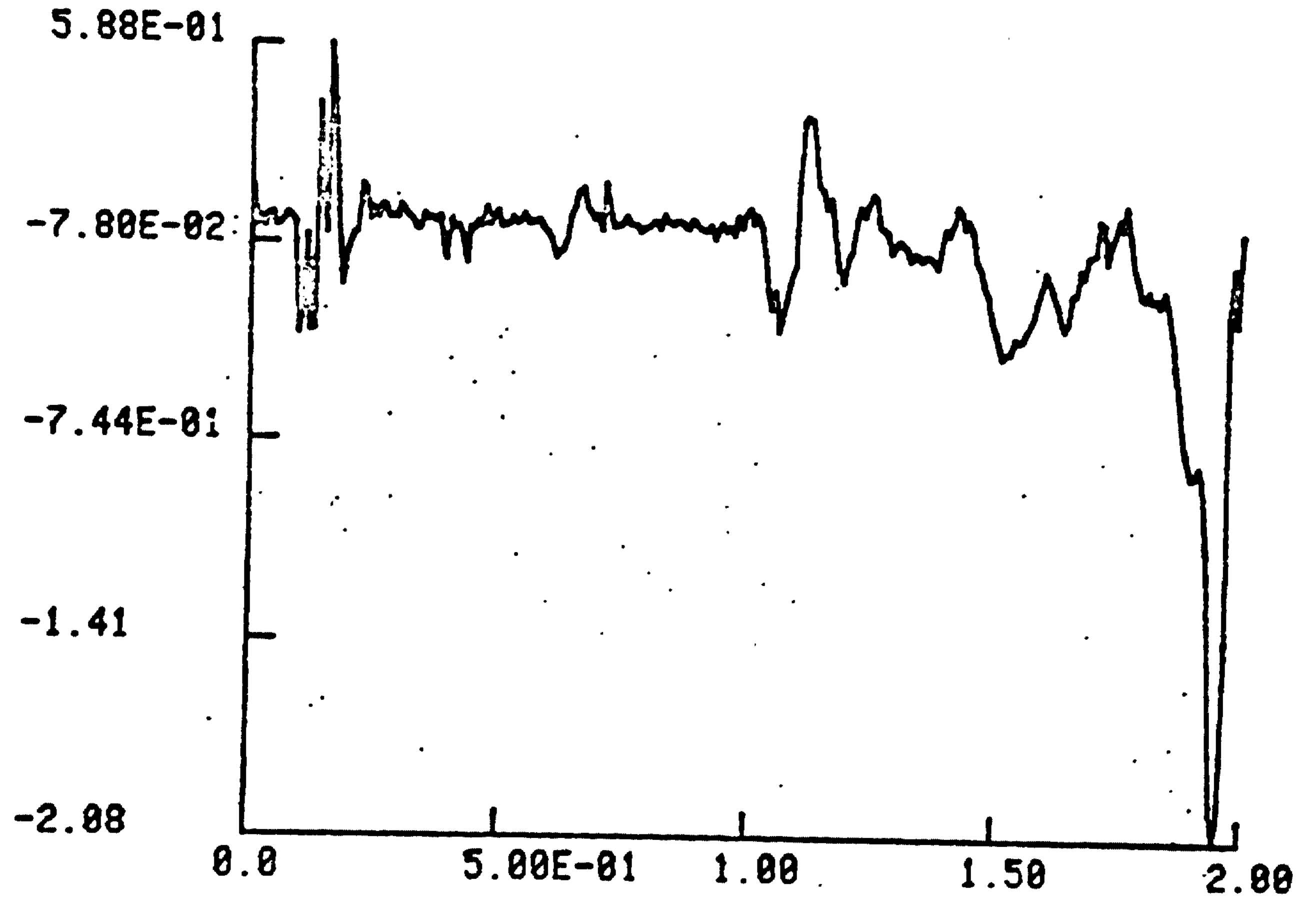


Figure 5. Another example of Doppler data presented as in Figure 1. The longitude, latitude, time information is given in the field of Figure 6.

