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GL-TR-90-0135

ELF Detection of Energetic Particle Precipitation

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25 July 1990

Final Report
25 November 1988-28 February 1990

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UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT **Approved for public release; distribution unlimited**
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) GL-TR-90-0135
6a. NAME OF PERFORMING ORGANIZATION Institute of Geophysics and Planetary Physics	6b. OFFICE SYMBOL *(If applicable)*
7a. NAME OF MONITORING ORGANIZATION Geophysics Laboratory	
6c. ADDRESS *(City, State, and ZIP Code)* 405 Hilgard Avenue University of California, Los Angeles Los Angeles, California 90024	7b. ADDRESS *(City, State, and ZIP Code)* Hanscom Air Force Base Massachusetts 01731-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL *(If applicable)*
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F19628-89-K-0004	
8c. ADDRESS *(City, State, and ZIP Code)*	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
6/10/F	ILIR	9B	AA

11. TITLE *(Include Security Classification)*
ELF Detection of Energetic Particle Precipitation

12. PERSONAL AUTHOR(S)
D.D. Sentman

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15 PAGE COUNT
Final Report	FROM 11/25/88 TO 2/28/90	7/25/90	30

16. SUPPLEMENTARY NOTATION

17 COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	ELF waves Schumann resonance Relativistic electrons

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The scientific objective of this project was to investigate the effects of relativistic electron precipitation on the characteristics of the Schumann resonances. The method of investigation was to establish a Schumann resonance and ELF observing station in Alaska to provide high-latitude measurements for comparison against similar measurements made at midlatitude stations in California and Australia. Observations of Schumann resonance eigenfrequencies and Q-factors during May-October, 1989 showed discontinuous changes that correlated well with the occurrence of several large solar events that produced notable enhancements in the intensities of magnetospheric relativistic electrons $1.2 < E_e < 2$ MeV, energetic protons $E_p > 1$ MeV, and solar x-rays 0.5-8A. The observed correlation suggests that the solar events produced a globally significant perturbation in the conductivity of the D-region forming the upper boundary of the earth-ionosphere cavity to produce the observed Schumann resonance response. A more refined analysis of the data will permit establishing the relative importance of the relativistic electron, energetic proton and x-ray contributions to the observed perturbations. In addition to making Schumann resonance measurements, the station in Alaska

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Howard Singer	22b. TELEPHONE *(Include Area Code)* | 22c. OFFICE SYMBOL GL/PHG

DD FORM 1473, 84 MAR   83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

ABSTRACT - Continued:

successfully detected for the first time ELF emissions in the frequency range 6-154 Hz generated by polar electroject modification by the HIPAS HF heater facility located near Fairbanks.

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ELF DETECTION OF ENERGETIC PARTICLE PRECIPITATION

1. Background

The scientific objective of this project was to investigate the effects of relativistic electron precipitation on the characteristics of naturally occurring ELF emissions 1-60 Hz, specifically, the Schumann resonances. The method of investigation was to compare ground-based observations of ELF emissions made within the high-latitude precipitation zone with similar observations made simultaneously at midlatitudes. The measurements to be performed were of the vertical electric field and two horizontal components of the magnetic field comprising the transverse-magnetic normal modes of the earth-ionosphere cavity.

The rationale for proposing that relativistic electron precipitation could produce a measurable response in the Schumann resonances lies in the changes to the middle atmospheric D-region conductivity that such precipitation is thought to produce (Baker et al., 1987). Since the eigenfrequencies and Q-factors of the Schumann resonances are determined by the dissipation that occurs primarily within the lower D-region (see, e.g., Polk, 1982; Greifinger and Greifinger, 1978; Sentman, 1990), modulations to the conductivity by precipitating relativistic electrons could yield a correlated change in these mode parameters. A previous preliminary study (Sentman and Baker, 1987), based on ELF observations made at a single midlatitude site, had suggested that a moderate negative correlation may exist between the line widths of the resonances and the intensities of precipitating electrons $E_e > 1.5$ MeV measured at synchronous orbit. However, observations from two widely separated sites were needed to separate out global effects from possible local effects.

UCLA had previously installed an ELF and Schumann resonance monitoring system at Table Mountain, California to provide the midlatitude measurements required for this work. The scope of work under the present contract was to:

(1) Establish an ELF and Schumann resonance data collection system near Fairbanks, Alaska to provide complementary auroral zone observations.

(2) Collect a minimum of four months of continuous and simultaneous data from both the Alaska and California stations.

(3) Obtain energetic electron data from the Los Alamos National Laboratory and solar EUV (or suitable proxy data), x-ray, and proton intensities from the SELDADS data set for time periods overlapping the ELF data.

(4) Perform a comparative analysis of ELF, relativistic electron, EUV, x-ray and energetic proton data to determine which of these ionospheric ionizing agents exerts the dominant perturbative effect on the Schumann resonance spectrum.

In addition to using the Alaska and California data for this study, we planned to include the data from a third ELF station established in Australia under another program to provide additional data for the analysis.

2. Description of Work Completed

1.1. First Quarter

Activities during the initial three months of the project were directed toward constructing the ELF measurement and data acquisition system for Alaska. Arrangements were made to establish the site at the NOAA satellite tracking station at Gilmore Creek, about 25 miles east of Fairbanks. Agreement was made with Lawrence Livermore National Laboratory to make use of a site that was previously used for ELF measurements as part of their Verification Program, and for which UCLA had provided experiment design expertise (Sweeney, 1989). We also entered into a collaborative agreement with A.Y. Wong, Director of the UCLA HIPAS heater facility near Fairbanks, that would permit on-site support in Alaska over the data collection period. Construction and field testing of the electronics for the electric and magnetic systems were completed at UCLA. The data acquisition system was assembled, with provisions made to support parallel and independent recording of ELF data and monitoring of HIPAS experiments. Modifications were made to existing software to accommodate differences between the microcomputer to be used and previous versions of the data acquisition system.

1.2. Second Quarter

During the second quarter of the project we traveled to Alaska and installed and tested the ELF system. After replacing the microcomputer system that was damaged during shipment, the system operated normally. A preliminary ELF noise survey of the site during this period showed it to be exceptionally clean, except for limited periods (~4 hr/wk) of tests of the NOAA backup power generator, during which time the ELF preamplifiers saturated. During the period of ELF system testing we also performed preliminary experiments to monitor the HIPAS activities to modulate the auroral electrojet. The data acquisition system was configured for automatic operation and placed into operation. A subsequent intense rainstorm flooded the preamplifier system. A new preamplifier system was designed and constructed at UCLA, and a second trip made to install the new system. Full time operation of the Alaska system commenced on June 6, 1989, and it has been operating continuously since that time, with short breaks for maintenance.

1.3. Third Quarter

During this interval we continued to collect continuous data from Alaska and Table Mountain. Under a different program we also installed a third, functionally identical, ELF station at the Learmonth Solar Observatory, Western Australia. Full time operation of this system began on September 2, 1989.

1.4. Fourth Quarter

During the final quarter of the project D. Sentman spent one month at the Los Alamos National Laboratory organizing data collected from the three ELF stations and constructing data sets of relativistic electron intensities from the Los Alamos SEE spacecraft. Overlapping data sets of GOES energetic proton and x-ray data, and of 10.7 cm radio flux, were also obtained from the SELDADS data set. A preliminary comparative analysis was performed of the combined data. Thermal covering and heaters were installed for the preamplifiers at the Gilmore Creek station to permit operation throughout the winter.

3. Principal Results

The following results of the experiment were obtained in the preliminary analysis carried out at Los Alamos Scientific Laboratory during October and November, 1989. These results are presently undergoing refinement and will be formally submitted for publication at a later time.

The principal scientific results obtained from the experiment to date are:

(1) A demonstration that there exists a local-time dependence in the amplitudes of the Schumann resonances that may be traced to the day-night difference in the height of the ionosphere. This new result was obtained by comparison of the diurnal variations in the Schumann resonances measured in California and Australia. It is an important verification of the concept motivating the proposed research, namely, that a localized perturbation in the height of the D-region, such as might occur from particle precipitation, may be detected in the amplitudes of the Schumann resonances.

(2) Detection of perturbations in the eigenfrequencies and Q-factors of the resonances coincident with several large solar flares occurring between May and October, 1989. These effects were observed simultaneously in California and Australia when the respective data sets overlapped, a new result, and demonstrate the global observability of solar perturbations on the earth-ionosphere cavity.

(3) Determination that the perturbations in the resonances are most likely to occur from energetic particle precipitation or solar x-rays. Solar EUV enhancements do not appear to have caused the observed perturbations.

In addition to the above results of relevance to the primary goals of the proposed research, we have demonstrated

(4) Successful detection of ELF waves in the frequency range 6-154 Hz generated by polar electrojet modification using the HIPAS HF heater facility located near Fairbanks, Alaska.

4. Sample Data

Figures 1-12 show samples of data obtained during the research period and document several of the findings of this program.

Figures 1 and 2 show frequency-time spectrograms from Gilmore Creek and Table Mountain, respectively, during the interval June 8-13, 1989. These spectrograms are constructed from 18 min average spectrograms accumulated in the field and stored on hard disk for periodic downloading via telephone. Each 18 min average spectrum is composed of the average of 512 raw spectrums, each of approximately 2 sec duration. The strong diurnal variation of the Schumann resonances is clearly discernible in these plots. The intensification that was observed at both stations at the end of June 10 demonstrates the global nature of the resonances. Integrated spectrums 6-23 Hz covering the lowest three eigenfrequencies, shown in Figures 3 and 4, reveal that variations in the average background are strongly correlated between both stations.

Figure 5 shows the lowest three eigenfrequencies computed at 18 min intervals for the east-west component of the magnetic field as measured at Table Mountain, California. This plot gives a general view of the nature of the variability of the eigenfrequencies. Short gaps occur during periods when data are being downloaded to UCLA.

