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HIGH LATITUDE CUSP SIGNATURE OBSERVATIONS FOR SOUTHWARD IMF B_Z

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High latitude coherent and incoherent radar systems have given much new information about the physical processes at auroral latitudes. This report presents observational features of the Cusp, situated close to magnetic noon at 70-75 degrees inv. latitude, when the Interplanetary Magnetic Field of the Solar Wind is southward and staying southward for more than half a day. For this condition, the observations of the convectional flow pattern comply with the two-cell model of the global convectional flow at auroral and polar cap latitudes. During moderate disturbed magnetic conditions, the temporal extent of the Cusp can be defined by an increased F-region electron density, while the E-region density decreases or stays constant for mostly northward convectional flow in the magnetic noon sector. The temporal extent of this condition is observed to be up to two hours. When the Cusp is overhead of the radars in Søndre Strømfjord, Greenland, the ionograms show enhanced spread-F condition. A phenomenon associated to electron density enhancements in a turbulent plasma, which flows into the polar cap. Ionogram oblique F-region traces are observed in conjunction with the drifting patches. Patches drift through the Cusp region, but they are also observed before and after the defined Cusp and seem not to be confined by the

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latter. Spectral analysis of the F-region electron density variations in the noon sector has been performed. Periods down to the Pc5 range are observed more frequently in the northward convectional flow regime near noon than in the adjacent time sectors. The same analysis of the magnetic pulsations from the Greenland Magnetometer Chain give periods of 10 minutes in the whole dawn sector until the time, when the Cusp is observed by the radars. This dawn side phenomena are often observed for IMF B_Z southward in the magnetometer chain data.

Table of Contents.

1. Abstract.

High latitude coherent and incoherent radar systems have given much new information about the physical processes at auroral latitudes. This report presents observational features of the cusp, situated close to magnetic local noon at 70 - 75 deg. inv. latitude, when the Interplanetary Magnetic Field (IMF) of the solar wind is southward and staying southward for more than half a day. For this condition the observations of the convectional flow pattern comply with the two-cell model of the global convectional flow at auroral and polar cap latitudes.

The ionosphere signature of the cusp for moderate disturbed magnetic conditions are an enhanced F-region electron density for mostly northward convectional flow in the magnetic noon sector. During the same time the ionosphere E-region electron density decreases or stays constant. Seasonal changes, mainly due to the changes in the solar ionization production rate, is observed to have the most significant effect on the E-region electron densities in the cusp region. The temporal extent of the cusp is observed to be up to two hours. When the cusp is overhead of the radars in Søndre Strømfjord, Greenland, the ionograms show enhanced spread-F condition. This phenomena is associated to electron density enhancements in a turbulent plasma, which flows into the polar cap.

Ionogram oblique F-region traces are observed in conjunction with the drifting patches. Patches drift through the cusp region. But they are also observed before and after the defined cusp and seem not to be confined by the latter.

Spectral analysis of the F-region electron density variations in the noon sector has been performed. Periods down to the Pc5 range are observed more frequently in the northward convectional flow regime near noon than in the adjacent time sectors. The same analysis of the magnetic pulsations from the Greenland Magnetometer Chain give periods of 10 minutes in the whole dawn sector until the time, when the cusp is observed by the radars. These dawn side phenomena are often observed for IMF B_z southward in the magnetometer chain data.

2. Introduction.

The paper will present observations of cusp signatures as measured by the Digisondes in Greenland. The data from the Digisonde in Søndre Strømfjord will be treated in detail together with the data from the Incoherent Scatter Radar Facility, which is also placed in Søndre Strømfjord and operated by US National Science Foundation, and data from the Greenland Magnetometer Chain.

The Greenland Digisonde Net consists of a Digisonde in Qaanaaq (86 deg. inv. lat.), Søndre Strømfjord (74 deg. inv. lat.) and Narsarssuaq (67 deg. inv. lat.). The chain of Digisondes is almost in the magnetic meridian plane covering plasma regimes from below the auroral oval to well into the center of the polar cap. Figure 1 gives the position of the stations with respect to the Feldstein statistical model of the auroral oval for magnetic moderate disturbed conditions (Q=3; Time: 14.00 UT). The bold curves of the hatched area, which traverses the magnetic latitudes, indicate the poleward and the equatorward boundary of the auroral oval. In the figure the magnetic local time at Søndre Strømfjord, Greenland, is 12.00 hours (MLT).

The Søndre Strømfjord site is for moderate to strongly magnetically disturbed conditions close to the equatorward edge of the polar cap or well in the polar plasma region. For quiet to slightly enhanced magnetic conditions the station is located near the poleward edge of the auroral oval. Under these geophysical conditions at or near magnetic noon the cusp passes the latitudes observed by the Digisonde in Søndre Strømfjord. The convectional flow changes within a few hours normally from eastward through northward directions to a westward flow direction. The Digisonde in Qaanaaq, close to the magnetic pole, gives the more uniform antisunward flow in the polar cap. Thus data from these two stations reveal conditions of the direction and magnitude of the IMF of the solar wind.

The Digisonde has two major operational modes (B.W. Reinisch, 1986; Reinisch et al., 1987). As a digital ionosonde it measures the virtual heights or ranges of the returned echoes, polarization and direction of the backscatter volume for each frequency, together with an estimate of the Doppler velocity of the plasma drift of the backscatter points. The ensemble of this data set forms the ionogram. These observations lead to the electron density profiles in true height resolution. The second major mode is the instruments capability to give the Doppler velocity of the plasma drift, when operating as a coherent radar with a maximum zenith angle of 45 degrees. Normally F-region drifts are observed up to a horizontal distance of 300 km within the radar site. Phased array technique make this possible with a very high time resolution (better than a second). Combinations of data from these operational modes from all three Digisondes give a good handle of the drift patterns at high latitudes.

3. Observations.

The cusp has traditionally been defined from satellite observations as the region of enhanced soft electron particle precipitation of a few hundreds eV, close to magnetic noon (Figure 2). In a rather confined region, dominated by ionospheric convectional flow into the polar cap, the average energy of the precipitating electrons decreases for the KeV-part of the particle spectrum. While the number flux of the ions and electrons increases in conjunction with the enhanced electron energy flux of the 100 eV electrons (Newell and Meng, 1992). The longitudinal extend of the region, when only considering the electrons, is up to 2.5 hours with a latitude extend of approximately one degree. This is a larger region and more spread out in longitude than the observed region for the changes in the ion distribution. Statistically, the extend of the latter is up to an hour in longitude, and in latitude as much as three degrees.

The cusp is a distinct plasma regime in the satellite observations of particle spectra. It is very different from the harder precipitation, observed to the north in the mantle, and the particle spectra characteristics observed to the south, which is linked to the Lower Latitude Boundary Layer (LLBL) and the dayside extension of the Boundary Plasma Sheet (BPS). Thus the cusp is an interesting region that directly reflects the conditions in the solar wind plasma and the interaction with the earth magnetosphere through the energy transfer mechanisms to the earths ionosphere (Friis-Christensen et al., 1985).

