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Color Spectrograms of Very-Low-Frequency Poynting Flux Data

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This paper discusses a new method of processing the VLF electric and magnetic field data from the Injun 5 satellite to produce color frequency–time spectrograms with the color indicating the Poynting flux direction, up or down the geomagnetic field. The Poynting flux sensing technique used on Injun 5 employs one electric and one magnetic antenna, both oriented perpendicular to the geomagnetic field and to each other. With this antenna geometry the Poynting flux direction, up or down the geomagnetic field, can be determined from the cross-correlation between the electric and magnetic field signals. The technique used to process these signals employs a new type of spectrum analyzer/cross-correlator to determine the cross-correlation between the electric and magnetic field signals as a function of frequency and time. These data can be displayed as a two-color frequency–time spectrogram by using appropriate display techniques. A survey of complex VLF radio noise phenomena analyzed by using this technique is presented.

This paper presents a new method of processing satellite VLF electric and magnetic field data to produce color frequency–time spectrograms with the color indicating the Poynting flux direction, up or down the geomagnetic field. This Poynting flux sensing technique requires the use of a magnetically oriented spacecraft with two orthogonal antennas, one electric and one magnetic, oriented perpendicular to the geomagnetic field. With this antenna geometry it is possible to determine the Poynting flux direction, up or down the geomagnetic field, from the cross-correlation between the electric and magnetic field signals. This Poynting flux sensing technique was first used on the low-altitude polar orbiting Injun 5 satellite [*Gurnett et al.*, 1969]. Initial results on the direction of propagation and source region of various magnetospheric VLF emissions were reported by *Mosier and Gurnett* [1969] and *Mosier* [1971], who used single frequency measurements. With the instrumentation described in this paper it is now possible to make Poynting flux measurements at many frequencies simultaneously and to display the data on a color frequency–time spectrogram, with the color indicating the direction of propagation. A survey of Poynting flux measurements made with Injun 5 using this new processing technique is presented.

The theory of the Injun 5 VLF Poynting flux measurement technique was discussed by *Gurnett et al.* [1969] and *Mosier and Gurnett* [1971] and is briefly reviewed below to point out the capabilities and limitations of the technique. For the Injun 5 antenna geometry it can be shown, under very general conditions, that the Poynting flux direction, up or down the geomagnetic field, can be determined from the cross-correlation between the detected electric and magnetic field signals. The physical reason for this simple result is that, for the Poynting flux component parallel to the geomagnetic field, $S_z = E_xH_y - E_yH_x$, the E_y and H_x fields are related to the E_x and H_y fields by Maxwell's equations and the cold plasma equations in such a way that the sign of $\langle S_z \rangle$ is the same as the sign of $\langle E_xH_y \rangle$. (Angle brackets indicate a time average.) For single waves this result is valid whenever the wave frequency is less than the electron plasma frequency. If many waves with different wave normal angles are present simultaneously, then this result must be qualified. If the cross-correlation $\langle E_xH_y \rangle$ is observed to be positive (or negative), then it can be

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shown that at least some of the waves must have a Poynting flux in the positive (or negative) z direction. There may also be waves with Poynting fluxes in the opposite direction, however, and the relative intensity of these waves cannot be determined without further information on the wave normal angles involved. Only under certain restricted conditions is it possible to determine the direction of the average Poynting flux when many waves are present (see discussions by *Mosier and Gurnett* [1971]).

DESCRIPTION OF INSTRUMENTATION

Since different phenomena often occur simultaneously at different frequencies, it is necessary to provide some frequency selection prior to performing the cross-correlation measurement, to avoid superimposing several different phenomena in the cross-correlation determination. For the initial Poynting flux measurements reported by *Mosier and Gurnett* [1969] and *Mosier* [1971], the frequency selection was accomplished by using two identical filters to band limit the electric and magnetic field signals prior to cross-correlation. The outputs of the two matched filters were multiplied and averaged, with a time constant appropriate for the filter bandwidth used, to provide a single frequency correlation measurement. This single frequency processing technique, although adequate for certain limited investigations, has the disadvantage of requiring a separate processing run for each frequency. To provide both cross-correlation and frequency spectrum analysis in a single operation, a new multi-frequency processing technique that uses the Federal Scientific Corporation Ubiquitous UA-6 spectrum analyzer was developed.