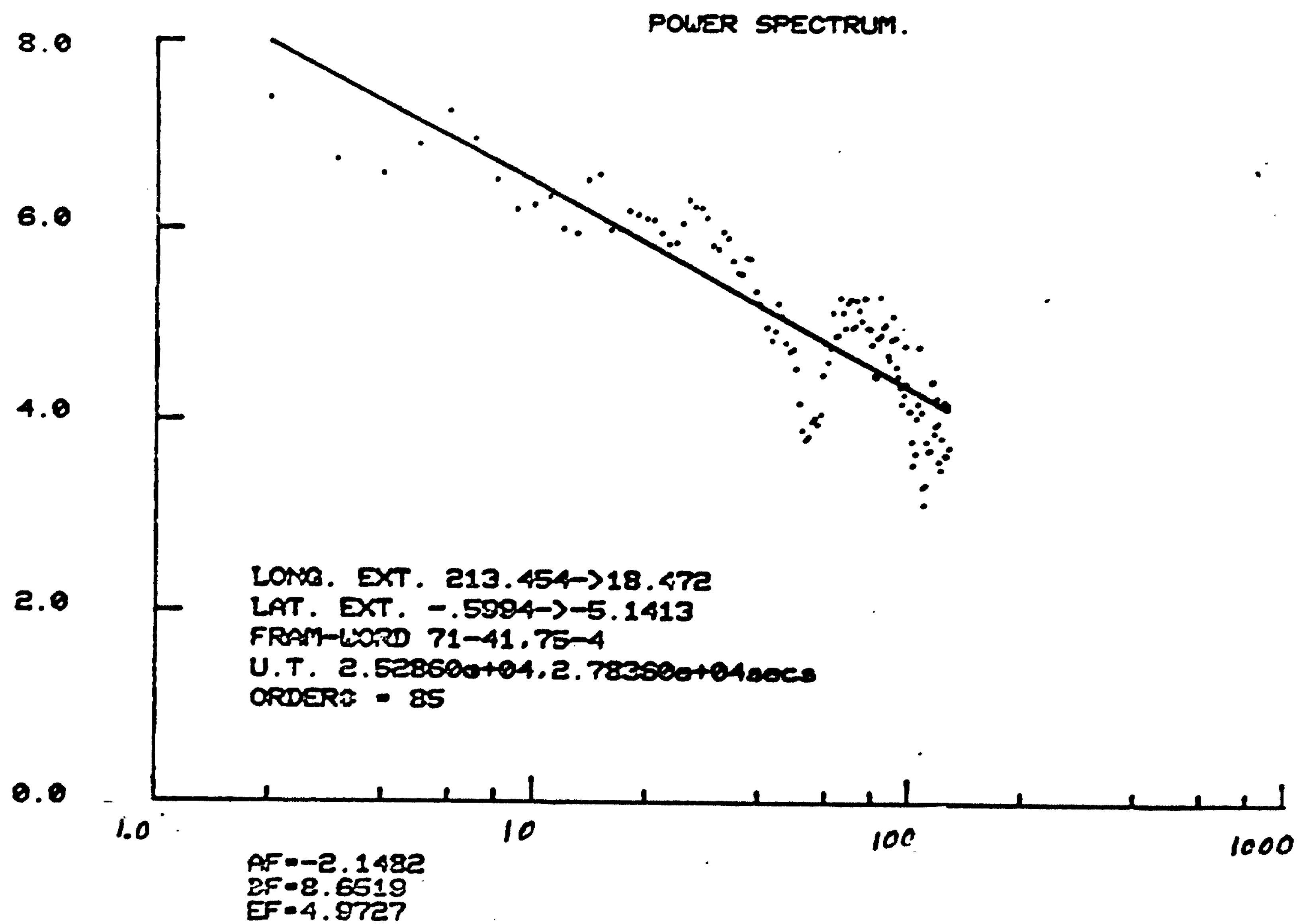


Figure 6. Spectrum of data in Figure 5. All other items are as in Figure 2, but for the applicable data

75-14, 78-50

NORTHERN HEMISPHERE

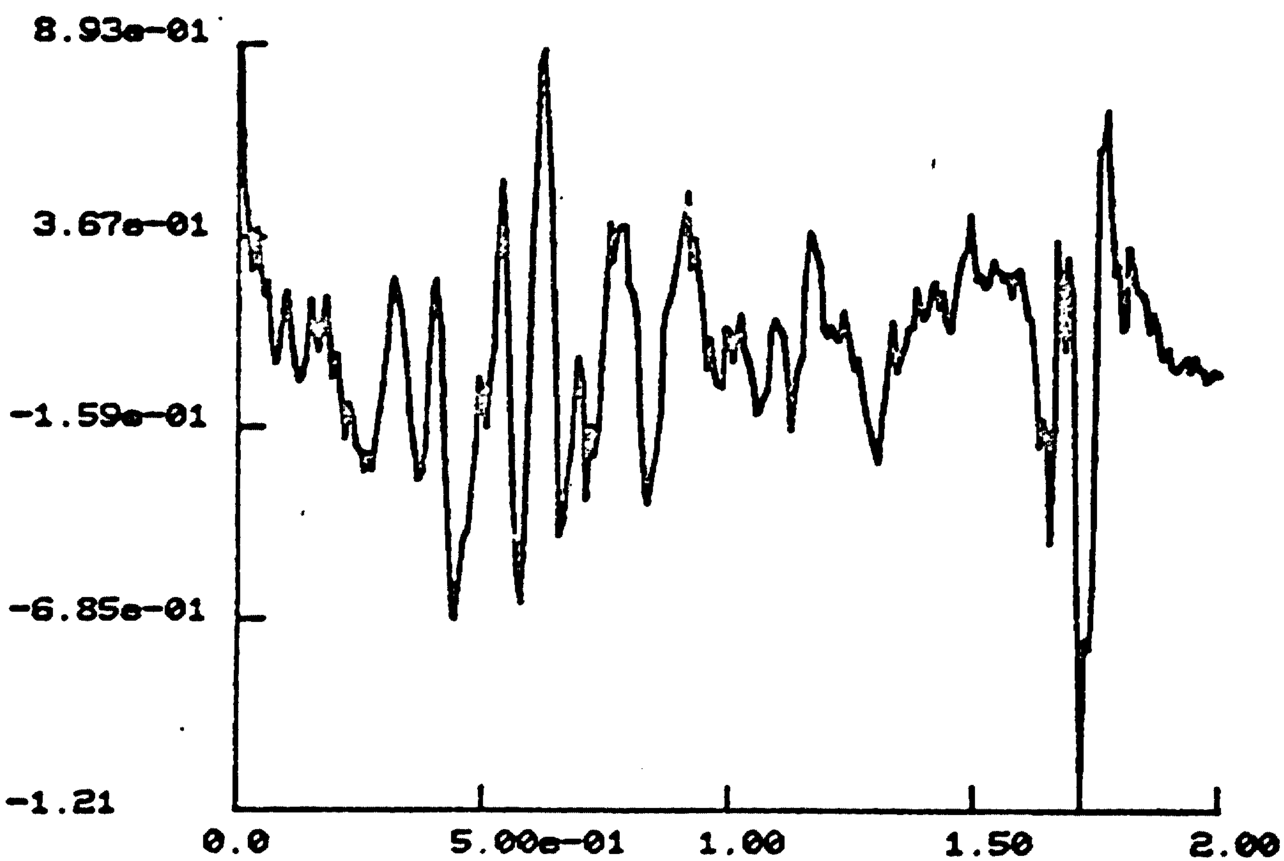


Figure 7. Another example of Doppler data as in Figure 1. The longitude, latitude time information are contained in the field of Figure 8.