This study presents data from July 10, 1989 (day 191), where the global polar convection followed a stable two-cell flow pattern, as is often observed for negative B_z of the IMF. Figure 3 from Heelis (1984) outlines a model for the behavior of the dayside high latitude two-cell convection pattern for varying IMF conditions. During the observational period, covering times from 6.00 UT to 18.00 UT, the IMF showed negative values for B_y and B_z. The drift velocity measurements of the radars in Søndre Strømfjord and Qaanaaq followed well the drift patterns given in the theoretical model (Figure 3). The below table A gives the state of the magnetosphere, described through the magnetic index K_p and the magnitude of B_y and B_z. The observations of plasma drift velocities with the Incoherent Scatter Radar (ISR) and the Digisonde in Søndre Strømfjord give cusp conditions for two hours around magnetic noon.

Time (UT)	6	7	8	9	10	11	12	13	14	15	16	17	18
(MLT)	4		6		8		10		12		14		16
K_p	3			2+			3-			3-			2+
B_y	2.0	-5.8	-8.1	-6.5	-7.3	-6.4	-4.3	-1.7	-1.9	-2.0	-1.9	-2.1	-2.1
B_z	2.1	-0.8	-2.0	-0.1	-1.3	-3.5	-5.5	-4.5	-5.9	-5.3	-5.8	-4.4	-1.2

Table A: The magnetic index K_p and the magnitude of B_y and B_z in units of nanoTesla of the solar winds Interplanetary Magnetic Field for day 191, July 10, 1989.

Between 6.00 UT and 7.00 UT (4-5 MLT) B_y and B_z turn negative. B_y becomes very negative (-5.8 nT), decreasing within an hour to -8.1 nT. The upper panels of Figure 3 show for this IMF condition the convectional flow for the dayside ionosphere. As time progresses, B_y increases gradually to a value of -1.9 nT at 16.00 UT, while B_z becomes more negative (from -2.0 nT to -5.8 nT) in the same time period. The change in convection flow configuration resembles the conditions shown in the three top panels of Figure 3. From 6.00 MLT to 16.00 MLT the convectional two-cell pattern goes through stages seen in the upper right panel, the upper left panel and the center panel. The enhanced negative B_z toward the end of the data set has the effect of setting up a more stable two-cell pattern with field-aligned current systems as given in Figure 4 (Potemra and Saflekos, 1978). Similar field-aligned currents can also be deduced from the magnetometer observations from the Greenland Magnetometer Chain. Data from the magnetometers will be discussed later in this paper.

The data sets from July 10, 1989 all support a scenario, where Søndre Strømfjord is close to or within the cusp region for most of the time of the experiment. The upper panel of Figure 5 gives in a polar plot the drift velocities from the Digisondes in Søndre Strømfjord and Qaanaaq. The data originates from the operational drift mode of the Digisondes (Reinisch, 1986). The inner circle shows Digisonde drift data from Qaanaaq, situated close to the center of the polar cap. The predominant direction of the convectional flow follows, for this B_z negative condition, very well the models of Heppner and Maynard (1987) and Heelis (1984).

Cannon et al. (1991) described in their paper the relation between the magnitude and direction of the IMF and the drift velocity observations performed with the Digisonde in Qaanaaq. Their statistically database consisted of 32 24-hour experiments, where the drift directions of the Digisonde were compared to IMF observations from the satellite IMP-8. For negative B_z (southward IMF) Cannon et al. (1991) find that the direction of the convectional flow, deduced from the Digisonde data, at all seasons reveals the direction of the IMF B_y component. The data from July 10, 1989, supports this model of the close connection between the plasma drift in the E- and F-region of the ionosphere and the magnetic field of the IMF. Even the changes in the magnitude of B_y is clearly observable.

The lower panels of Figure 5 give from top to bottom the Digisonde observations of the horizontal (V_h), vertical (V_z) magnitude and the azimuthal direction (AZ) of the F-region convectional flow at Søndre Strømfjord, Greenland. At magnetic noon the northward plasma flow gives velocities of around 200 m/s, which equals an ambient electric field of 10-15 mV/m. This correlates well to the deduced convectional flow velocities from the magnetometer observations, when using a model of the height-integrated conductivities of the ionosphere. The bold straight line in the lower panel of Figure 5 give the antisunward direction of the flow as function of time (Buchau et al., 1988). During the time periods, when the station is in the auroral region, the flow directions follow the plasma flow in the electrojets, i.e. eastward flow in the morning sector (the westward electrojet) and westward flow in the afternoon sector (the eastward electrojet) with reference to magnetic coordinates. At midnight we observe antisunward flow, indicating a position of Søndre Strømfjord in the polar cap. Ionograms from this time sector reveals a less dense plasma with electron density profile characteristics of the polar cap plasma.

In the magnetic noon sector we observe northward plasma flows varying from 100 m/s to 300 m/s. The Digisonde data follow the F-region flow directions and magnitudes, observed by the Incoherent Scatter Radar, which is collocated with the Digisonde in Søndre Strømfjord.

The ionosonde mode of the Digisonde shows from 10-12 MLT, F-region oblique traces that are associated with large electron density enhancements flowing into the polar cap. Simultaneously spread-F condition is observed. These observations combined are indications of the presence of patches drifting into the polar cap (Weber et al., 1984). It has been suggested, that the electron density enhancements called patches may be the result of rapid changes in the size of the polar cap in response to changes in the IMF (Anderson et al., 1988). This data set however indicate, that other mechanisms may also be operating in the generation of patches.

Outside the time sector, where the cusp can be defined by the changes in the electron density profiles, patches are also observed. Figure 6 presents as function of time curves of the critical frequencies, foE (bottom), foF1 (middle) and foF2 (top). They are compared with an 3 hour sliding average that has been shifted 1.5 hours backwards in time. The vertical line in the figure at 13.15 UT gives the start time for cusp plasma observations at Søndre Strømfjord.

The averaged data of foE reflects nicely the solar produced ionization of the ionosphere, when taking into account the time constant for the recombination rate of the lower ionosphere. The same is also observed in the F-region (foF1 and foF2). But here other disturbances are also monitored. They are patches and large scale global changes in the auroral oval and associated phenomena related to the dawn and dusk sector of the auroral oval.

The differences between the curves of the critical frequencies and the time shifted sliding averages indicate the occurrence of patches. From 13.45 UT to 15.30 UT the critical frequency of the upper ionosphere, the F2-region, is persistently higher than the averaged data. This can be taken as evidence of a patch or patches drifting through the region associated to the cusp. The drift direction of the electron density enhancements are poleward along the direction of the convectional flow in the cusp region. This first patch has character of a solid patch. While the second patch from 15.45 UT to 17.10 UT is a structured patch, which is related to the auroral region plasma.