Figures 6a and 6b show the eigenfrequencies and Q-factors of the lowest three Schumann modes as observed in the east-west component of the magnetic field at Gilmore Creek, Alaska from DOY (Day Of Year) 156 (June 6, 1989) to DOY 274. The small dots are hourly values, and the heavy dots are daily averages. The dropout that occurred on between DOY 181-197 is due to lost data from a crashed hard disk at UCLA. The large variability commencing on DOY 250 is due to the signal contamination at the Gilmore Creek site by a nearby S-band transmitter that began operation at that time.

Figures 7a and 7b show eigenfrequencies and Q-factors computed from the east-west magnetic channel of Table Mountain, California starting in early May (DOY 126) and extending through the end of October (DOY 305), 1989. The data gap in the center is due to a crashed hard disk at UCLA. The discontinuous changes that occurred on DOYs 225, 273 and 293 correspond to large solar events that occurred at these times.

Figure 8 plots the eigenfrequency of the second mode, as measured at Table Mountain, in the east-west magnetic component against the relativistic electron intensity $1.2 < E_e < 2$ MeV, as measured at synchronous orbit. There is a moderate-to-good inverse correlation between these parameters over the plotting interval. This correlation suggests that increased particle precipitation into the atmosphere may increase the ionospheric dissipation of ELF, resulting in a lowered phase speed and eigenfrequency.

While the effects of relativistic electrons on the Schumann resonances are the principal subject of this research, other potentially competing sources of enhanced D-region conductivity may also produce measurable effects. The following two figures document the activity of these ionization sources during the analysis interval.

Figure 9 shows daily averages of proton intensities $E_p > 1$, 10 and 100 MeV at synchronous orbit during May-October, 1989. The very large events occurring on DOYs 225, 273 and 293 were accompanied by measurable perturbations in the Schumann resonances.

Figure 10 plots daily averages of the 10.7 cm radio flux and solar x-ray intensities over the analysis interval. The radio flux was used as a proxy measure of solar EUV emissions. The smooth variation over the analysis interval shows no impulsive signatures corresponding to the discontinuous changes in the eigenfrequencies evident in Figures 7a and 7b; hence EUV variations do not appear to be a primary modulating agent for the Schumann resonances. X-ray activity increased dramatically for the DOY 225, 273 and 293 periods, and may therefore have played a role in the observed variations in the Schumann resonances.

Finally, the nature of the results obtained from HIPAS experiments to modulate the auroral electrojet are illustrated in the final two figures.

Figure 11 is an example of the results obtained June 6, 1989 during experiments in electrojet modulation (taken from McCarrick et al, 1989). The upper spectrum is a 4 min incoherent average of the output from the east-west coil obtained during a period when the 1 MW heater was modulated at a frequency of 11 Hz. No line at 11 Hz is visible. When a coherent spectrum is computed from the same data (bottom, 30 sec integration time) both the 11 Hz signal and the third harmonic at 33 Hz are visible. Similar results have subsequently been obtained with ELF modulation frequencies of 6, 11, 21, 23, 41, 76 and 154 Hz.

Figure 12 shows the amplitude of the 11 Hz modulation frequency as a function of time for a four hour HIPAS test performed on 18 October, 1989 (after McCarrick et al., 1989). The 11 Hz modulation was alternately turned on for 15 min and off for 15 min, producing the observed square wave appearance. There is excellent correlation between times when aurora are present and the times when ELF signal strength is greatest. Exceptions occur when riometer data indicate strong absorption by energetic precipitating particles.

5. Summary

A preliminary analysis of Schumann resonance data collected between May and October, 1989 from stations in Alaska, California and Australia indicates that variations in the Schumann resonances contain information about the variable state of the local and global ionospheric D-region. Discontinuous changes in resonance parameters occurred within a day following three large solar flares that occurred August-October, 1989. These changes are believed to be the result of enhanced D-region conductivity from flare-related precipitating energetic electrons or protons, or of enhanced solar x-ray fluxes. Solar EUV does not appear to play a role in producing the observed variations in the resonance parameters. A more refined analysis based on precise onset times of particle intensity and x-ray enhancements compared to the observed times of discontinuous changes in the Schumann resonance parameters should permit positive identification of the dominant perturbative agent to be made.

Observations of the artificial modification of the auroral electrojet at ELF spanning 6-154 Hz were made. These observations lay the groundwork for additional investigations in this new area of ionospheric research.

6. Present Status of the Gilmore Creek Station

The Gilmore Creek ELF station has collected continuous data from June 6, 1990 to the present. However, in late September, 1989 NOAA commenced operation of an S-band transmitter at Gilmore Creek that produced serious noise contamination at 5.8 and 17.4 Hz in the ELF observations. The contamination was of sufficient severity so as not to permit accurate determination of the Schumann resonance eigenfrequencies and Q-values from the measured spectrums. The S-band emissions, which are in support of the SPOT-2 satellite operations, will extend through the Spring of 1990, following which we anticipate resumption of high-quality ELF observations.

The interference from the S-band transmitter occurred during the time period that was originally planned for this project, and therefore forced a revision of our analysis strategy. We plan to resume the original program involving comparison of the Gilmore Creek data with Table Mountain data following cessation of S-band activities in the late Spring of 1990.

7. References

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Sweeney, J.J., An investigation of the usefulness of extremely low-frequency electromagnetic measurements for treaty verification, Final Report, Verification Program, Lawrence Livermore National Laboratory, Livermore, 1989.

8. Publications, Talks and Seminars Resulting From Contract

The present research resulted in the following publications, talks and seminars.

8.1. Publications

D.D. Sentman, "Approximate Schumann Resonance Parameters for a Two-Scale-Height Ionosphere,", J. Atmos. Terr. Phys., 52, 35, 1990.

M.J. McCarrick, D.D. Sentman, A.Y. Wong, R.F. Wuerker and B. Chouinard, Excitation of ELF Waves in the Schumann Resonance Range by Modulated Heating of the Polar Electrojet," Radio Science, (submitted), 1989.

8.2. Talks

Sentman, D.D., "TM Normal Mode Response to Perturbations in the D-Region Electrical Conductivity," 1989 General Assembly, International Association of Geomagnetism and Aeronomy, Exeter, England, June, 1989.

Sentman, D.D., Simultaneous Measurements of Schumann Resonances in California and Alaska During June-July, 1989, invited presentation, International Workshop on Global Atmospheric Electricity Measurements, Warsaw, Poland, September, 1989

McCarrick, M.J., A.Y. Wong, R.F. Wuerker, and D.D. Sentman, Excitation of ELF Waves in the Schumann Resonance Range by Modulated HF Heating of the Polar Electrojet," Fall Meeting, American Geophysical Union, San Francisco, December, 1989.

Sentman, D.D., Amplitude Modulation of the Schumann Resonances by the Day-Night Height Asymmetry of the D-Region, invited talk to be presented at the Seventh Quadrennial Symposium on Solar-Terrestrial Physics, COSPAR, The Hague, The Netherlands, June, 1990.

Sentman, D.D., Effects of the Ionospheric Day-Night Asymmetry on the Intensities of Schumann Resonances, invited talk to be presented at the Commission HG Symposium on Magnetospheric and Ionospheric Effects of Lightning, XXIII General Assembly of URSI, Prague, Czechoslovakia, September, 1990.

Sentman, D.D., Effects of the 19 October 1989 Solar Flare on the Schumann Resonances, invited talk to be presented at the Commission E Symposium on Atmospherics, XXIII General Assembly of URSI, Prague, Czechoslovakia, September, 1990.

8.3. Seminars

"Simultaneous Observations of Earth-Ionosphere Cavity Resonances in California, Alaska and Australia," Department of Earth and Space Sciences Seminar, University of California, Los Angeles, California, September, 1989.

"Simultaneous ELF Observations in California, Alaska and Australia," TRW Space and Technology Group, Redondo Beach, California, October, 1989.

"Simultaneous Observations of Schumann Resonances Made in California, Alaska and Australia," Atmospheric Sciences Seminar, Los Alamos National Laboratory, Los Alamos, New Mexico, November, 1989.

"Effects of the Oct. 19, 1989 Solar Flare on the Schumann Resonances as Simultaneously Observed in California, Alaska and Australia," Space Science Seminar, Air Force Geophysics Laboratory, Hanscom Air Force Base, Bedford, Massachusetts, January, 1990.

9. Acknowledgements

This work was performed under Contract No. F19628-89-K-000[illegible] from the Air Force Geophysics Laboratory, Hanscom Air Force Base, Bedford, Massachusetts. We are grateful for the assistance in installing and maintaining the ELF system in Alaska provided by A.Y. Wong, M.J. McCarrick, B. Chouinard, and W. Huhn under Office of Naval Research Contract No. N00014-88-K-0687. We thank Mr. Gregory White of the NOAA station at Gilmore Creek for permitting us to use their facilities. Support for the ELF station at Table Mountain, California, operated by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration, was provided by the Ionospheric Monitoring Program at the Los Alamos National Laboratory under U.S. Department of Energy Contract No. W-7405-ENG-36. U.S. support for the station at Learmonth Solar Observatory, Western Australia was provided by the U.S. National Science Foundation under Grant No. ATM8815711, and support in Australia was provided by the Australian Ionospheric Prediction Service. We thank Professor Brian Fraser, Newcastle University, New South Wales, for making arrangements for installation of the ELF station at Learmonth. We also thank Dr. John Kennewell, Director of the Learmonth facility, and his staff for their generous and enthusiastic support in installing the station, and for his continuing assistance in maintaining it in operational order. Finally, we thank Dr. Howard Singer of the Geophysics Laboratory for his interest in this research.