The UA-6 spectrum analyzer uses a single analysis filter that is swept in frequency automatically by using a hetrodyne technique. Because of a special time compression technique used on the UA-6, very fast sweep rates are possible. All frequencies may be completely scanned in a time comparable to the normal response time for a single frequency measurement. With an additional item of equipment called a Multifunction Computational Unit (MCU-2), also manufactured by Federal Scientific Corporation, two UA-6 spectrum analyzers can be operated together to perform cross-correlation spectrum analysis. A block diagram of the combined spectrum analysis/cross-correlation system used is shown in Figure 1. The function of the MCU-2 is to synchronize the frequency sweeps of the two UA-6 spectrum analyzers so that the two analysis filters are always at the same center frequency. The cross-

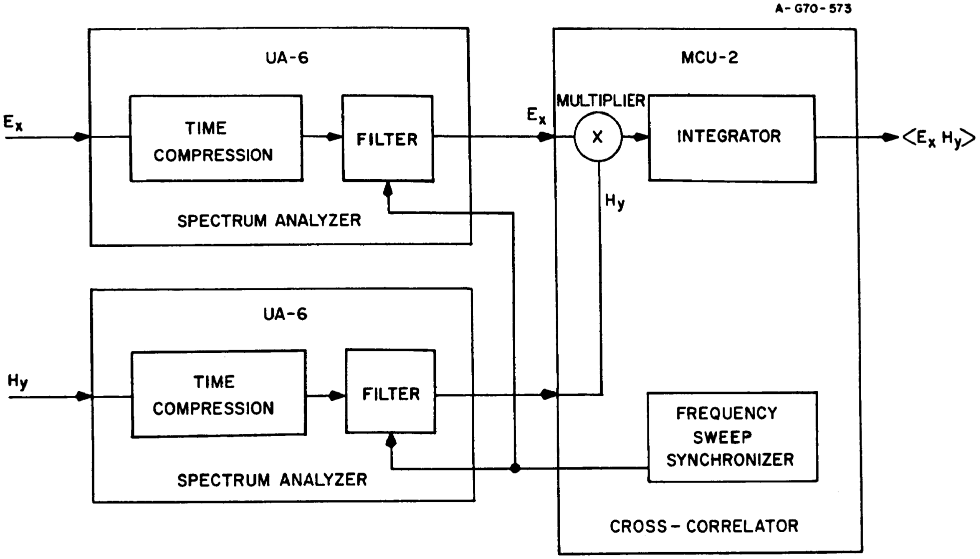


Fig. 1. Block diagram of the Federal Scientific Corporation UA-6/MCU-2 spectrum analyzer and cross-correlator used for Poynting flux spectrum processing.

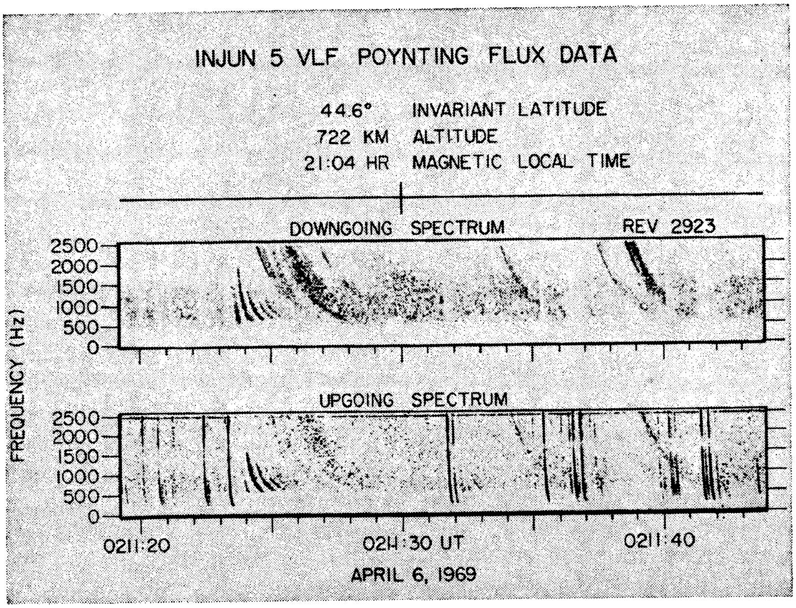


Fig. 2. Separate black and white spectrograms of upgoing and downgoing waves.

correlation between the two input signals is obtained by analog multiplication and integration of the signals from the two filters.

Since the sign of the cross-correlation spectrum output contains the essential information on the Poynting flux direction, the display technique must indicate the sign (positive or negative) as well as the frequency–time spectrum of the cross-correlation magnitude (which is proportional to the wave amplitude). An obvious solution is to separate the cross-correlation spectrum into positive and negative cross-correlation spectra, corresponding to downgoing and upgoing waves, respectively, in the northern hemisphere. This separation can be accomplished by using electronic circuits to sense the sign of the cross-correlation output voltage and to control the intensity of the two oscilloscopes used in producing the upgoing and downgoing spectrograms. Examples of separate upgoing and downgoing spectrograms produced with this technique are shown in Figure 2. Within the dynamic range of the film the exposure (darkness) of these spectrograms is proportional to the logarithm of the magnitude of the cross-correlation output. The separation of upgoing from downgoing waves is evident in Figure 2 from the absence of downgoing waves at all frequency–time points where upgoing waves are observed and vice versa. The interference line at 2.5 kHz on the upgoing spectrogram in Figure 2 is generated within the VLF experiment. The cross-correlation of this interference signal between the electric and magnetic channels is such that the interference line appears on the upgoing spectrogram.