Figure 7 gives in the lower panel a contour plot of the electron density profiles as function of time. The upper panel gives the calculated height integrated Pedersen and Hall conductivities based on the electron density profiles measured by the Digisonde. Starting from 13.15 UT (11.15 MLT) and over the following 2.5 hours we observe some interesting features of the electron density content in the E- and F-region. A decrease in the electron density occurs in the upper ionosphere right after 13.15 UT with smaller height integrated conductivities as the result (upper panel). At 13.45 UT this trend is reversed to an increase in the electron density contours leading to enhanced conductivities. foF2 reaches values above 7 MHz, which equals an electron density of $6 \cdot 10^{11}$ m^{-3}. This enhancement can be derived to fit to an intensified precipitation of soft particles of 100 eV.

A patch indicated in the bowl-shaped dropping and subsequent raising of the upper ionosphere equidensity contours of the electron density passes through the zenith from 13.45 UT to 15.30 UT. A second patch is observed from 15.45 UT to 17.10 UT even though foF2 is decreasing.

The patches lead to large variations in the height integrated conductivities (Figure 7). The conductivities are based on the temperature profile observations made by the Incoherent Scatter Radar on July 10, 1989, and models of the collision frequencies.

The Greenland Magnetometer Chain data are presented in Figure 8. The upper 11 curves presents data from the west coast of Greenland from Narsarssuaq (NAQ) in the south to Qaanaaq (THL) to the north. The lower 4 curves are stations on the east coast of Greenland. At 13.30 UT the magnetic H and Z components show a rapid change, which is larger than 100 nT. Such a quick response in the magnetometer data to changes in the ionosphere is often indicating another plasma regime with significant different structure in the field-aligned currents. At the same time the Pc5 fluctuations, seen most prominent in the H component, disappear. These fluctuations are often associated to the morning sector and the time period before magnetic noon. At 13.30 UT the convectional flow turns northward. All these conditions are normally taken as evidence of cusp plasma.

To verify the magnetometer data we have done a spectral analysis of the electron density altitude variations as shown in Figure 7. The data have been divided into two time periods, 8.00 - 12.00 UT and 12.00 - 16.00 UT (10 - 14 MLT), to improve the statistics of the analysis. We have performed the analysis for plasma frequencies from 3.0 MHz to 7.0 MHz covering both the conditions in the E-region and F-region of the ionosphere (see Figure 7). The spectra in Figure 9 gives the results for a plasma frequency of 5.0 MHz. These results resemble very much the spectra seen at other plasma frequencies.

In the magnetic pre-noon sector the Digisonde data give wave periods of the strongest fluctuations of 13, 16, and 41 minutes, which equals the observations of Pc5 fluctuations in the magnetometer data. While in the cusp region, where the magnetometer data show no or very little wave activity, we observe even stronger power in fluctuations with periods from 10 to 40 minutes. This effect is the strongest in the upper part of the F-region of the ionosphere. Which again could be the reason why the magnetometer is not capable of observing the fluctuations since the magnetometer data are mostly driven by the E-region Hall currents. Table B gives the frequencies of the three largest peaks in the spectra.

Electron density fluctuations in the cusp have also been observed with the Millstone Hill Incoherent Scatter Radar (J. Foster, private communication, 1992). They observed bursts of a period of 8 minutes in the F-region plasma structures in the cusp region. Similar observations have been observed with the Goose Bay Coherent Radar, where pulsations of a wave period of 15 minutes were monitored in the cusp (R.A. Greenwald, private communication, 1992).

Pre-noon Sector			Noon Sector	
6.00 - 10.00 MLT			10.00 - 14.00 MLT	
Period (min)	Frequency (mHz)		Period (min)	Frequency (mHz)
15.5	1.1	1	21.6	0.8
12.6	1.3	2	13.6	1.2
40.7	0.4	3	33.3	0.5

Table B: Dominant peaks in the power spectra of the altitude variations of the electron density profiles of the ionosphere. The power spectrum analysis is for a plasma frequency of 5.0 MHz, which equals a wavelength of 30 meter and a critical electron density of $3.1 \cdot 10^{11}$ m^{-3}. The data have been grouped in two time intervals, the pre-noon sector and the noon sector. The peak powers are ordered with the largest classified as number one.

4. Conclusion.

- The Greenland Digisonde Net has proven to be a very good tool for monitoring ionospheric signatures of the dayside cusp. Together with other groundbased instrumentation (the Greenland Magnetometer Chain and the Incoherent Scatter Radar in Søndre Strømfjord) it has been possible to describe characteristics of cusp plasma and it's relations to the IMF of the solar wind.

- For southward IMF the observations give the following characteristics of the cusp: The drift measurements show a northward flow into the polar cap in the cusp time sector. At Søndre Strømfjord the convectional flow are strongly related to the direction given by the IMF B_y component.

- Drift velocities tend to be smaller in the cusp ionosphere than the convectional flow measured in the adjacent time sectors dominated by drift velocities of the electrojets.

- Ionograms show increasing spread-F and oblique F-region traces.

- Patches drift with the convectional flow into the polar cap through the cusp region. But patches are also observed in the adjacent afternoon sector drifting into the polar cap.

- In the cusp region electron density profiles enhance in the upper F-region. This effect that can be associated to the enhanced soft particle precipitation measured by satellites of the particle distribution in the ionosphere. The phenomenon could also be related to transport of more dense plasma from the south of the cusp into the region.

- Spectral analysis of the height variations of the electron density profiles give substantial power at frequencies with periods from 10 to 30 minutes. A connection to the northward drifting patches can partly explain the fluctuations. The electron density fluctuations are a F-region phenomenon. The same effect is absent in the Hall current measurements in the ionospheric E-region.

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7. Figure captions.

Figure 1. Geographic map showing the Greenland Digisonde Net. The latitude and longitude grids refer to the geographic and geomagnetic invariant coordinates, respectively. Included is also the Feldstein statistical model of the auroral oval for magnetic moderate disturbed conditions (Q=3; Time: 14.00 UT). The time difference between magnetic local noon at Søndre Strømfjord and universal noon time is two hours (MLT = UT - 2 hours).

Figure 2. Map in geomagnetic coordinates of a statistical representation of the different plasma regions in the dayside ionosphere (from Newell and Meng, 1992). The position of the plasma regimes are based on DMSP satellite observations, which have been averaged over all IMF and magnetic activity conditions.

Figure 3. Schematic representation of the dayside high-latitude convection pattern showing its dependence on the B_y component of the IMF when B_z is southward (After Heelis, 1984).

Figure 4. Diagram of the convective flow patterns and the field-aligned currents in the polar regions during conditions of positive and negative B_y (from Potemra and Saflekos, 1978).

Figure 5. Upper panel give a polar plot of the drift velocities observed by the Digisondes in Qaanaaq and Søndre Strømfjord for July 10, 1989. The outermost circle represents data from Søndre Strømfjord.
The lower three panels show the drift velocity components, the horizontal velocity (V_h), the vertical velocity (V_z) and the direction of the flow in azimuth (AZ).