10. Figure Captions

Figure 1. Frequency-time spectrogram of horizontal magnetic field over the frequency range 0-50 Hz as recorded at Gilmore Creek, Alaska during June 8-13, 1989. The power is encoded in a gray scale shown at the right. The power scale is relative, but the average power over the spectrum is known to be roughly 1 pT^2/Hz. The Schumann resonances appear as power intensifications at approximately 8, 14, 20, 26...Hz. A strong intensification in the resonances is evident at the end of June 10. At the bottom of the plot are shown the average power in the 6-23 Hz band covering the lowest three resonances. The solid curve shows total power, while the dotted curve shows the power in the north-south channel and the dashed curve shows the power in the east-west channel. A time-varying anisotropy between the north-south and east-west channels is evident.

Figure 2. Frequency-time spectrogram from Table Mountain, California covering the same time interval as Figure 1. The intensification observed at the end of June 10 in Figure 1 is also evident here.

Figure 3. Comparison of the average power in the 6-23 Hz band observed at Gilmore Creek and Table Mountain. Each data point covers an approximately 18 min interval. The first part of the Gilmore Creek plot covers the same interval as Figure 1. This plot shows the strong diurnal variation that exists at both stations.

Figure 4. Daily averages of the power 6-23 Hz recorded at Gilmore Creek and Table Mountain. The plot shows the day-to-day variability that occurs in the intensities of the resonances, and demonstrates that these variations are strongly correlated between the two stations.

Figure 5. The peak frequencies of the lowest three Schumann resonances recorded at Table Mountain in September, 1989. The plot shows the variability in the resonances.

Figure 6a. Hourly and daily averages of the Schumann resonance peak frequencies as measured at Gilmore Creek during June-September, 1989. The left hand scales are in Hz. The large data gap near the center of this and the following figures is due to data lost when a hard disk containing data archives crashed. The small dots record hourly averaged eigenfrequencies, while the large dots show daily averages. The large scatter beginning on DOY 250 is due to contamination of the data from a nearby S-band transmitter that commenced operations at that time.

Figure 6b. Hourly and daily averages of the Q-factors corresponding to the eigenfrequencies shown in Figure 6a.

Figure 7a. Hourly and daily averages of Schumann resonance peak frequencies as measured at Table Mountain during May-October, 1989. The large variability in the second resonance frequency (F2) near Days 225, 273 and 293 correspond to large solar flares recorded on August 10, September 21 and October 19, 1989, respectively.

Figure 7b. Hourly and daily averages of the Q-factors corresponding to the eigenfrequencies shown in Figure 6b. As with the eigenfrequencies, sharp discontinuities in Q2 are evident on Days 225, 273 and 293.

Figure 8. Comparison of relativistic electron intensities J(1.4-2 MeV) observed at synchronous orbit (lower curve, left-hand scale) and hourly averages of the second Schumann resonance eigenfrequency (top curve, right-hand scale) during May-October, 1989. The Schumann resonance data were obtained from Table Mountain observations. A negative correlation

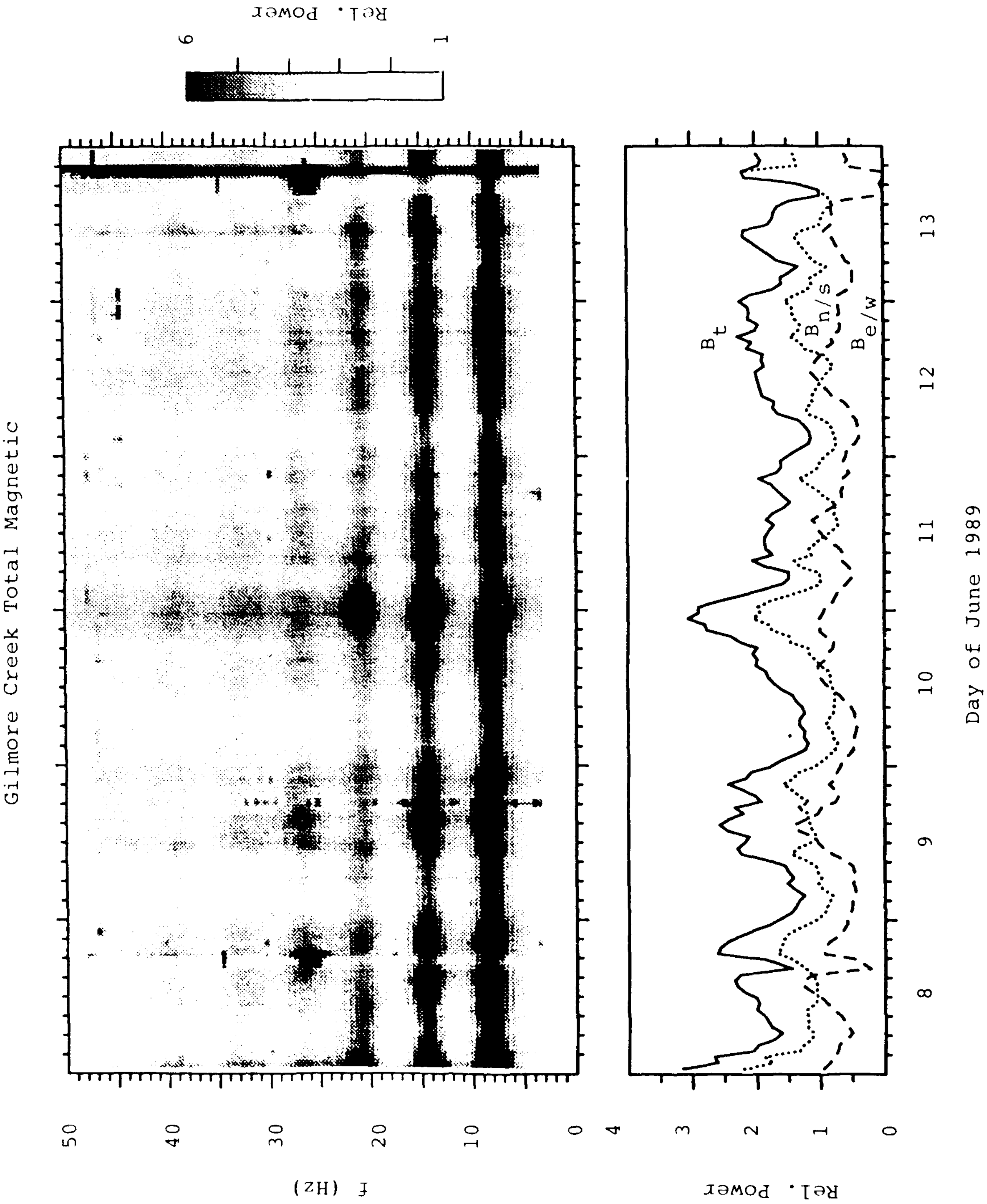
between the two parameters (higher electron intensities corresponds to lower eigenfrequency) is evident. Strong intensifications of the electron fluxes near days 145, 225, 273 and 293 are accompanied by decreases in F2. The correlation is not perfect, however, with moderately strong electron intensifications unaccompanied by changes in F2 occurring near Days 162, 243 and 250.

Figure 9. Proton intensities at 1, 10 and 100 MeV observed at synchronous orbit by the GOES 7 spacecraft during May-October, 1989. Comparison of proton intensities with the electron intensities in Figure 8 shows that strong increases occurred in both at roughly the same time.

Figure 10. Hourly averages of intensities of solar radio flux at 10.7 cm and solar x-ray intensities at 1-8 A and 0.5-4 A during May-October, 1989. The 10.7 cm flux is used as a proxy measure of solar Lyman alpha emissions. The radio flux is seen to vary much too smoothly to account for the discontinuous behavior of F2 and Q2 in Figures 7a and 7b. The variations in F2 and Q2 are better correlated with variations in both energetic electrons and protons than with 10 cm intensities.

Figure 11. Observation at Gilmore Creek of electrojet modulation by the HIPAS heater using a beam spreading modulation technique. Top plot shows the background power spectrum of the magnetic field 0-50 Hz observed during one experiment. The 11 Hz heater modulation frequency is not visible above the background Schumann resonances. The bottom plot shows the coherent power spectrum obtained by synchronizing the phases of the FFTs used to compute the power spectrum with the phase of the 11 Hz modulation signal. The 11 Hz modulation is clearly visible here, as well as the 33 Hz third harmonic. (After McCarrick et al., 1989)