The separate display of upgoing and downgoing spectrograms has the disadvantage of making close time comparisons between the two spectrograms difficult. A more convenient technique would be to display both upgoing and downgoing waves on the same spectrogram by using different colors for upgoing and downgoing waves. This type of color display can be obtained by using a color oscilloscope with two color intensity controls in the same way that a conventional oscilloscope is used for black and white spectrogram production. Although such a color display system is being designed at the University of Iowa, difficulties in developing a suitable color oscilloscope have led to an alternative method of color spectrogram production utilizing a technique developed by Dr. L. A. Frank at the University of Iowa. This technique consists of separately projecting the two spectra shown in Figure 2 onto a screen thus indicating that the altitude of reflection above the satellite is progressively decreasing. Also of interest is the systematic variation of the upper and lower cutoff frequency on successive echoes. The detailed explanation of these variations in the reflection altitude and cutoff frequencies of the successive subprotonospheric whistler echoes is not known.

A very diffuse long hop whistler trace is also evident in Figure 4 several seconds after the initial short fractional hop whistler. This diffuse whistler has many ill-defined red and green components. This mixture of rather poorly resolved upgoing and downgoing components is typical of such diffuse whistlers and is believed to result from a variety of propagation paths, each with a different delay time, from the lightning stroke to the satellite.

Chorus and ELF hiss. The Poynting flux direction of ELF hiss and chorus was investigated by *Mosier and Gurnett* [1969] and *Mosier* [1971]. Their results indicate that, although ELF hiss and chorus are generally observed to be downgoing, occasionally ELF hiss and chorus are observed to be upgoing at invariant latitudes less than 60°. The transition from downgoing to upgoing in these cases often occurs near the boundary between the plasmapause and the light ion trough, with the upgoing waves being observed on the low-latitude side of the boundary, inside the plasmapause.

Figure 5 shows a Poynting flux spectrogram of such a transition for a mixture of ELF hiss and chorus in the frequency range from about 250 Hz to 1 kHz. From the AFCRL electron density probe on Injun 5, the plasmapause boundary in this case is estimated to occur at about 1417:45 ± 15 sec UT. The transition in the Poynting flux direction for the ELF hiss/chorus band in Figure 5 is seen to occur at about 1418:30 UT at a latitude corresponding, as closely as can be determined, to the plasmapause boundary. Certain features of the noise spectrum, particularly the sharp low-frequency cutoff and the general upper frequency limit of the noise, are essentially unchanged for the upgoing and downgoing noise. There is, however, some change in the fine structure of the noise, with a tendency for less discrete structure (ELF hiss) inside the plasmapause boundary and more discrete structure (risers and chorus) outside the plasmapause boundary.

Two general ideas have been considered to explain this reversal in the direction of propagation at the plasmapause boundary. (1) The altitude at which the noise is generated may change from above to below the satellite at the plasmapause, so as to give the observed reversal in the direction of propagation. (2) The upgoing waves observed inside the plasmapause boundary may actually originate at high altitudes outside the plasmapause and may have been reflected or refracted upward at some point below the satellite after crossing the plasmapause boundary. As discussed by *Mosier* [1971], the fact that certain spectrum characteristics, such as the sharp low-frequency cutoff of the ELF hiss, are often essentially unchanged in both the upgoing and downgoing noise suggests that the noise is coming from the same source region. On this basis, it is our tentative conclusion that these reversals in the direction of propagation of ELF hiss and chorus, sometimes observed at the plasmapause boundary, are due to the reflection or refraction of these waves from downgoing to upgoing near the