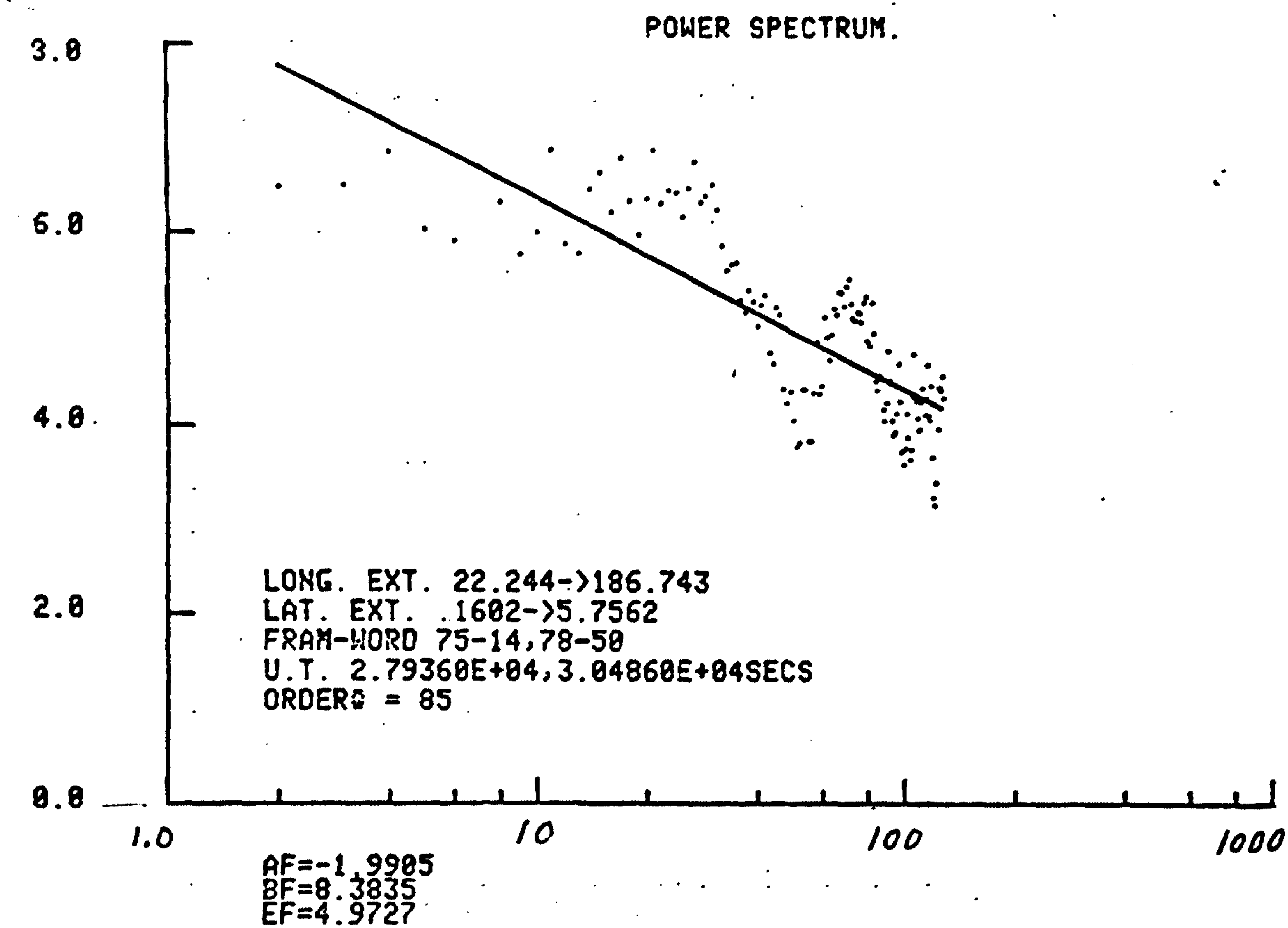


Figure 8. Spectrum of data in Figure 7. All other items are as in Figure 2, but for the applicable data.

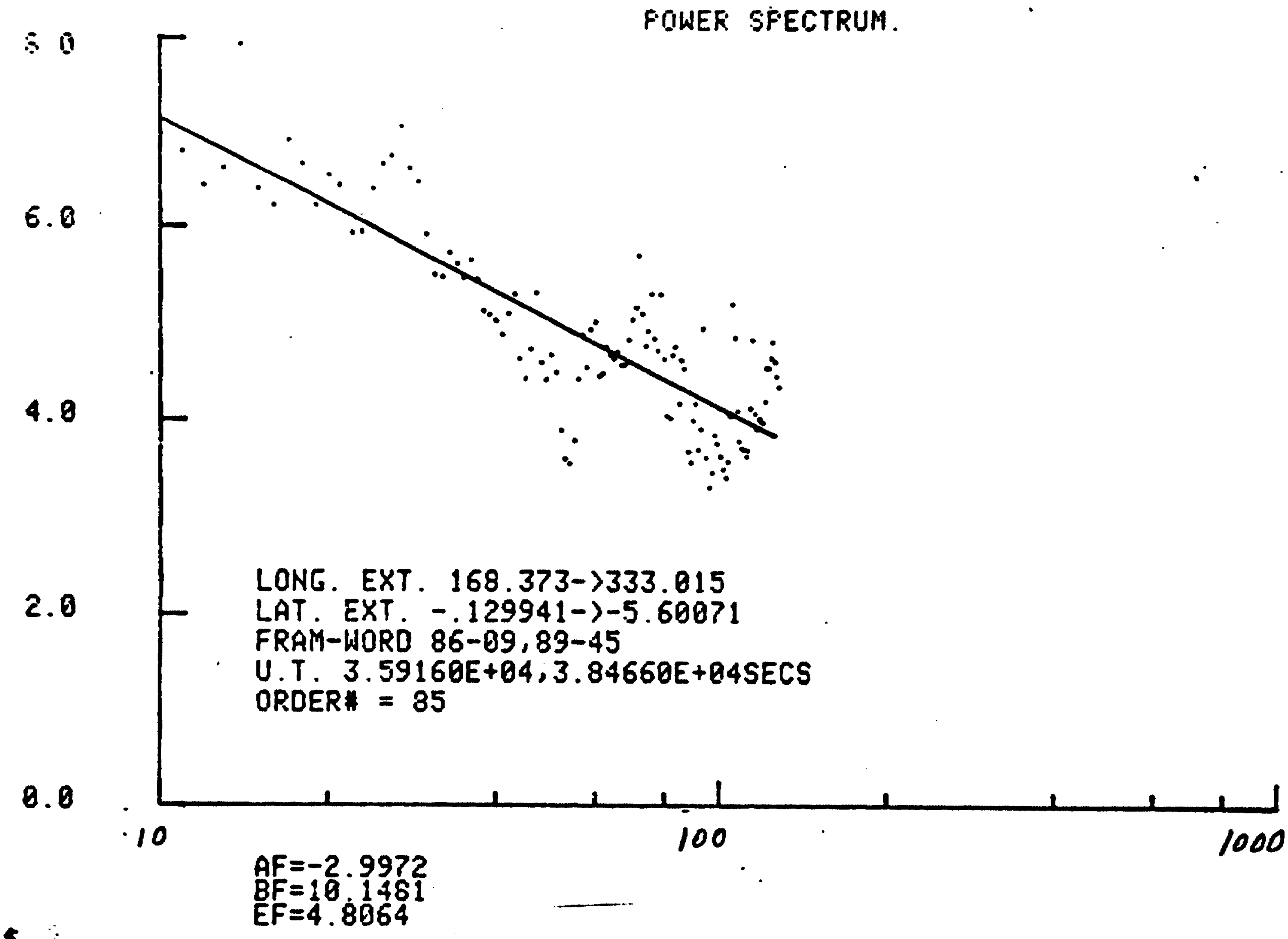


Figure 9. Spectrum and fit from the tenth harmonic to the Nyquist frequency for the spectrum in Figure 4. The straight line fits the data better than that in Figure 4.