Figure 12. Power of the 11 Hz signal received during a 6 hr HIPAS run. The heater power was alternately turned on and off for 15 min at a time. The variation in the 11 Hz power over the 6 hr test interval is believed to be a measure of the variability in the strength with which the heater beam modulates the electrojet. (After McCarrick et al., 1989)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30
20
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Rel. Power
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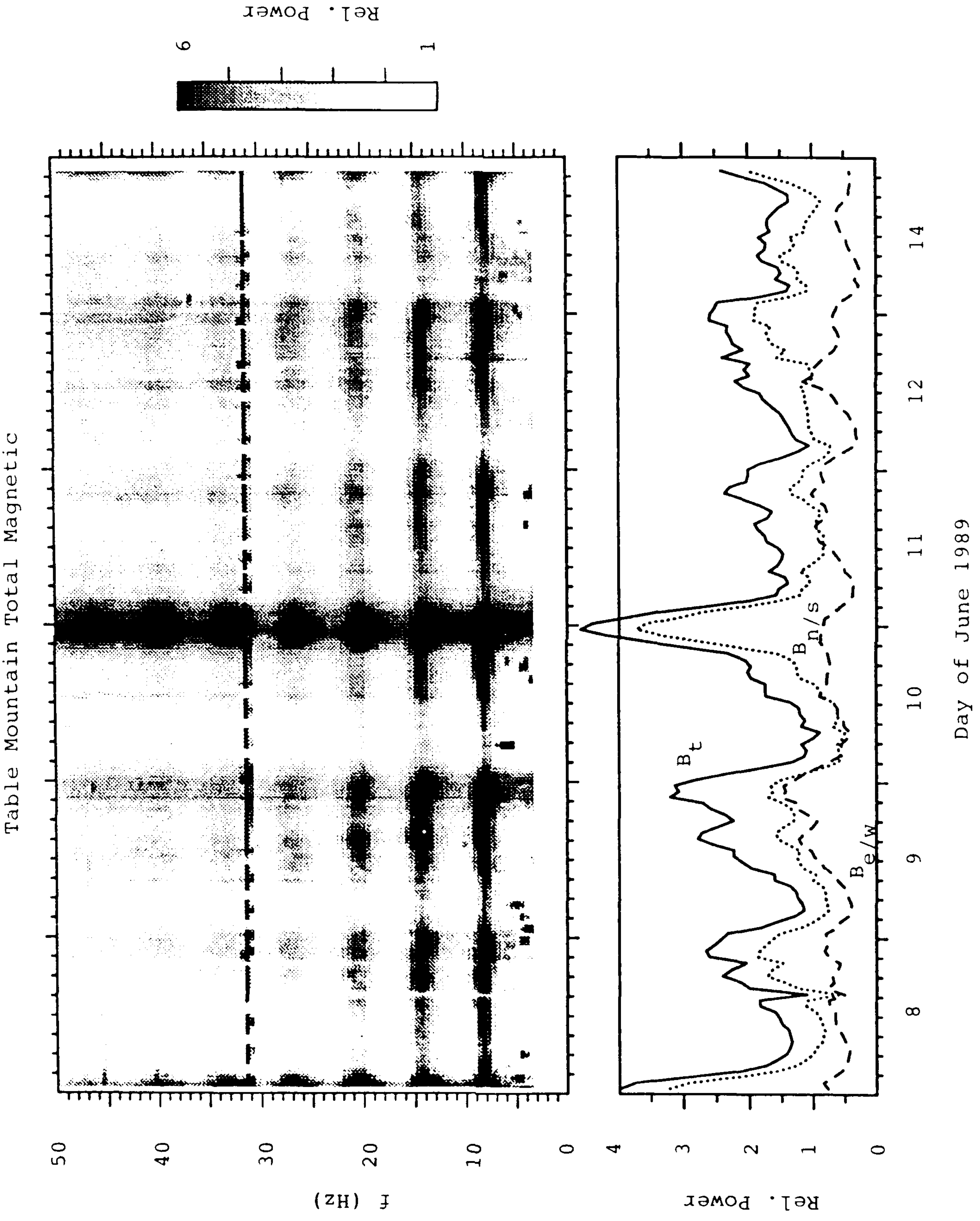
13
Day of June 1989

Figure 1.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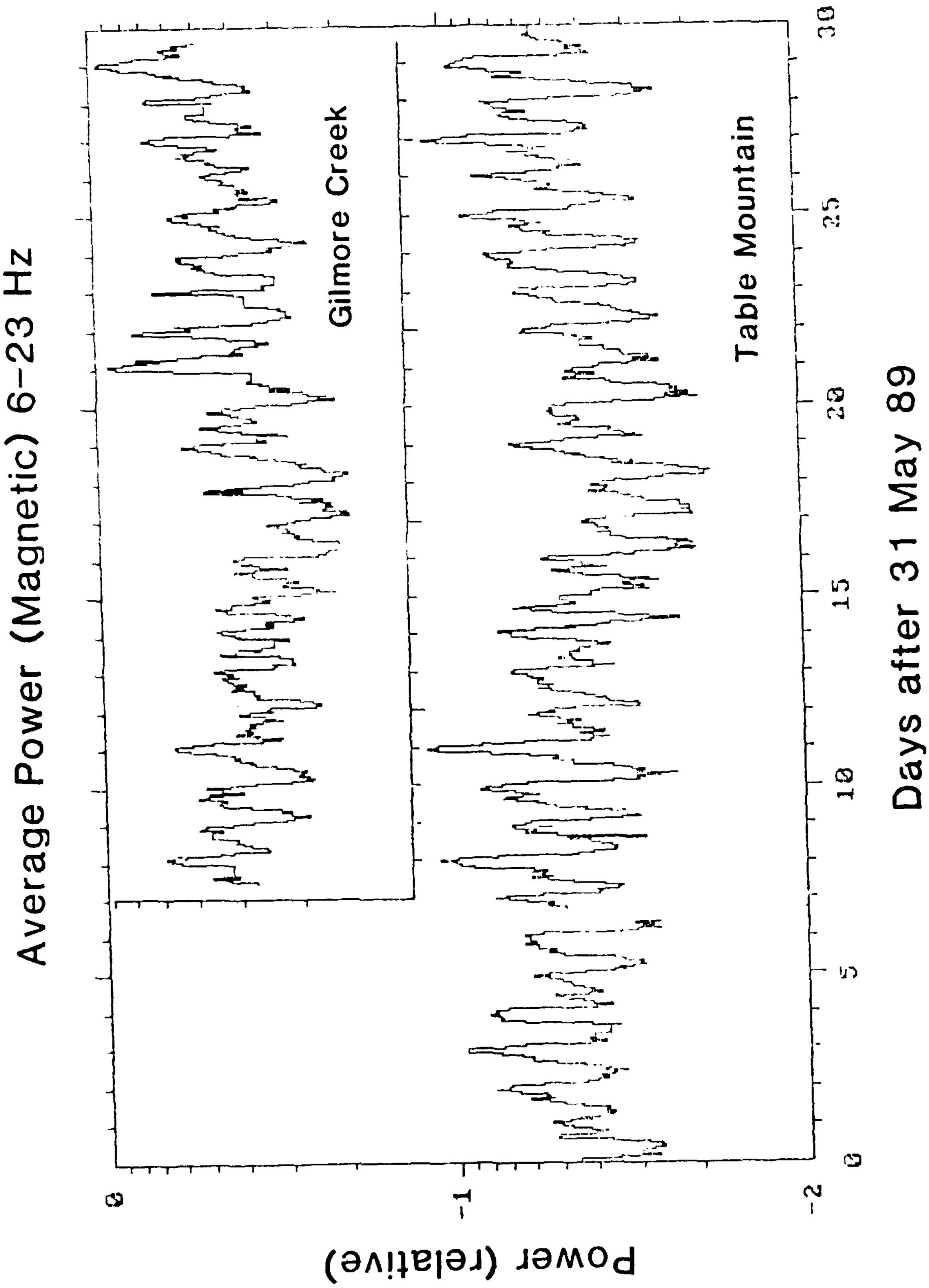
Day of June 1989

Figure 2.



Average Power (Magnetic) 6–23 Hz
Gilmore Creek
Table Mountain
Power (relative)
0
-1
-2
Days after 31 May 89
0
5
10
15
20
25
30

Figure 3.

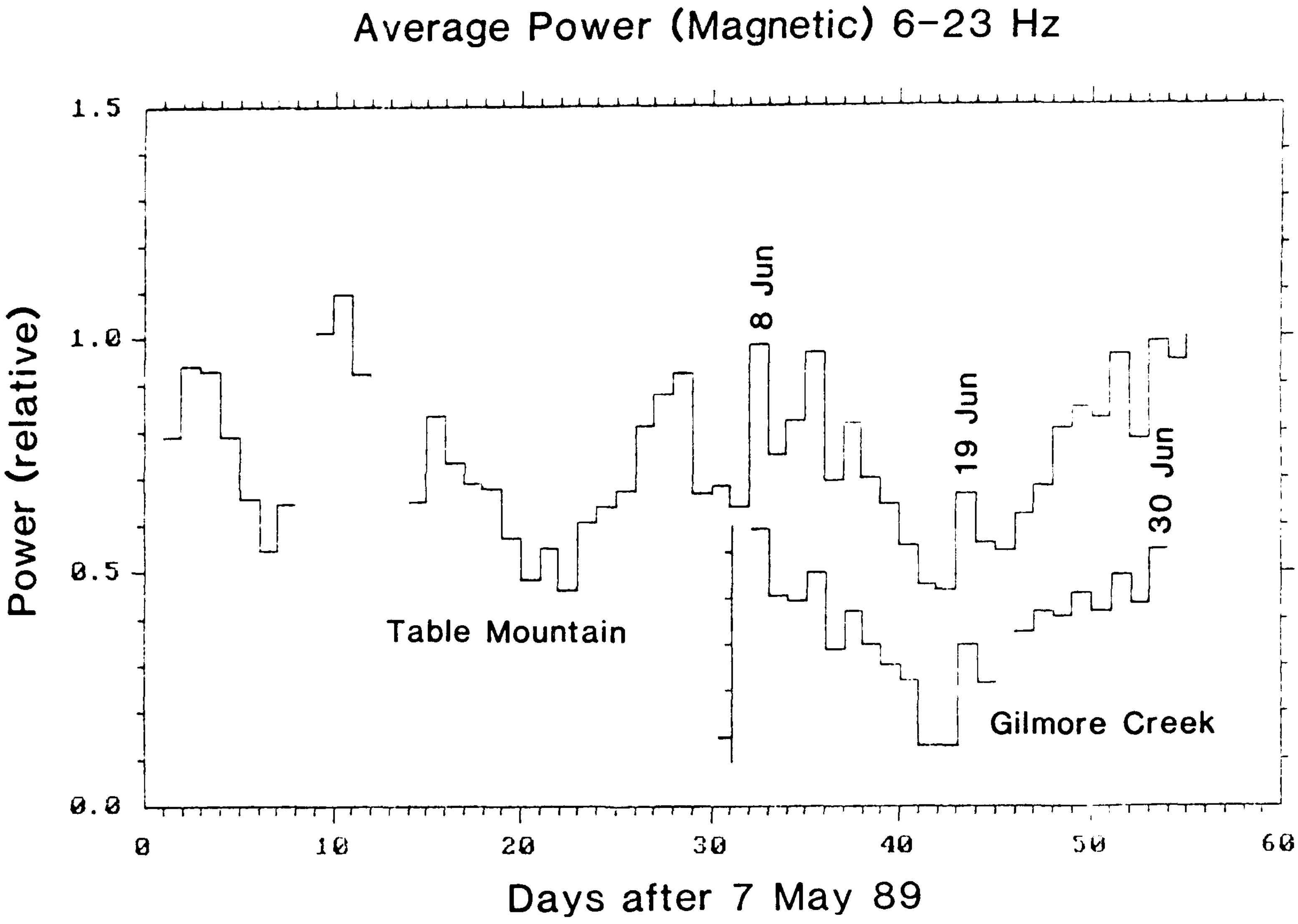

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Table Mountain
Gilmore Creek

Figure 4.