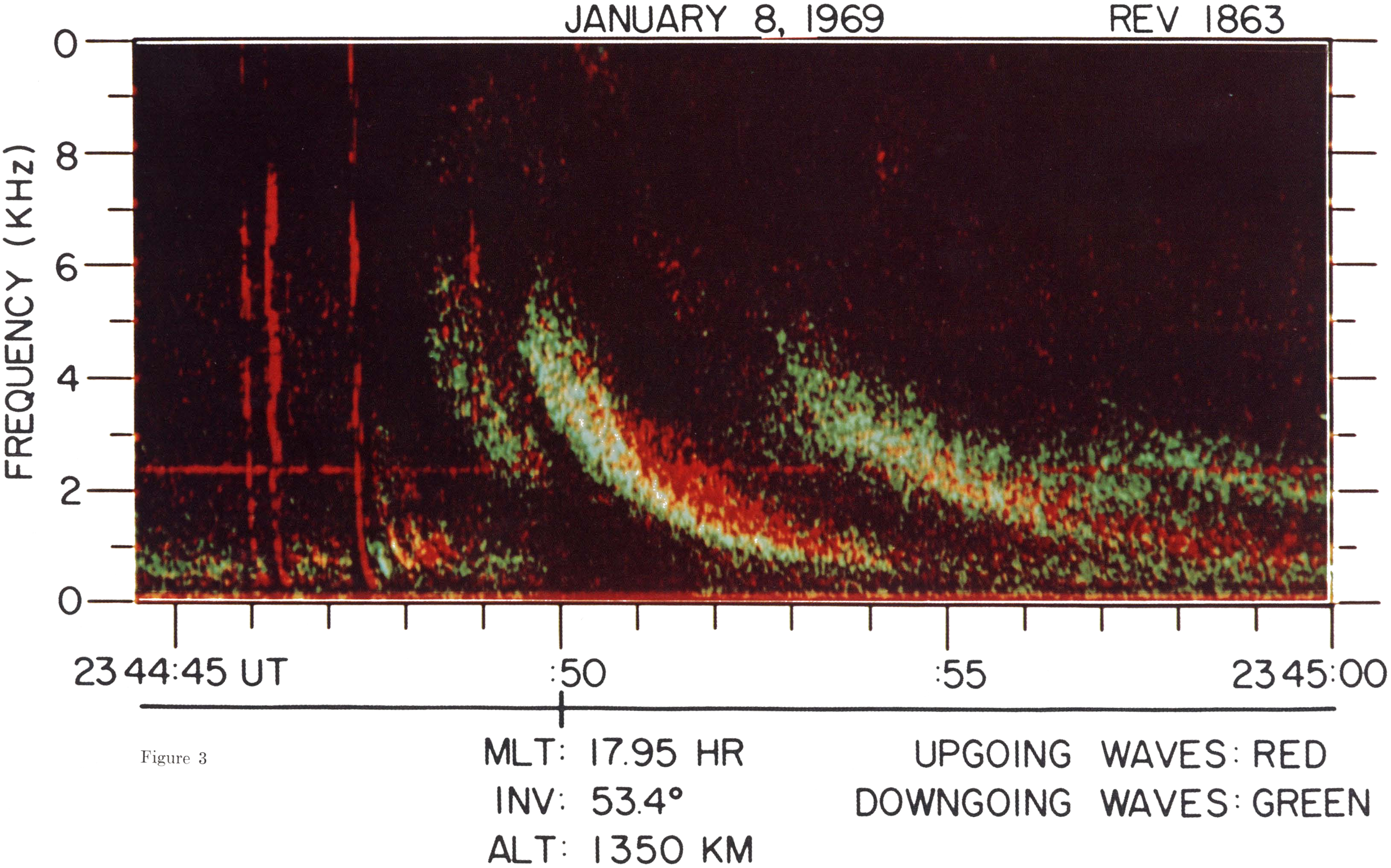
Fig. 3. Poynting flux spectrograms of several upgoing short fractional hop whistlers (red) and their associated long hop whistlers. The green component of the long hop whistler is the downgoing echo returning from the opposite hemisphere, and the red component immediately following is the reflection from the base of the ionosphere.

Fig. 4. Poynting flux spectrogram of a series of alternately upgoing (red) and downgoing (green) subprotonospheric whistler echoes.

Fig. 5. Poynting flux spectrogram of a combination of chorus and ELF hiss, showing the transition in the direction of propagation often observed near the plasmapause boundary (upgoing inside the plasmapause boundary).

Fig. 6. Poynting flux spectrogram of an upgoing saucer-shaped VLF emission.