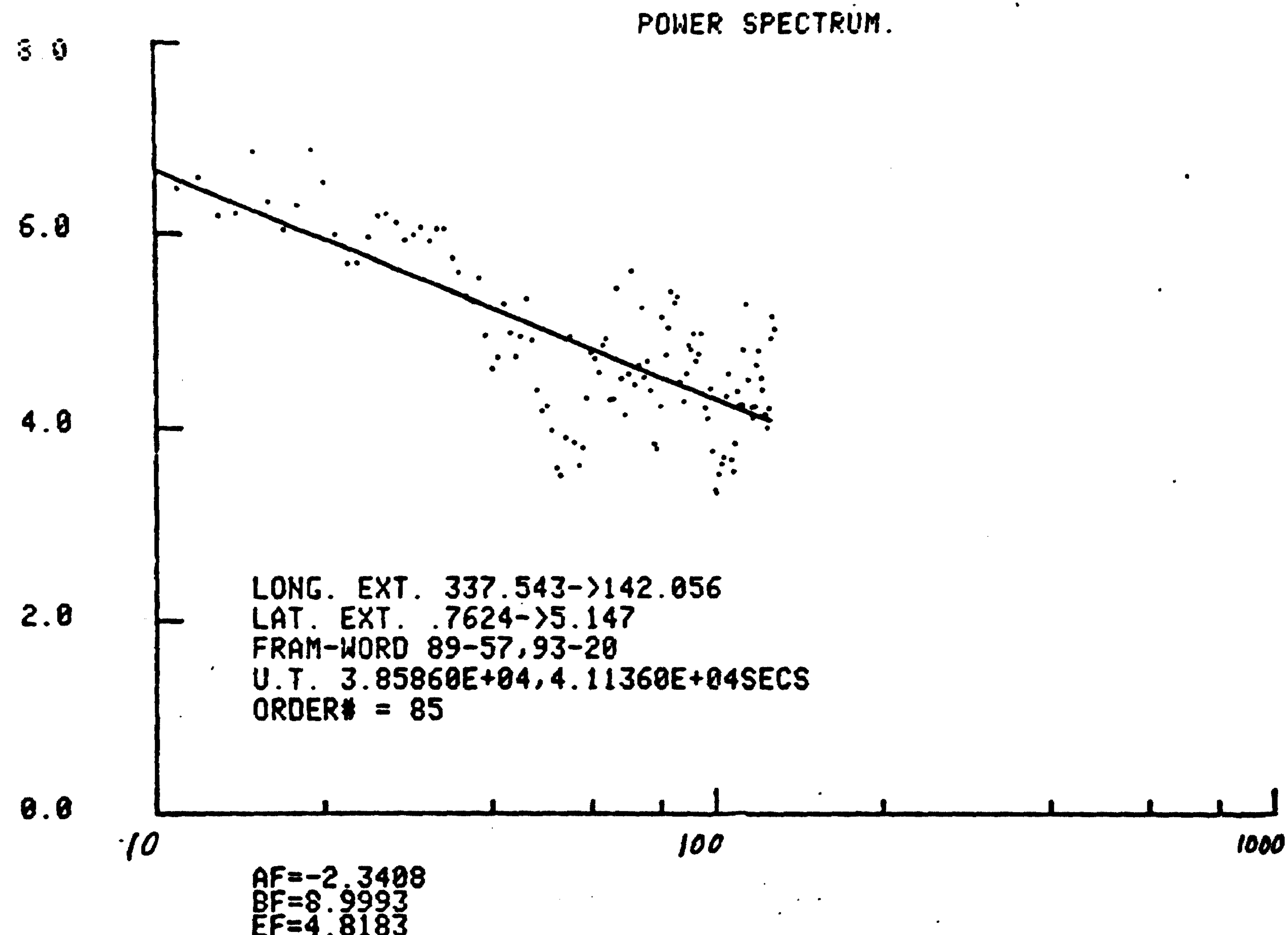


Figure 10. Another spectrum as in Figure 9.