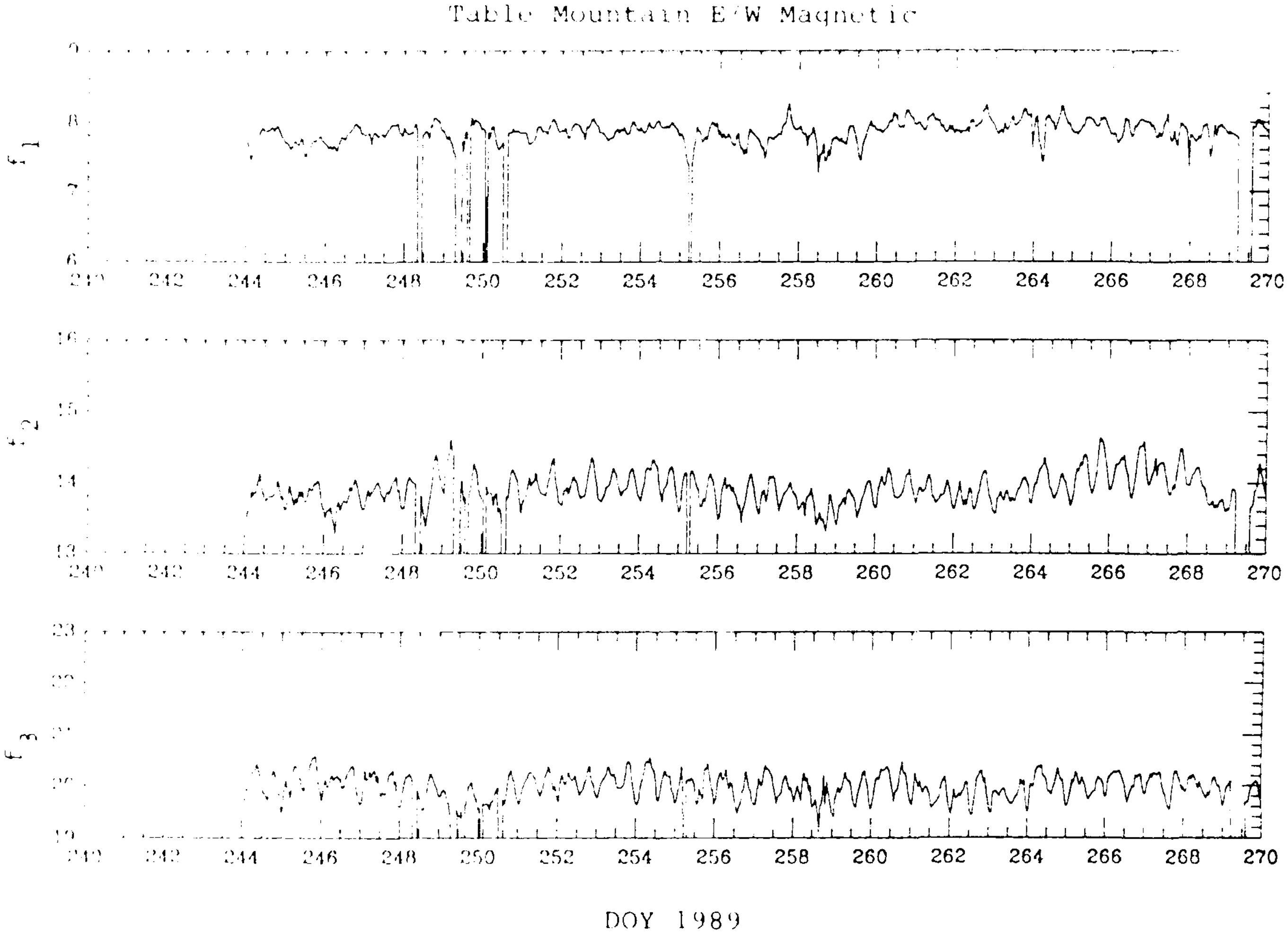
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Figure 5.

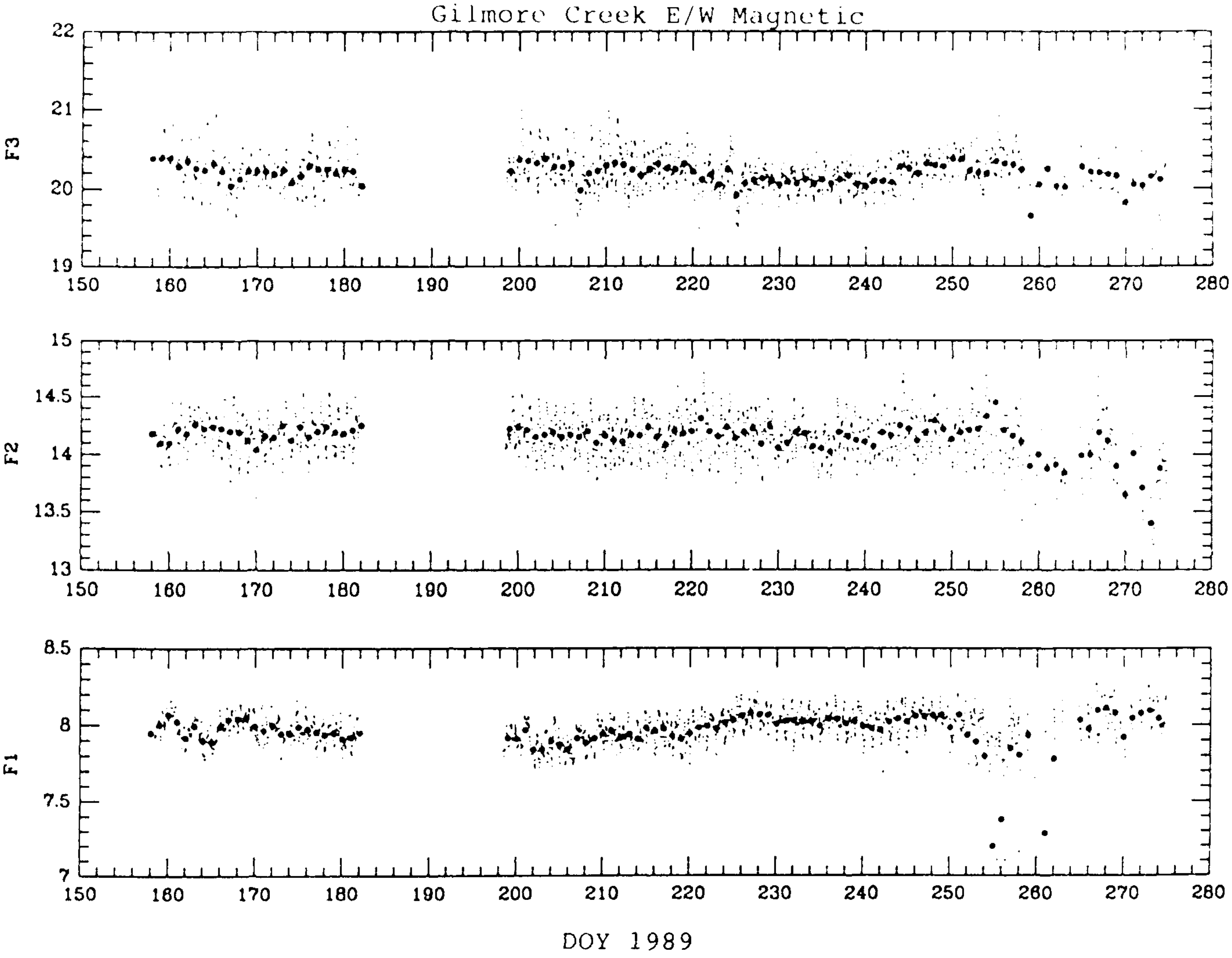

Gilmore Creek E/W Magnetic
F3
22
21
20
19
F2
15
14.5
14
13.5
13
F1
8.5
8
7.5
7
150
160
170
180
190
200
210
220
230
240
250
260
270
280
DOY 1989

Figure 6a.