Fig. 7. Poynting flux spectrogram of VLF hiss consisting of both upgoing and downgoing waves.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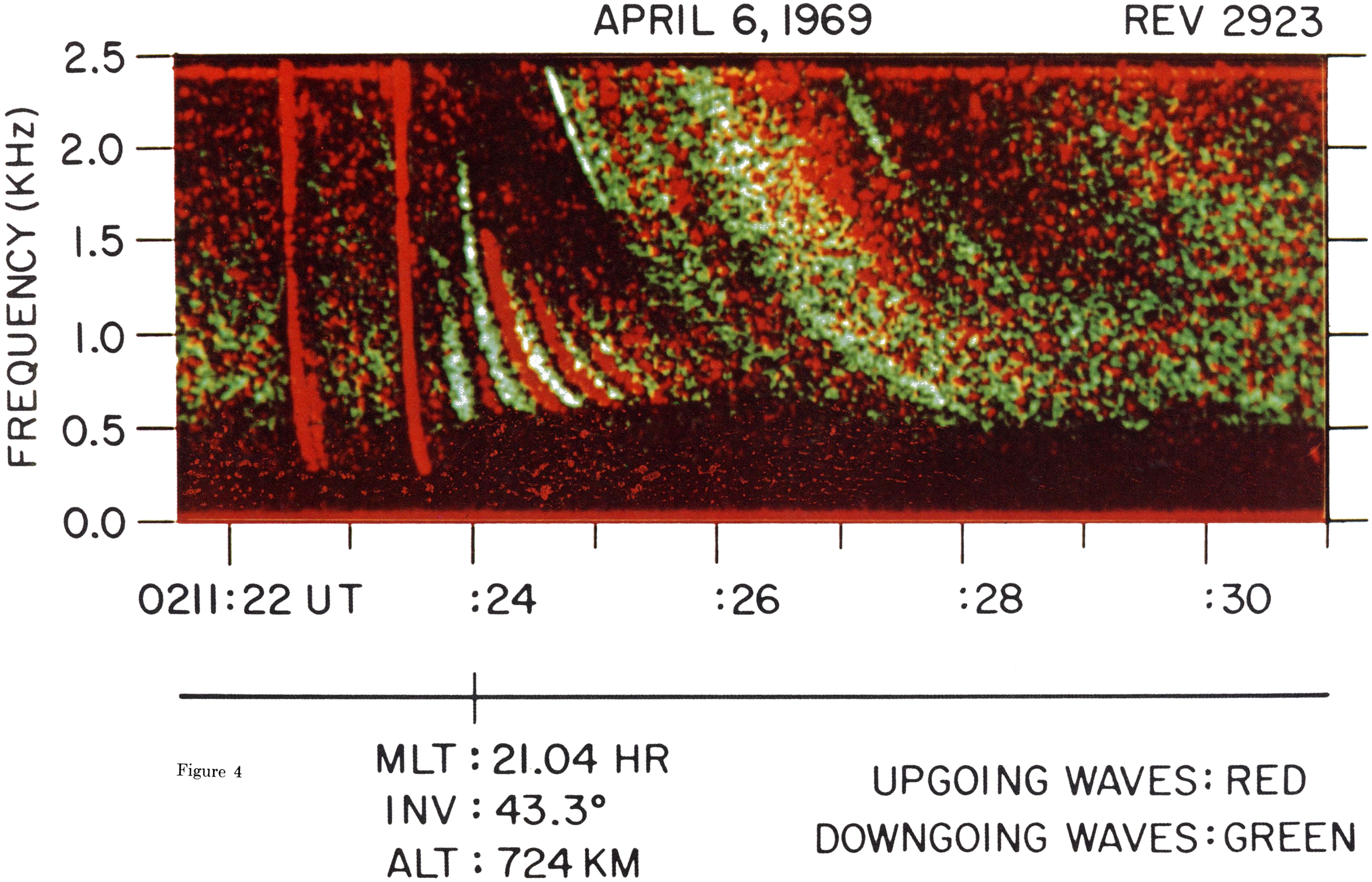
REV 1863
FREQUENCY (KHz)
0
8
6
4
2
0
23 44:45 UT
:50
:55
23 45:00
MLT: 17.95 HR
INV: 53.4°
ALT: 1350 KM
UPGOING WAVES: RED
DOWNGOING WAVES: GREEN