Figure 6. Presentation of the ionosphere critical frequency parameters for the E-, F1- and F2-region in units of MHz for day 191, July 10, 1989.
The smoothed curves are the three hour sliding averages of the same parameters shifted 1.5 hour backwards in time.

Figure 7. Lower panel is a contour plot of the electron density profiles. The vertical line at 13.15 UT gives the start time of the cusp region. The two marked time sectors (13.45 - 15.30 UT and 15.45 - 17.10 UT) define the periods when patches are observed The slowly variation, seen most clearly from 9.00 UT to 20.00 UT for the frequencies from 3 to 5 MHz, is due to the changes in the solar ionization production rate caused by the variations in the solar zenith angle. The upper panel give the temporal variations in the height-integrated Hall and Pedersen conductivities.

Figure 8. H, D and Z components of the magnetic field of the Earth observed by the Greenland Magnetometer Chain.

Figure 9. Power spectra of the height variations of the electron density profiles for a plasma frequency of 5.0 MHz. The upper panel represents data from the time period 8.00 - 12.00 UT (6.00 - 10.00 MLT) before the cusp is present in the data set. The lower panel gives the spectral analysis for the time period 12.00 - 16.00 UT (10.00 - 14.00 MLT), when the cusp is observed at the radar site.

8. Figures.

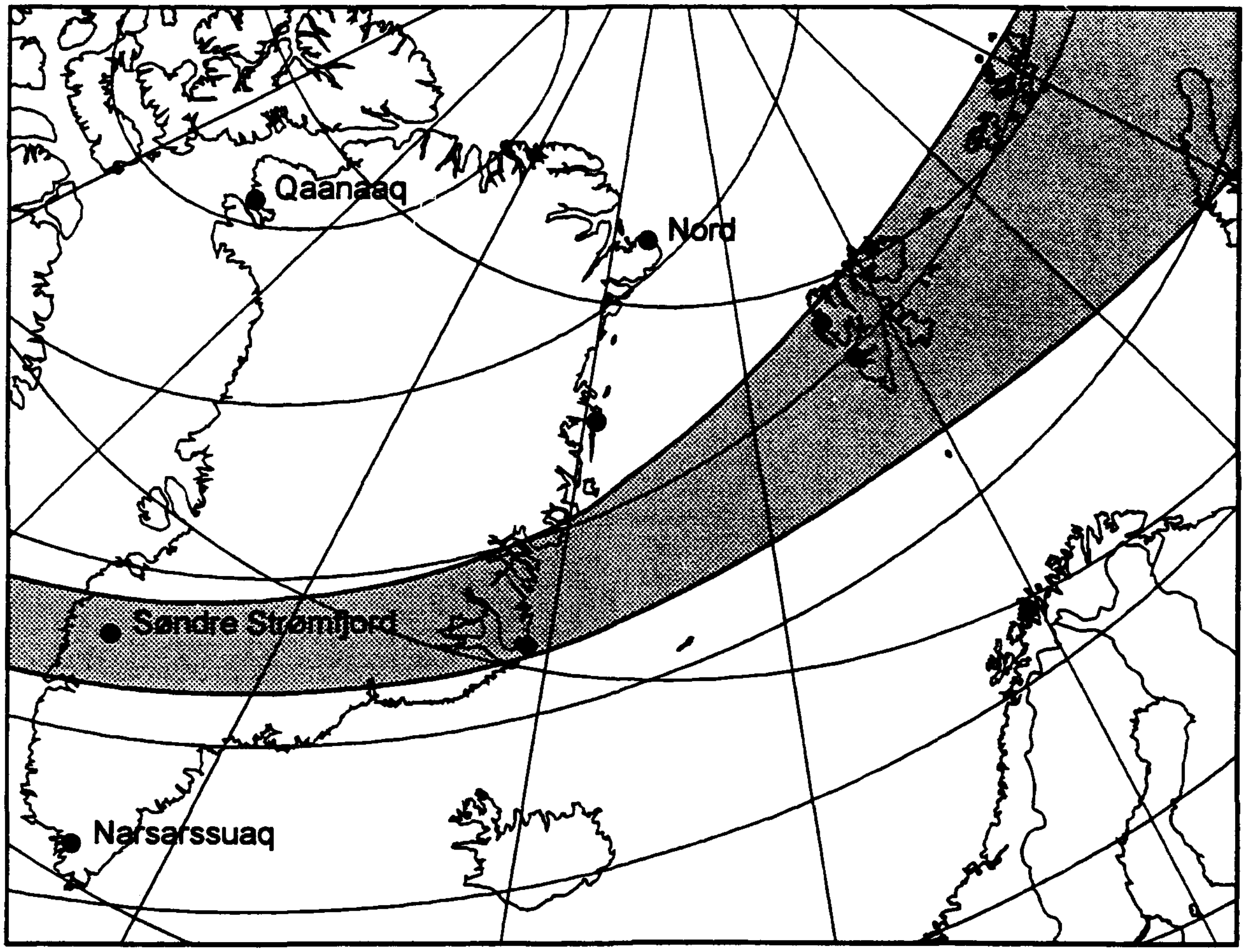

FIGURE 1

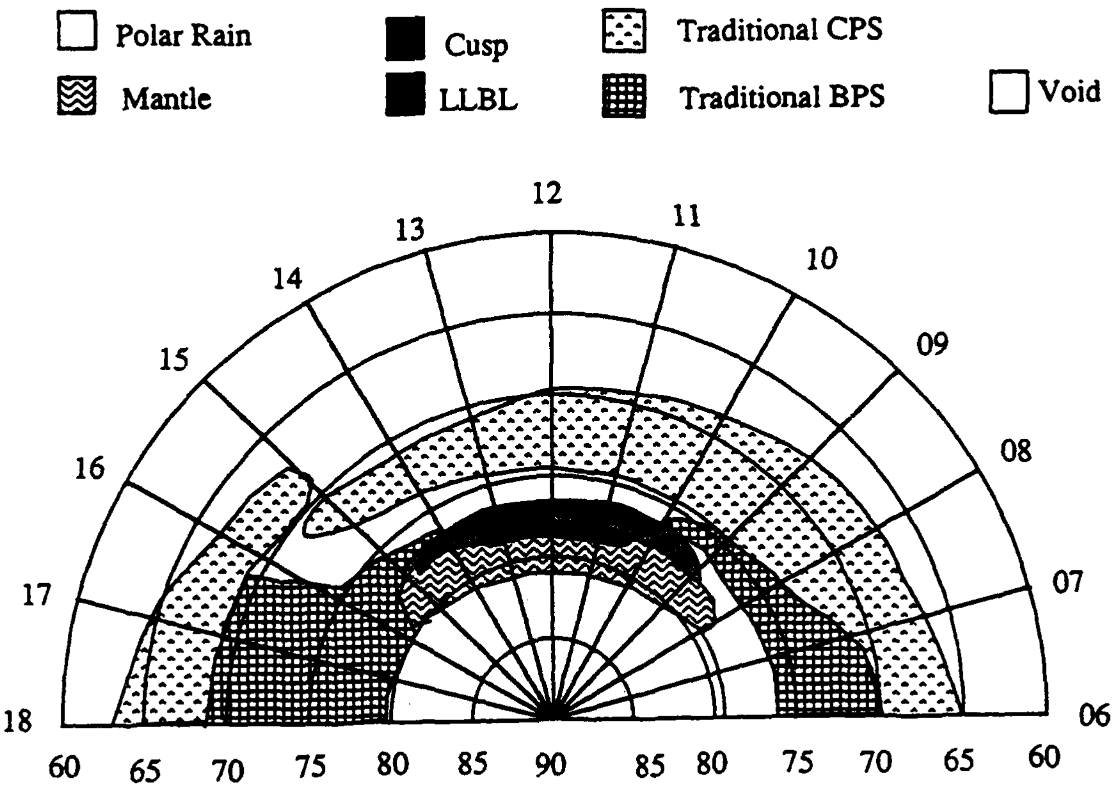
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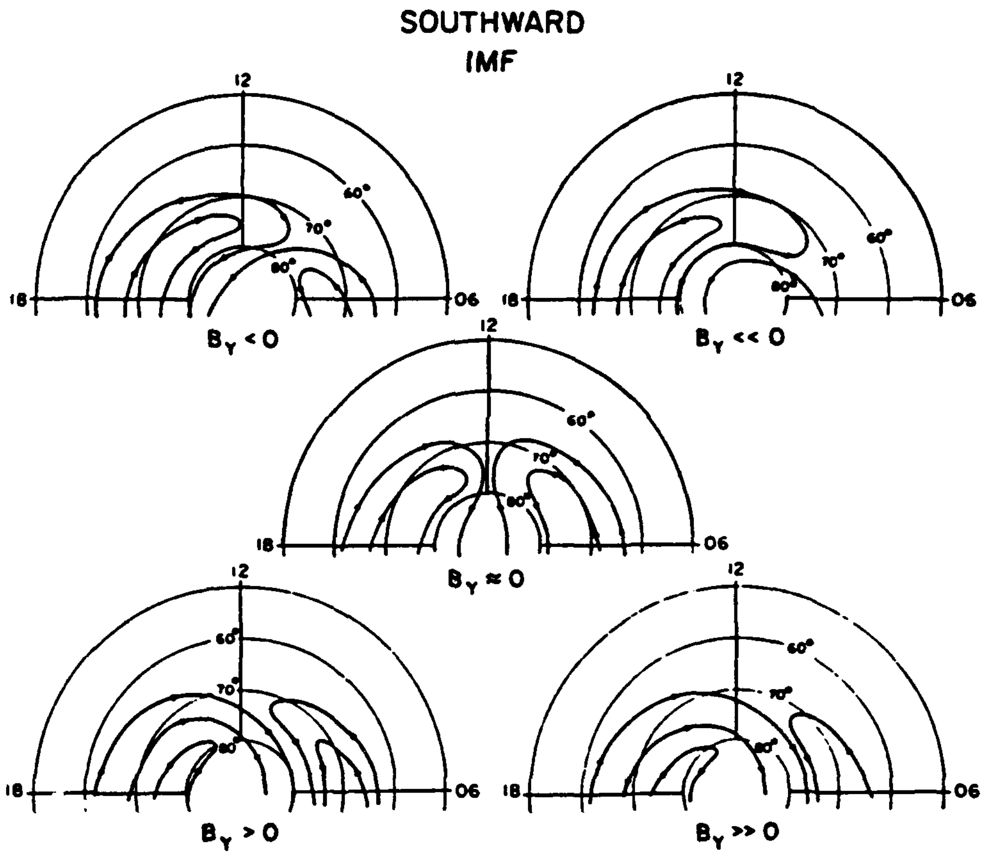
FIGURE 2