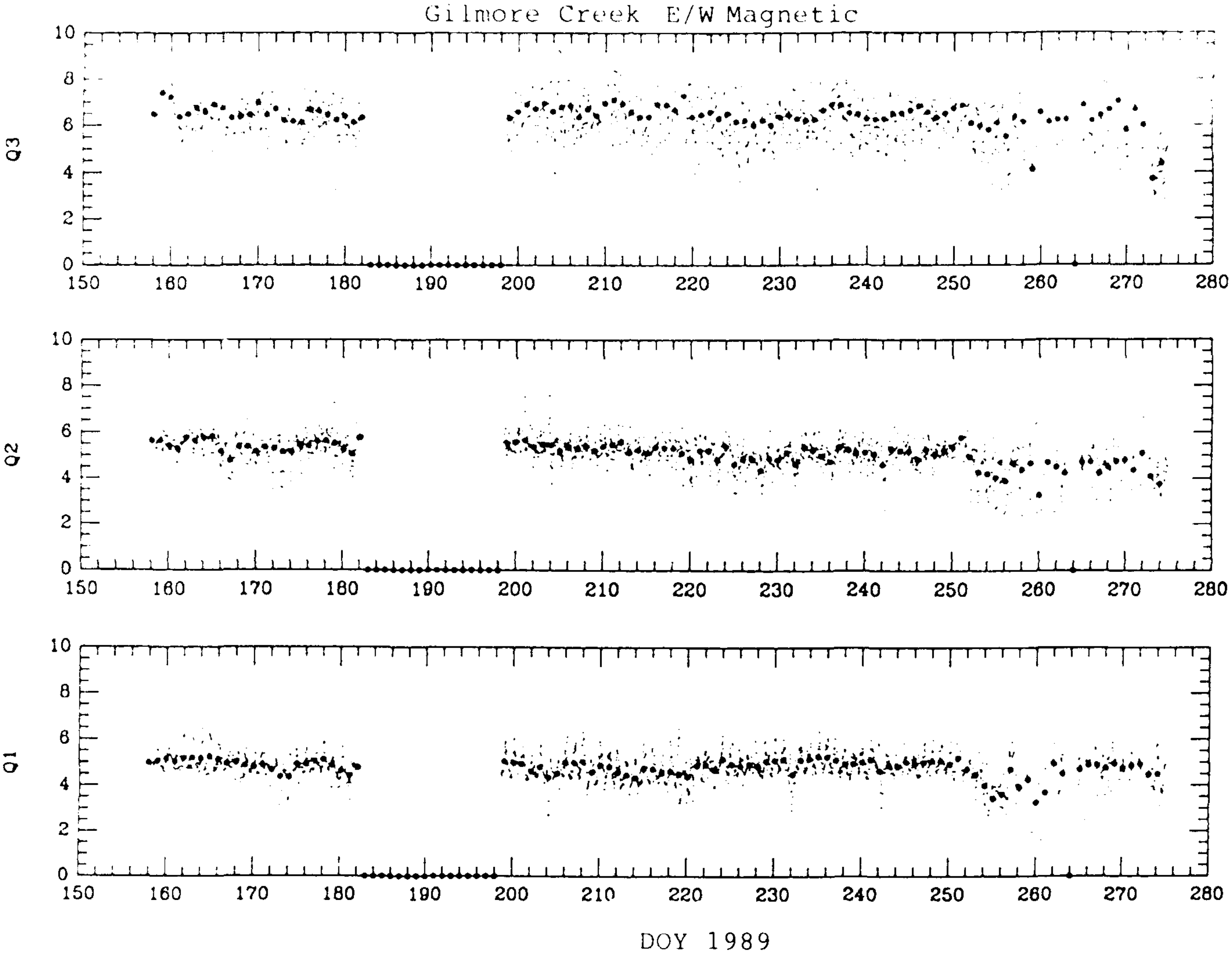

Gilmore Creek E/W Magnetic
Q3
Q2
Q1
10
8
6
4
2
0
150
160
170
180
190
200
210
220
230
240
250
260
270
280
DOY 1989

Figure 6b.

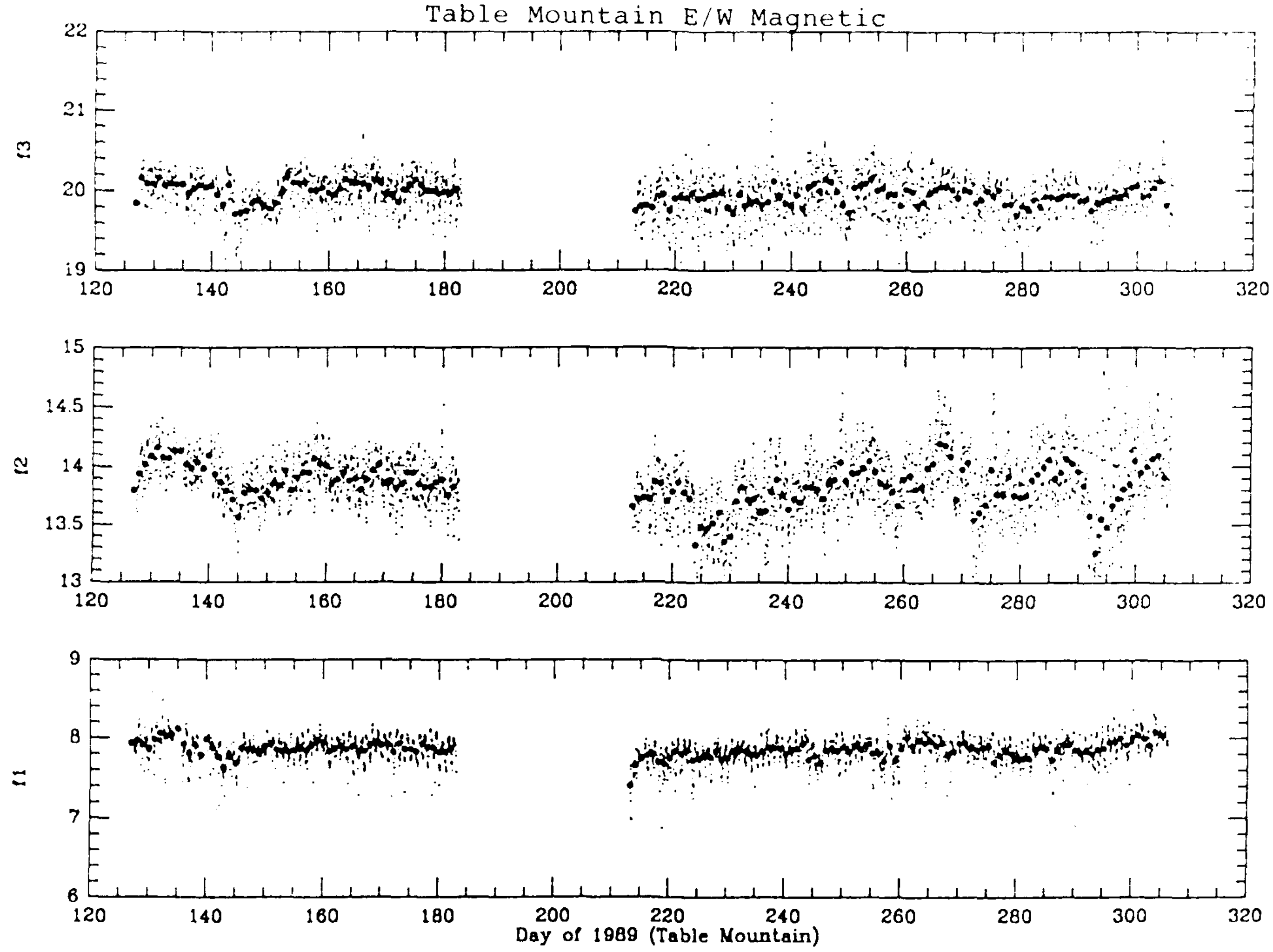


Table Mountain E/W Magnetic
f3
22
21
20
19
f2
15
14.5
14
13.5
13
f1
9
8
7
6
120
140
160
180
200
220
240
260
280
300
320
Day of 1989 (Table Mountain)

Figure 7a.