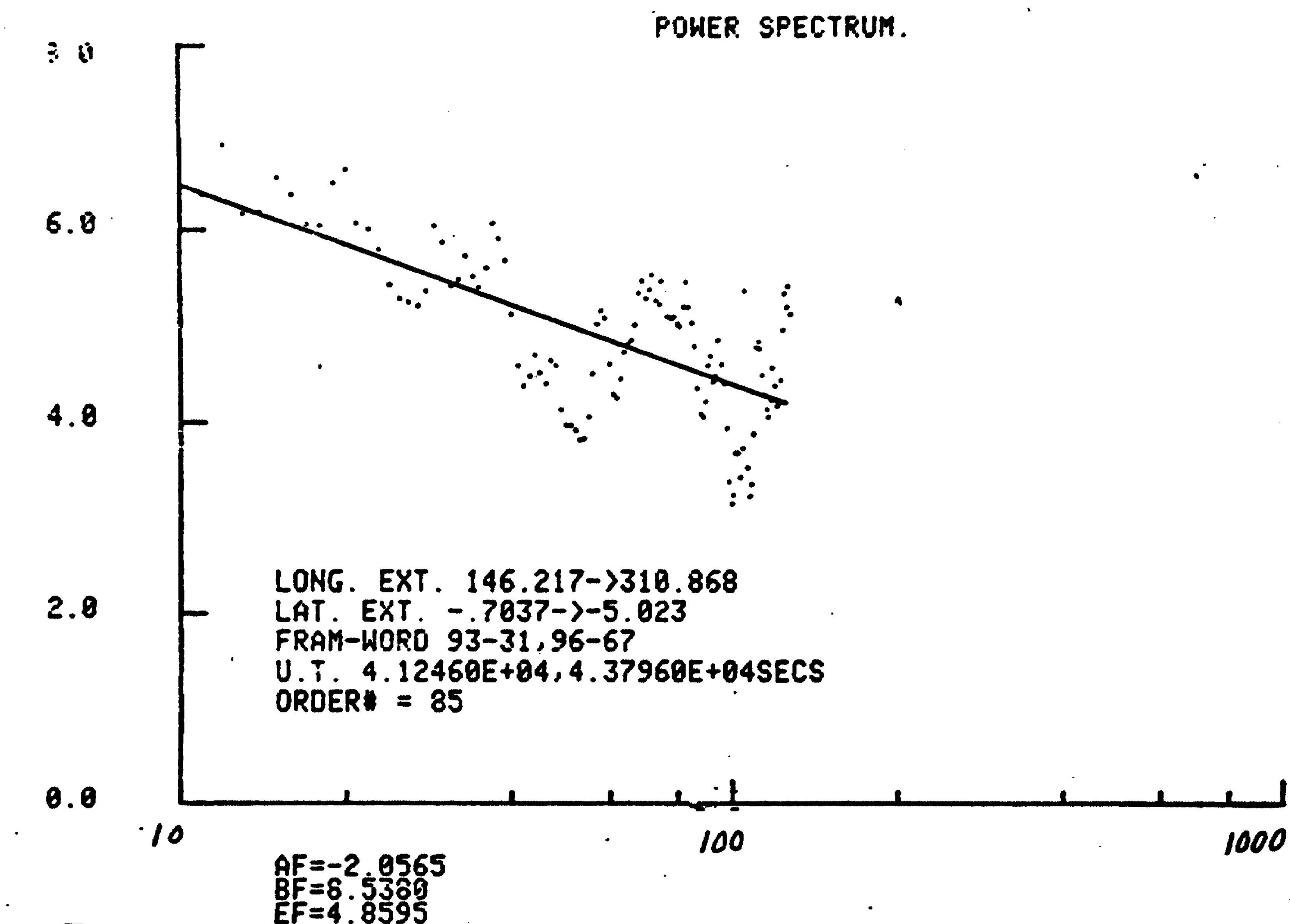


Figure 11. Another spectrum as in Figure 9 or Figure 10.

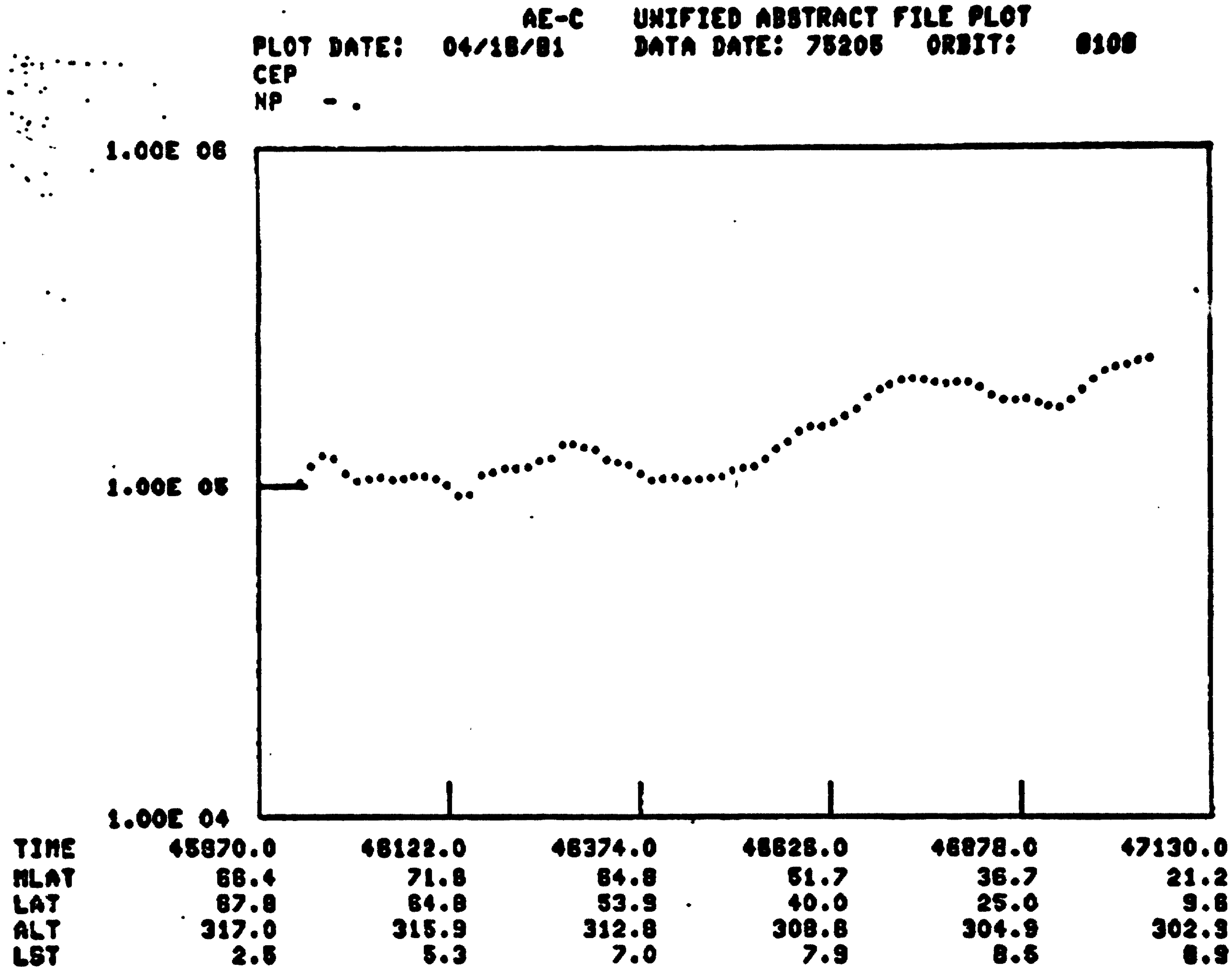


Figure 12. Electron density in cm^{-3} measured by Atmosphere Explorer (AE)-C on the day of the Apollo-Soyuz experiment. Time, magnetic latitude (MLAT), latitude (LAT), altitude (ALT) and local time (LST) are indicated along the abscissa. The ordinate scale is logarithmic. The orbit number is 8108.