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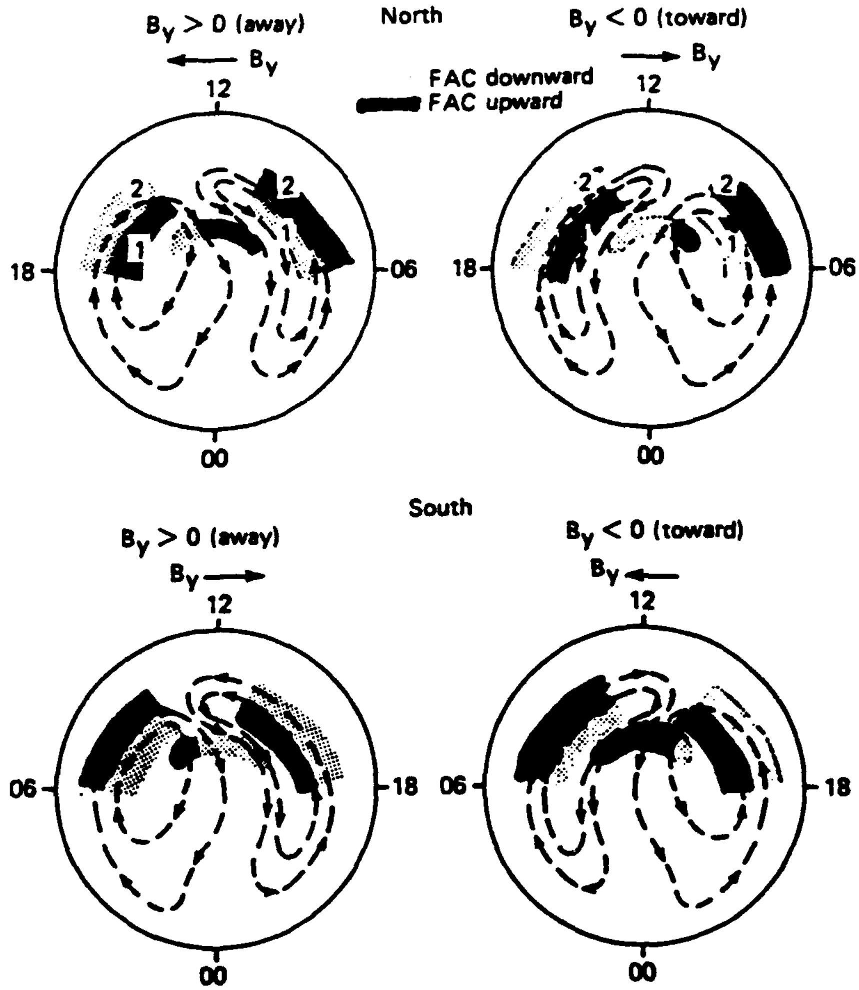
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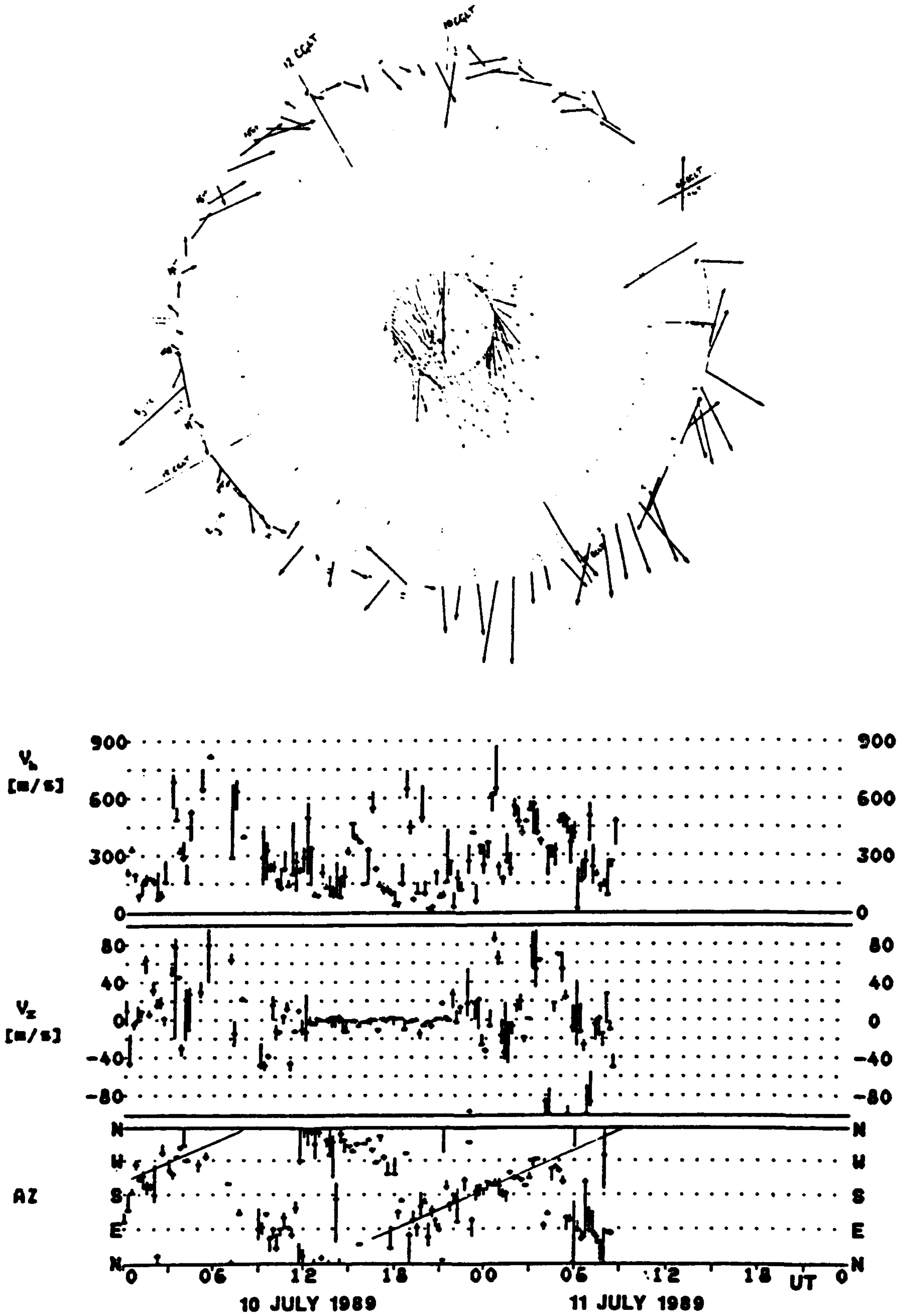

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0
V_z [m/s]
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40
0
-40
-80
AZ
N
W
S
E
N
0
06
12
18
00
06
12
18
UT
0
10 JULY 1989
11 JULY 1989