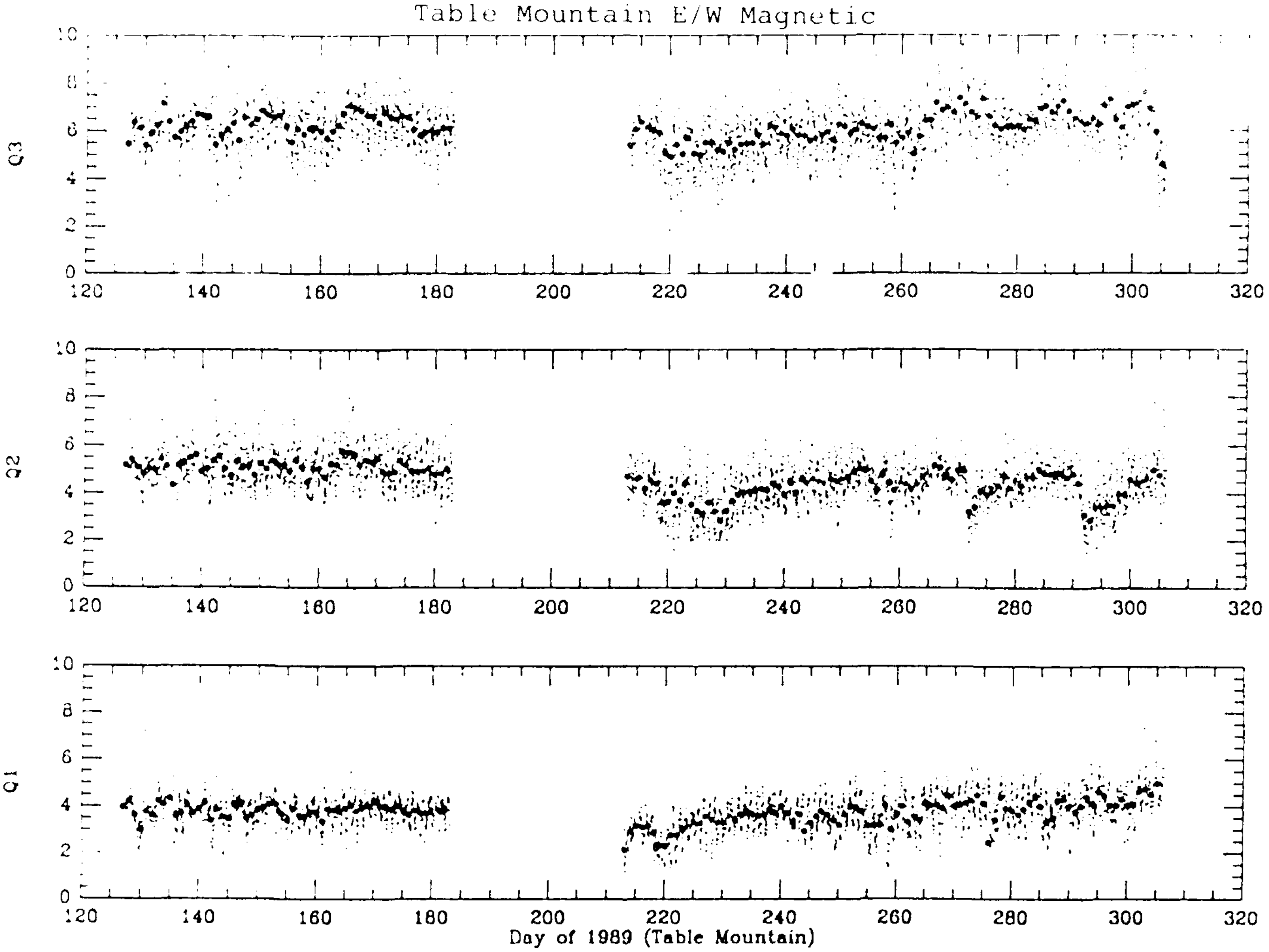
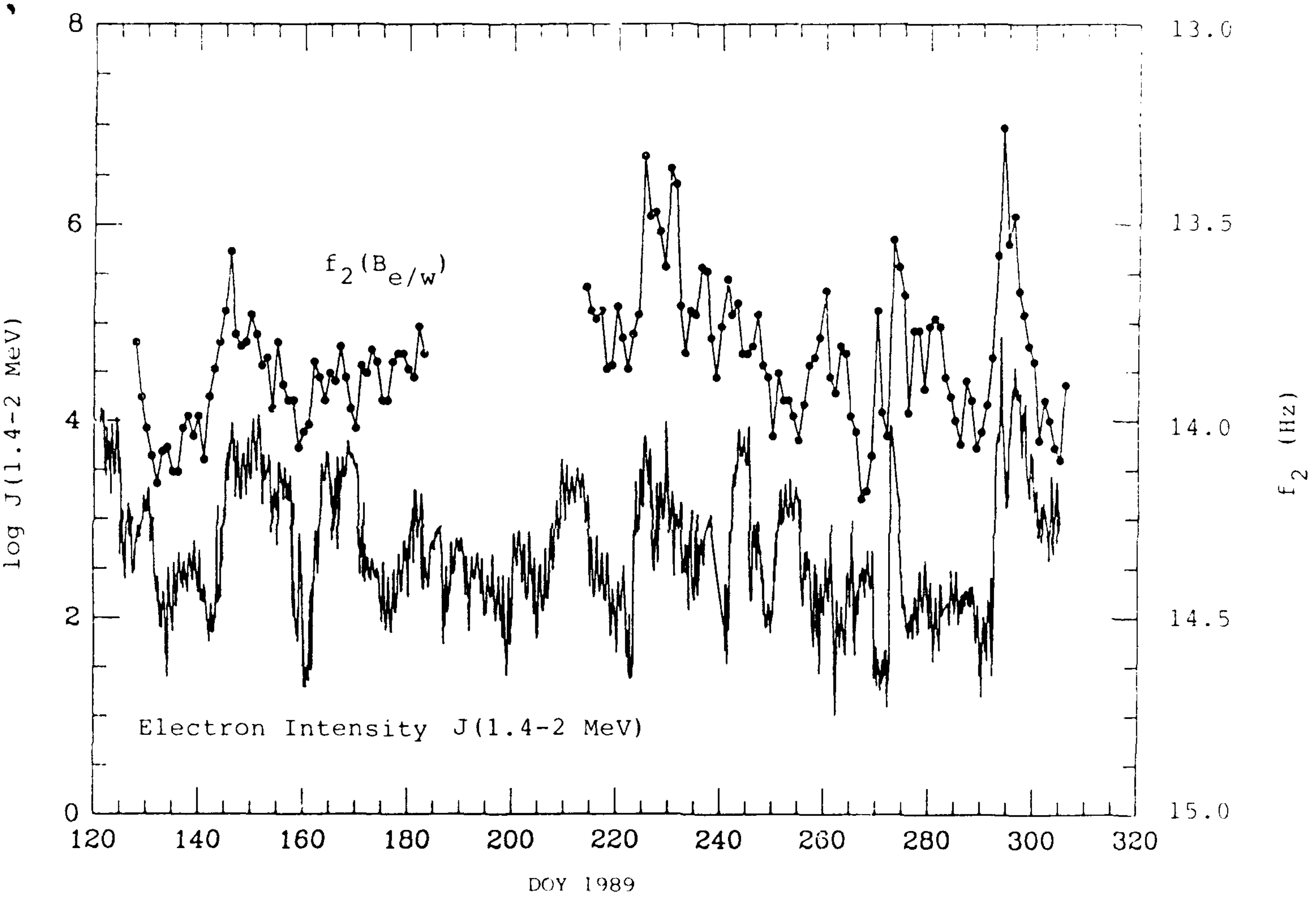


Table Mountain E/W Magnetic
Q3
Q2
Q1
0
2
4
6
8
10
120
140
160
180
200
220
240
260
280
300
320
Day of 1989 (Table Mountain)

Figure 7b.



8
6
4
2
0
13.0
13.5
14.0
14.5
15.0
log J(1.4-2 MeV)
f_2 (Hz)
$f_2(B_{e/w})$
Electron Intensity J(1.4-2 MeV)
120
140
160
180
200
220
240
260
280
300
320
DOY 1989

Figure 8.

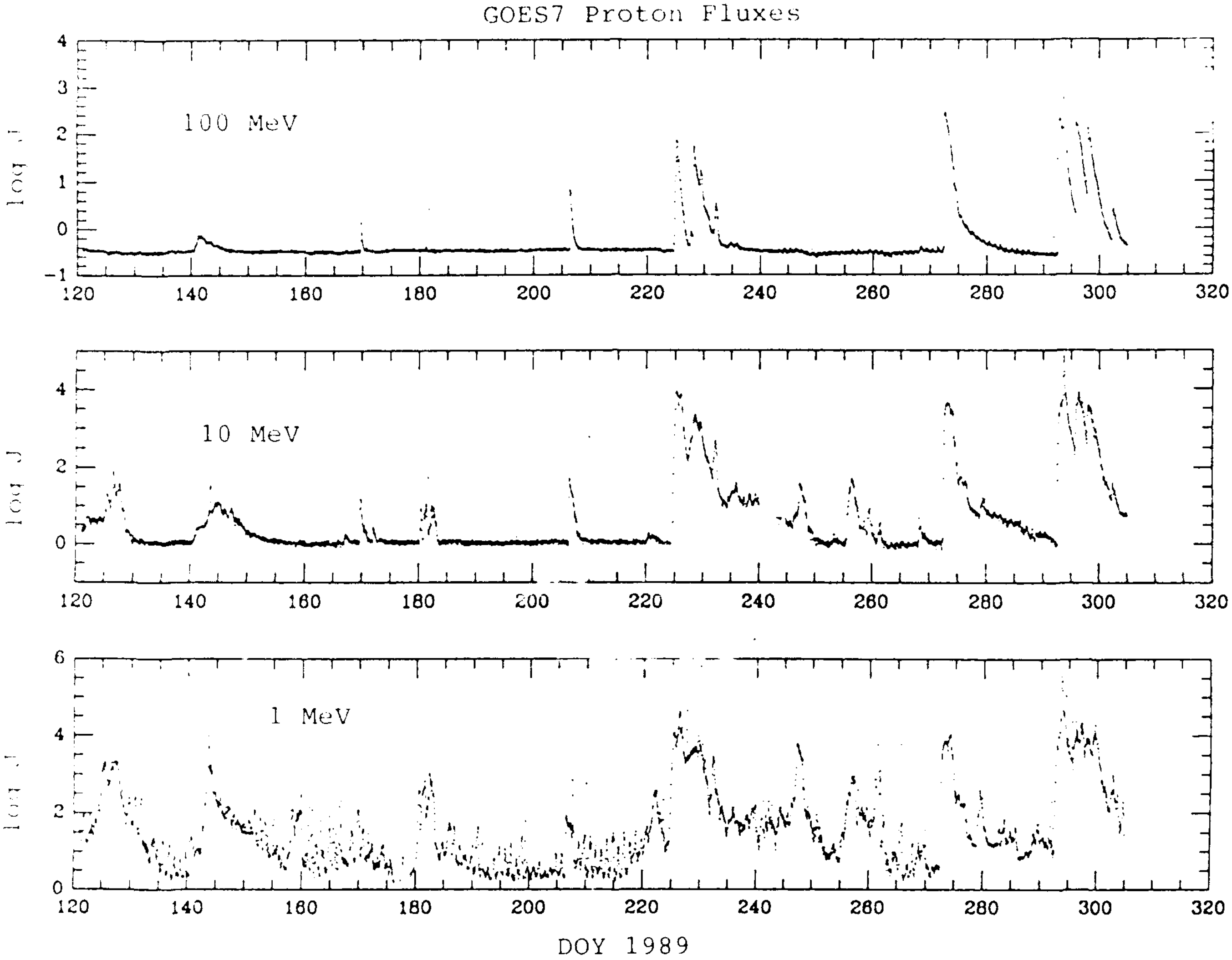

GOES7 Proton Fluxes
100 MeV
10 MeV
1 MeV
log J
4
3
2
1
0
-1
6
120
140
160
180
200
220
240
260
280
300
320
DOY 1989

Figure 9.