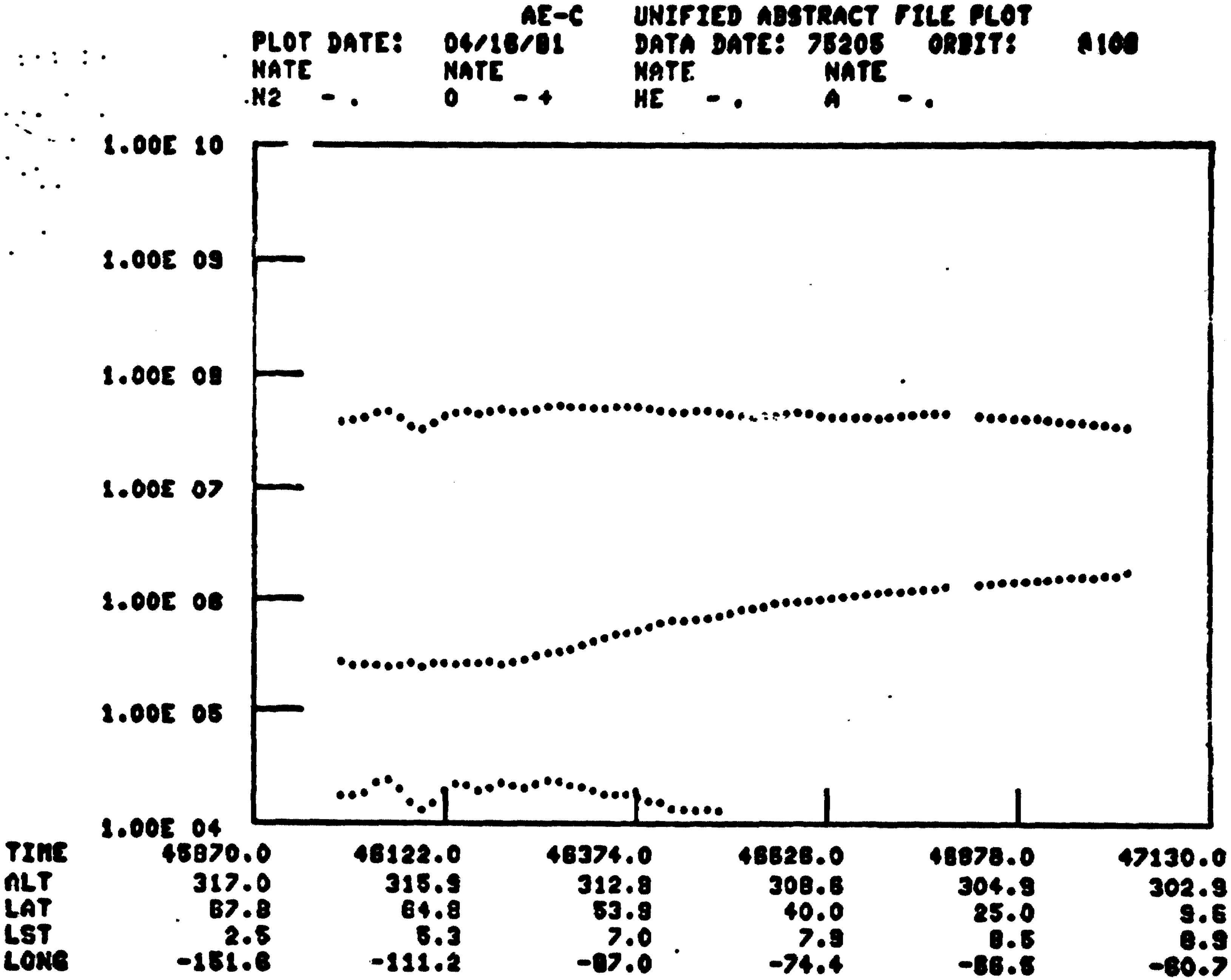


Figure 13. The density of nitrogen (top graph), helium (center) and argon (bottom) for the same AE-C orbit as in Figure 12. The abscissa also includes longitude.

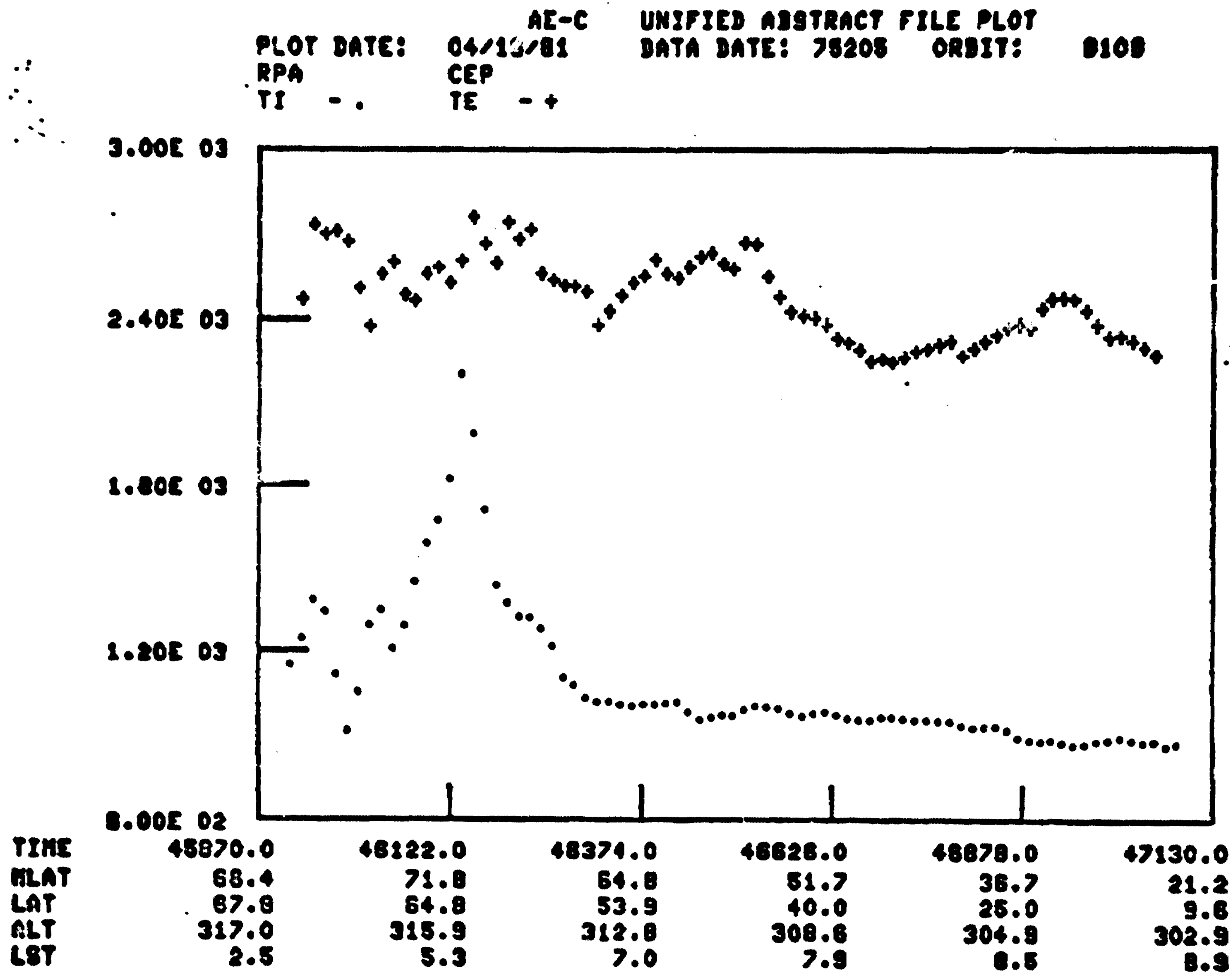


Figure 14. Electron temperature (upper graph) and ion temperature (bottom curve) for the same AE-C orbit as in Figure 12.