Figure 3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REV 2923
FREQUENCY (KHz)
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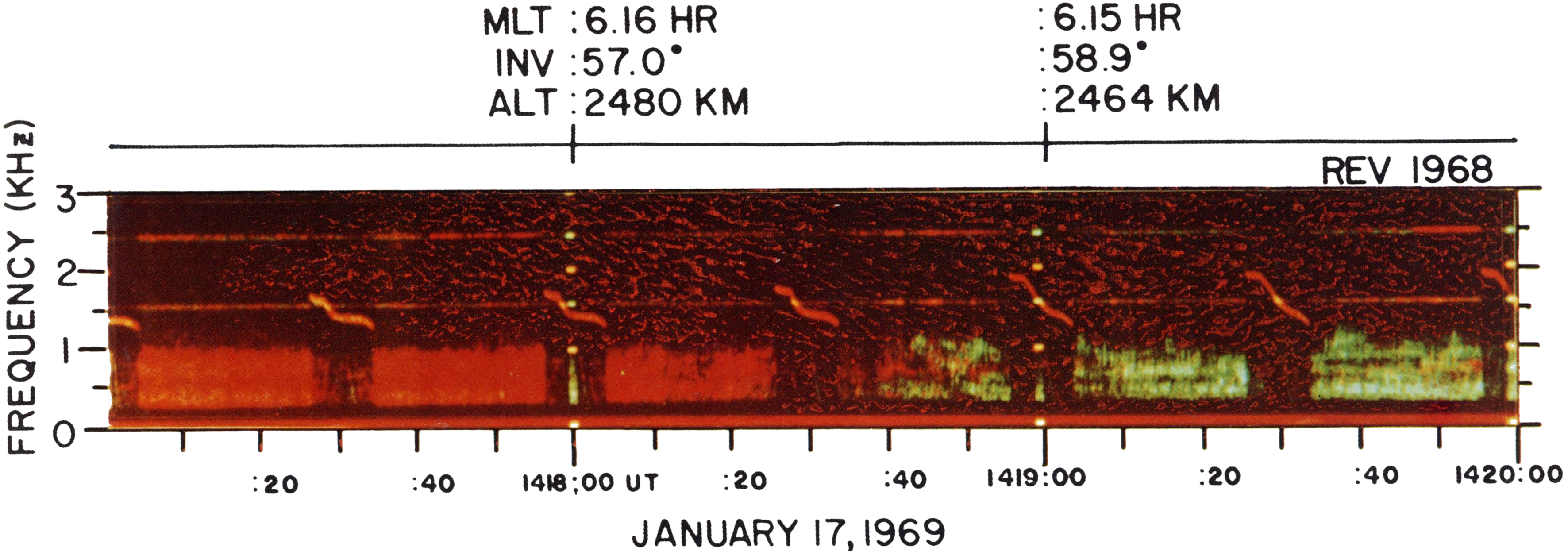
2.0
1.5
1.0
0.5
0.0
0211:22 UT
:24
:26
:28
:30
MLT : 21.04 HR
INV : 43.3°
ALT : 724 KM
UPGOING WAVES: RED
DOWNGOING WAVES: GREEN

Figure 4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INV :57.0°
ALT :2480 KM
:6.15 HR
:58.9°
:2464 KM
REV 1968
FREQUENCY (KHz)
3
2
1
0
:20
:40
1418:00 UT
:20
:40
1419:00
:20
:40
1420:00
JANUARY 17, 1969