FIGURE 5

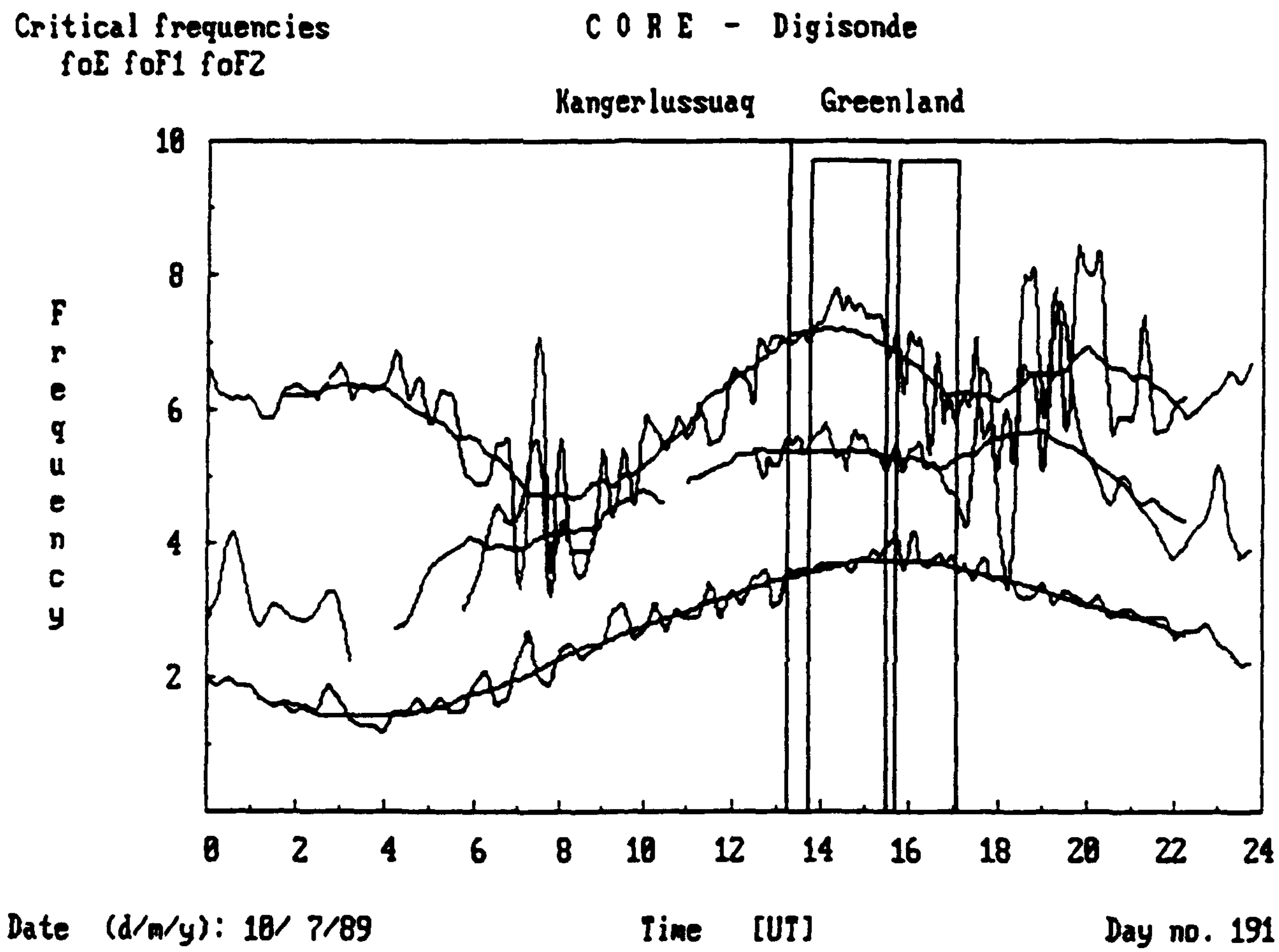
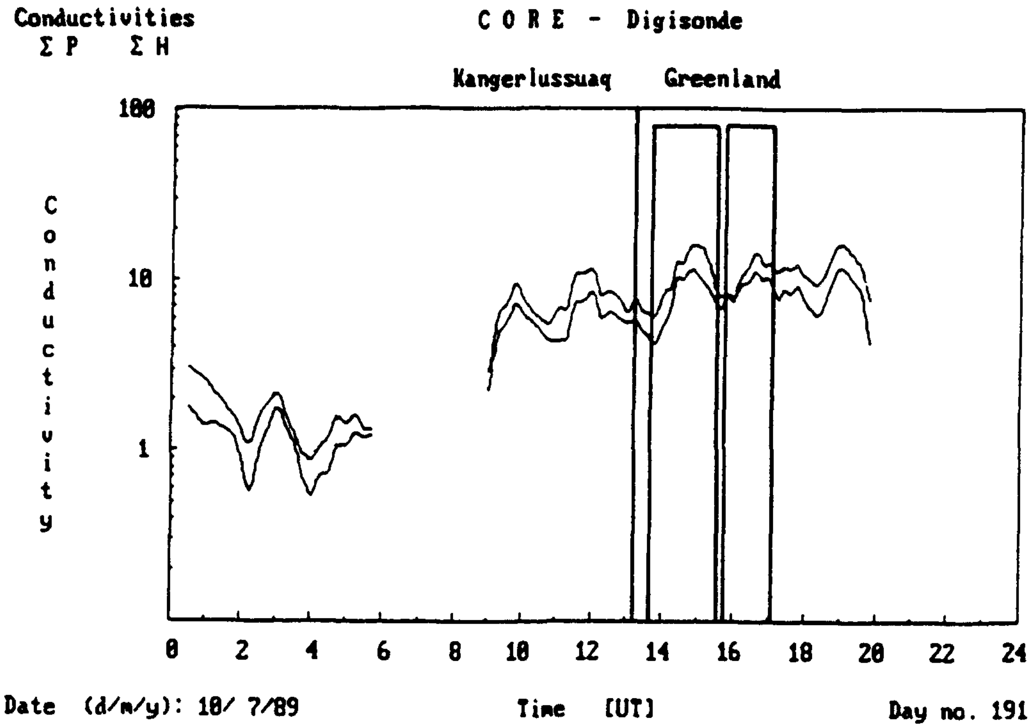

Critical frequencies
foE foF1 foF2
C O R E - Digisonde
Kangerlussuaq Greenland
10
8
6
4
2
Frequency
0 2 4 6 8 10 12 14 16 18 20 22 24
Date (d/m/y): 10/ 7/89
Time [UT]
Day no. 191

FIGURE 6


Conductivities
Σ P Σ H
C O R E - Digisonde
Kangerlussuaq Greenland
Conductivity
100
10
1
0 2 4 6 8 10 12 14 16 18 20 22 24
Date (d/m/y): 10/ 7/89
Time [UT]
Day no. 191