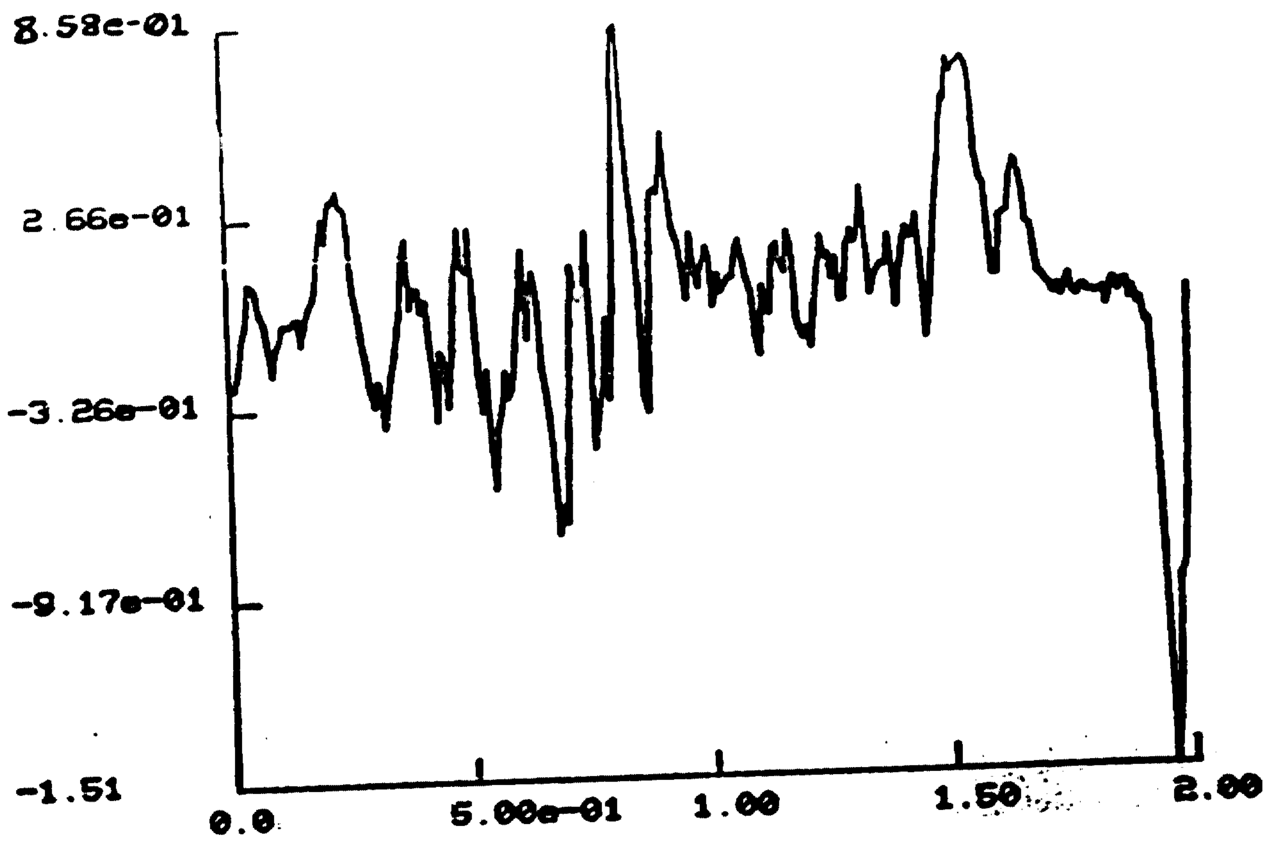


Figure 15. Apollo-Soyuz Doppler data for a time period 2970 seconds later than the AE-C data. The longitude, latitude, time information are given in the field of Figure 16. The time span corresponds to 2560 seconds.