Figure 5

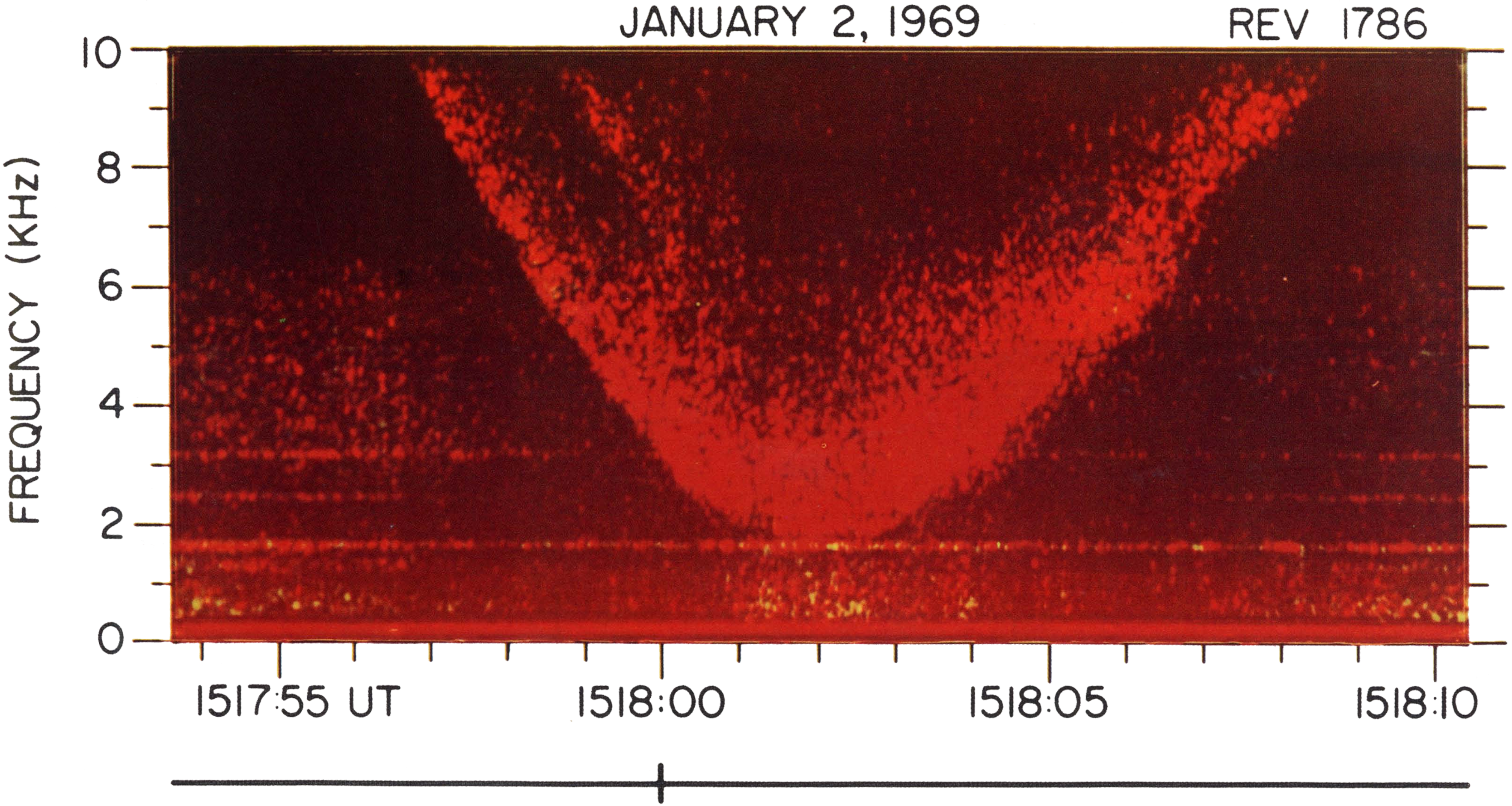
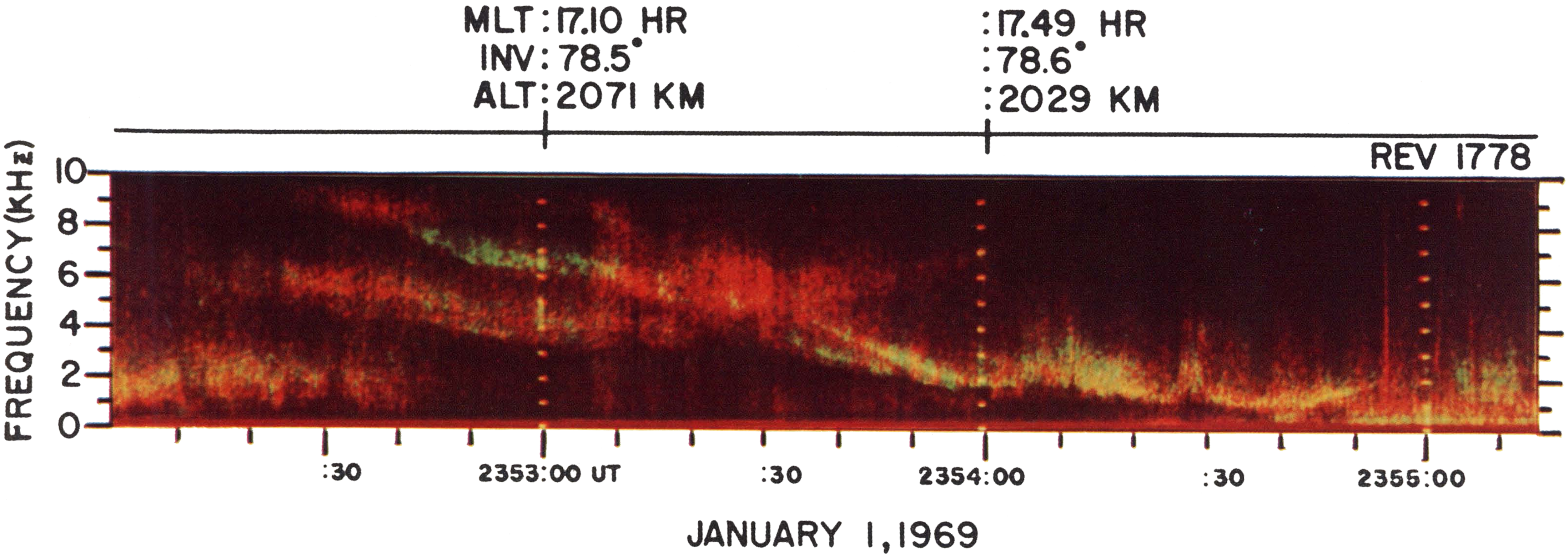


Figure 6

MLT : 7.78 HR
INV : 69.5°
ALT : 2539 KM

UPGOING WAVES : RED
DOWNGOING WAVES : GREEN



MLT: 17.10 HR
INV: 78.5°
ALT: 2071 KM
: 17.49 HR
: 78.6°
: 2029 KM
REV 1778
FREQUENCY (KHz)
10
8
6
4
2
0
:30
2353:00 UT
:30
2354:00
:30
2355:00
JANUARY 1, 1969

Figure 7

plasmapause boundary. Certain characteristics, however, such as the change in the relative intensity of the hiss and discrete emission intensities sometime observed upon crossing the plasmapause boundary (as evident in Figure 4), are not fully understood and require further investigation.