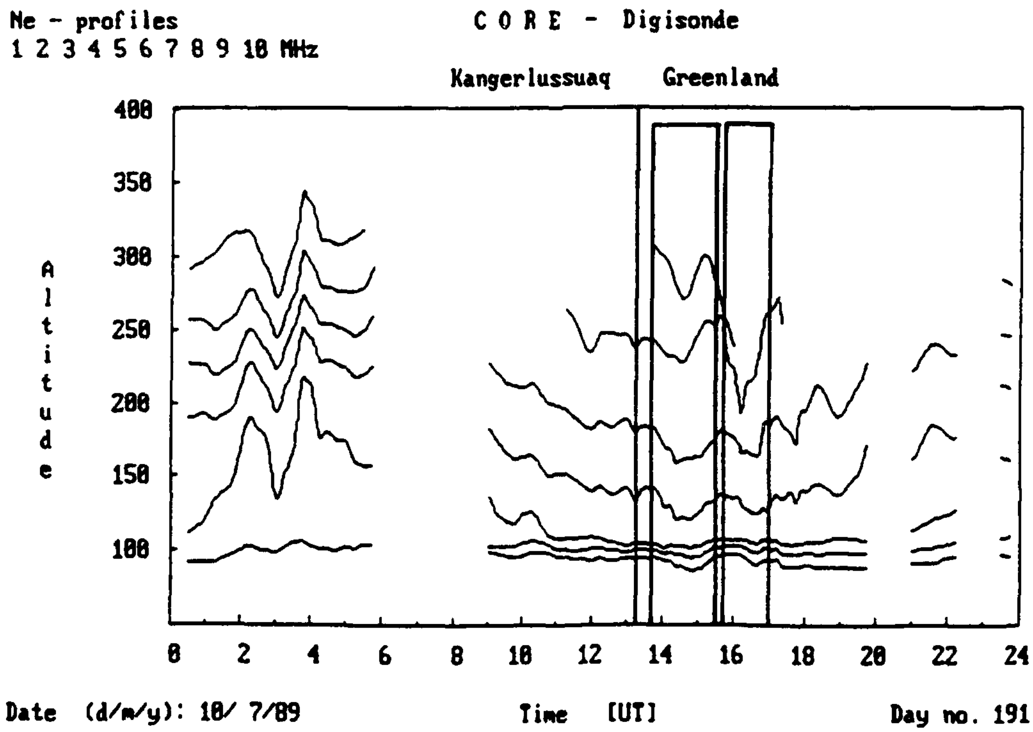
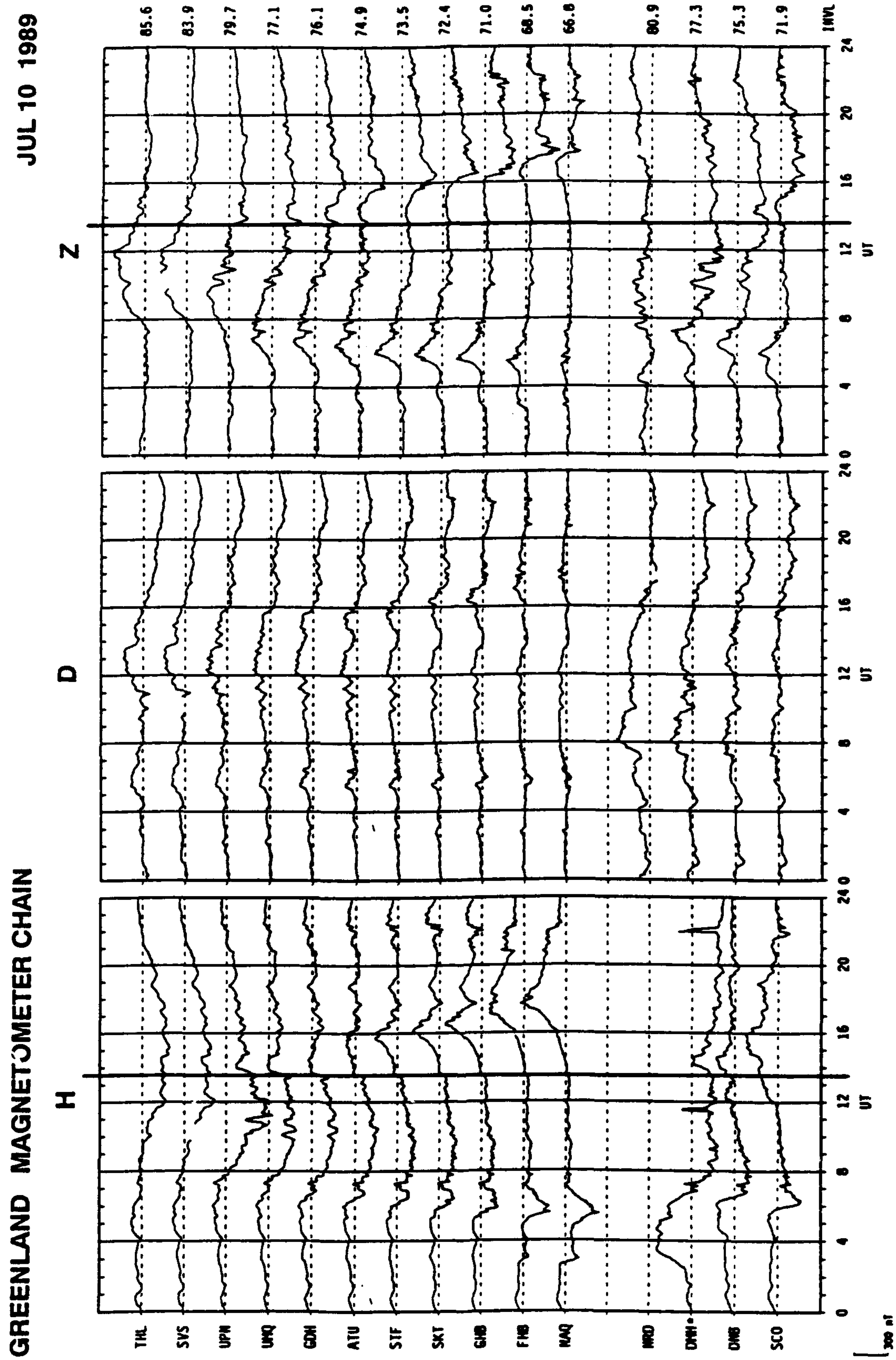

Ne - profiles
1 2 3 4 5 6 7 8 9 10 MHz
C O R E - Digisonde
Kangerlussuaq Greenland
Altitude
400
350
300
250
200
150
100
0 2 4 6 8 10 12 14 16 18 20 22 24
Date (d/m/y): 10/ 7/89
Time [UT]
Day no. 191

FIGURE 7



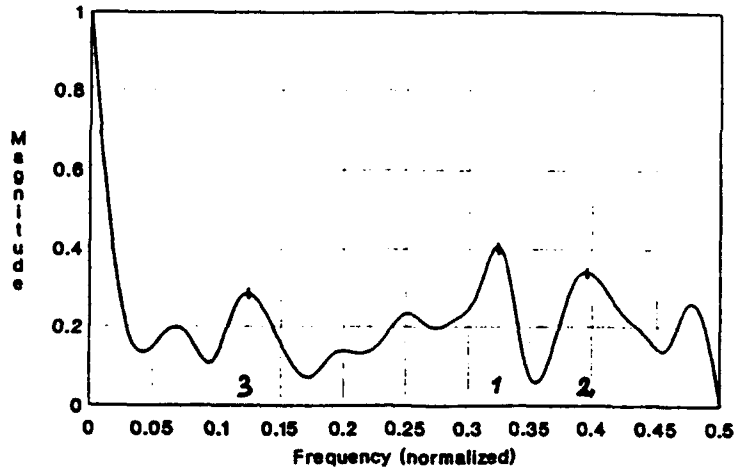
GREENLAND MAGNETOMETER CHAIN
JUL 10 1989
H
D
Z
THL
SVS
UPN
UMQ
GDH
ATU
STF
SKT
GHB
FHB
NAQ
NRD
DMH
DNB
SCO
85.6
83.9
79.7
77.1
76.1
74.9
73.5
72.4
71.0
68.5
66.8
80.9
77.3
75.3
71.9
INVL
UT
300 nT

FIGURE 8

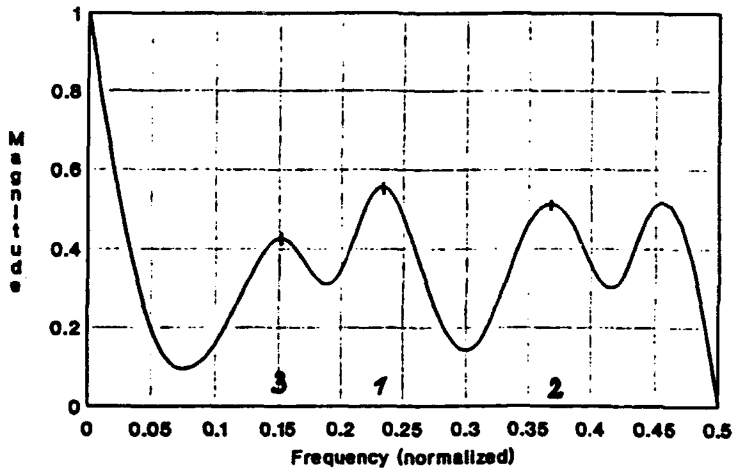
Power Spectra

Frequency: 5.0 MHz

Kangerlussuaq Greenland



1989 191 Time: 0.00 - 12.00 UT



1989 191 Time: 12.00 - 16.00 UT

FIGURE 9