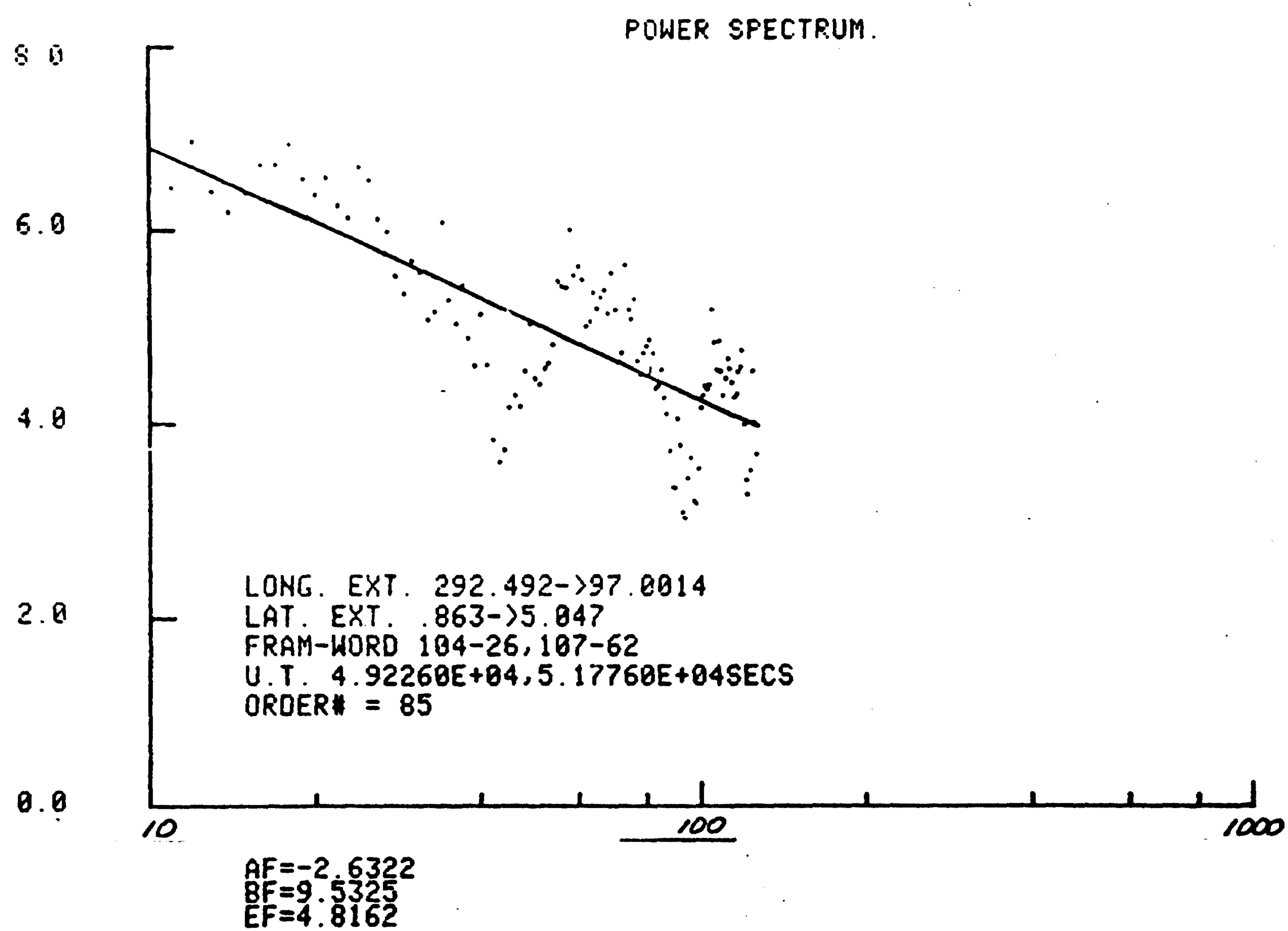
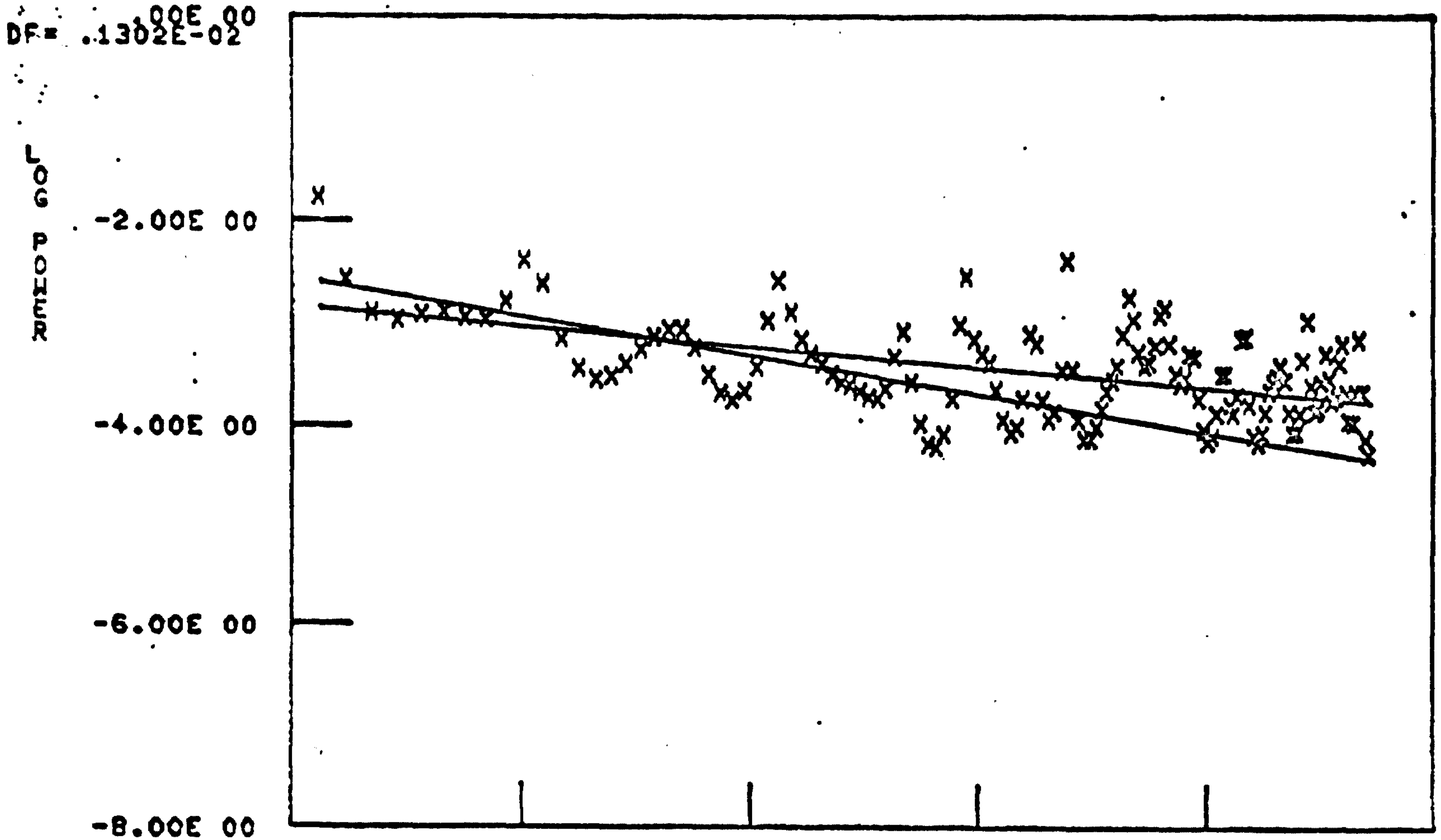


Figure 16. Spectrum of data in Figure 15 and straight line fit from the tenth harmonic to the Nyquist frequency similar to Figure 9.

Figure 17. Spectrum shown as crosses from MEM analysis of the AE-C measured electron density in Figure 12. Two fits are given. The abscissa are the logarithm of frequency in Hertz, frequency in mHz, wavelength along orbit in kilometers and harmonic number. The ordinate is logarithm of spectral power. The equation of the lines are given above the figure together with the frequency range of their fits. See text.

POWER FOR GU DATA YRDAY 75205 48250.0 47000.0 MAXIMUM ENTROPY
LOGPOWER = -.447E 01 + -.975E 00*LOGFREQ UA .0000 .0000 GU .0208 .1302
LOGPOWER = -.585E 01 + -.185E 01*LOGFREQ UA .0000 .0000 GU .0208 .0651



LOG FREQ	-1.68000	-1.47520	-1.27040	-1.06560	-.86080	-.65600
FREQ(.001/S)	20.9	33.5	53.7	86.0	137.8	220.8
WAVELGTH	363.8	227.0	141.8	88.4	55.2	34.4
HARMONICNO.	16.0	25.7	41.2	66.0	105.8	169.6

NC1= 80 LG1= 100 NC2= 80 LG2= 100
LATMIN= .00 LATMAX= .00 CEP DENSITY

Fig. 17