Saucer-shaped emissions. The Poynting flux spectrogram in Figure 6 shows a type of VLF emission called a saucer, which is clearly propagating up the geomagnetic field at all frequencies. At the present time the saucer-shaped VLF emission is the only type of magnetospheric VLF emission definitely known to be generated at low altitudes in the magnetosphere (below a few thousand kilometers). Saucer-shaped emissions were first observed with the Alouette 1 and 2 satellites (R. E. Barrington, personal communication, and *Smith* [1969]) and are commonly observed in the auroral zone with low-altitude polar orbiting satellites. Poynting flux measurements with the Injun 5 satellite provided the first evidence that the saucer-shaped emissions were propagating up the geomagnetic field from a source below the satellite [*Mosier and Gurnett,* 1969; and *Mosier,* 1971]. Subsequent (unreported) observations of the same saucer event on as many as three successive orbits with Injun 5 established that the frequency–time spectrum of this emission is primarily a spatial effect caused by satellite motion rather than a temporal effect. The frequency–time shape of this emission is believed to be due to a frequency dependent limiting ray angle for whistler mode propagation from the source to the satellite [see *Mosier and Gurnett,* 1969]. The intensity variations at a given frequency are thought to be entirely attributable to the horizontal motion of the satellite through the 'beam' of allowed ray paths from the source to the satellite, with the frequency dependence of the beamwidth accounting for the observed frequency–time envelope of the emission. The instability mechanism responsible for this emission at relatively low altitudes in the ionosphere has not been established.

VLF hiss. Several distinct forms of VLF hiss are observed in the Injun 5 data, all of which consist of a mixture of both upgoing and downgoing waves. A cross-correlation spectrogram of a V shaped VLF hiss event observed with Injun 5 is shown in Figure 7. This type of VLF hiss, first discussed by *Gurnett* [1966], consists of one or more narrow bands of emission usually occurring with a relatively symmetrical V shaped frequency–time spectral form or a portion thereof. In contrast to the saucer-shaped emissions, which typically occur on a time scale of 10 sec or less, the duration of the V shaped VLF hiss event is 30 sec or more. The mixture of red and green colors in the spectrogram of Figure 7 indicates that both upgoing and downgoing waves are present in this VLF hiss event. Except for three very brief (2 sec) saucer-shaped emissions located around 2355:00 UT, there is no evident pattern to the upgoing and downgoing components of the VLF hiss at different frequencies. Because of the presence of many waves, both upgoing and downgoing, it is not possible to determine the sign of the average Poynting flux.

The observation of downgoing VLF hiss means that at least part of the VLF hiss must be generated at altitudes above the satellite or in the opposite hemisphere, since at frequencies above the lower hybrid resonance frequency (which is believed to be the case for most of the VLF hiss observed with Injun 5) the waves cannot reverse their direction of propagation relative to the geomagnetic field. At the present time it is not possible to determine whether the upgoing VLF hiss is generated below the satellite or is caused by the reflection of downgoing waves at some point below the satellite.

DISCUSSION

These spectrograms illustrate the application of this new Poynting flux sensing technique and summarize the primary results obtained from the Injun 5 Poynting flux measurements. Since most types of VLF emissions detected by Injun 5 are observed to be propagating downward from source regions above the Injun 5 altitude, there is still considerable uncertainty as to where these noises are generated along the geomagnetic field lines. Recent theoretical considerations by *Kennel and Thorne* [1967] and *Helliwell* [1969], as well as experimental evidence by *Burtis and Helliwell* [1969] and *Russell et al.* [1970], suggest that many of these waves may be generated very near the magnetic equatorial plane. It is therefore highly desirable that Poynting flux measurement be extended to much higher altitudes in the magnetosphere, particularly near the equatorial plane. Because of the requirement for orienting the antenna axes perpendicular to the geomagnetic field, this simple Poynting flux sensing scheme is not always possible, particularly at high altitudes where magnetic stabilization cannot be used. Because the geomagnetic field within the magnetosphere is directed northward near the equatorial plane, however, the Injun 5 Poynting flux sensing technique can be used on earth-oriented satellites and spin stabilized satellites (provided that the spin axis is directed northward) with orbits near the geomagnetic equatorial plane. Therefore, with proper consideration to antenna orientation, the Poynting flux sensing technique described in this paper may also be applicable to other future VLF electric and magnetic field experiments being planned to investigate the region near the geomagnetic equatorial plane.

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