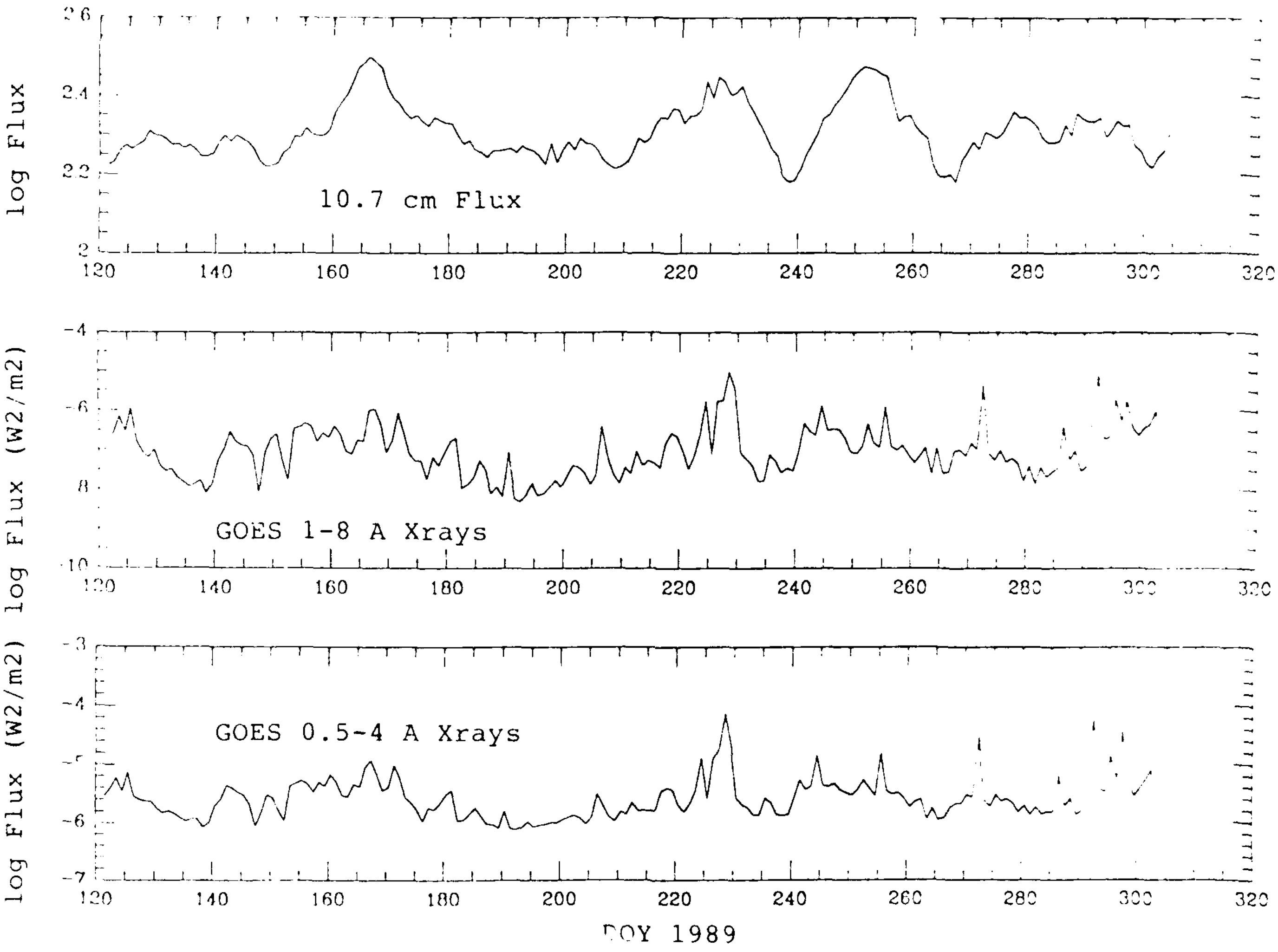
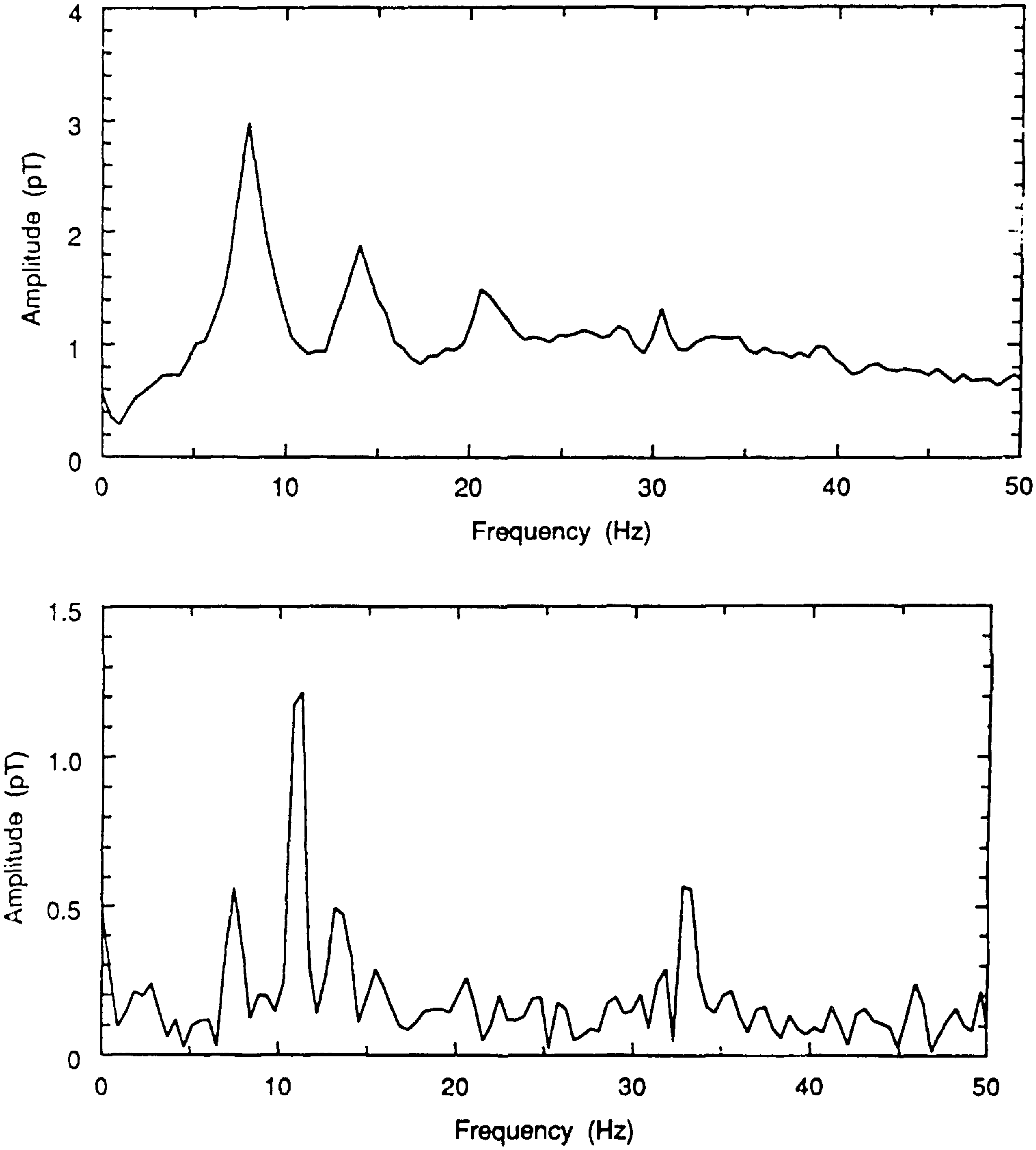

2.6
2.4
2.2
2
log Flux
10.7 cm Flux
120
140
160
180
200
220
240
260
280
300
320
-4
-6
-8
-10
log Flux (W2/m2)
GOES 1-8 A Xrays
-3
-4
-5
-6
-7
log Flux (W2/m2)
GOES 0.5-4 A Xrays
DOY 1989

Figure 10.



4
3
2
1
0
Amplitude (pT)
0
10
20
30
40
50
Frequency (Hz)
1.5
1.0
0.5
0
Amplitude (pT)
0
10
20
30
40
50
Frequency (Hz)

Figure 11

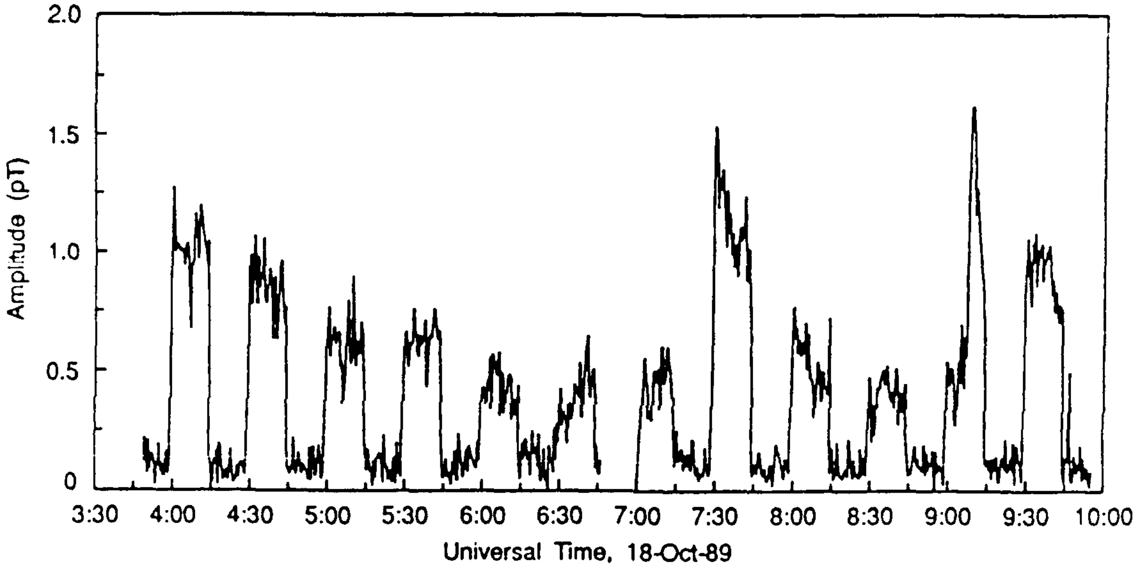

2.0
1.5
1.0
0.5
0
Amplitude (pT)
3:30
4:00
4:30
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Universal Time, 18-Oct-89

Figure 12.