TAO, Vol. 10, No. 4, 787-804, December 1999

The ROCSAT-1 IPEI Preliminary Results: Low-Latitude Ionospheric Plasma and Flow Variations

Shin-Yi Su[1], Huey Ching Yeh[1], Roderick A. Heelis[2], Jing- Mei Wu[1], Shu Chih Yang[1], Li- Fan Lee[1] and Hsin Liang Chen[1]

(Manuscript received 25 September 1999, in final form 5 November 1999)

ABSTRACT

The IPEI payload onboard ROCSAT-1 has observed many well-known low-latitude ionospheric phenomena at 600 km altitude, such as the diurnal variations of ion density, composition and temperature. The equatorial spread F events, such as bubbles and blobs, together with the flow variations are also recorded with an unprecedented high time resolution at a sampling rate of 1024 Hz. The satellite-borne data on power spectral density of the equatorial spread F event on the transitional scale (10 - 100 m) is presented here for the first time. The local-time and longitudinal variations of the vertical drift velocity in the dawn sector indicated strong hemispheric asymmetry.

(Key words: ROCSAT-1, IPEI, Low-latitude Ionosphere)

1. INTRODUCTION

ROCSAT-1 was launched into a 600 km circular orbit with a 35° inclination at 1934 EST, January 26, 1999 from Cape Canaveral, Florida. The Ionospheric Plasma and Electrodynamics Instrument (IPEI) is one of the three payloads onboard ROCSAT-1. The IPEI payload consists of four sensors: an ion trap (IT) to measure the ion concentration; a pair of drift meters (VDM and HDM) to measure the cross-track velocity components perpendicular to the satellite velocity, and a retarding potential analyzer (RPA) to derive the ion composition, temperature and the ram velocity. The IPEI hardware, system architecture, and the operation procedure, as well as the scientific objectives have been published elsewhere in the literature (Chang et al., 1999; Yeh et al., 1999a).

The in-situ measurement of low-latitude ionospheric plasma parameters has been, at best, intermittent since the completion of the AE-E and Hinotori missions in the early 80s. The ROCSAT-1 IPEI payload, operated on a 100% duty cycle, will certainly quench the scientific thirst for new data as the sun-spot cycle returns to maximum activity. The fast longitudinal

[1]Institute of Space Science, National Central University, Chung-Li, Taiwan, ROC

[2]W. B. Hanson Center for Space Sciences, The University of Texas at Dallas, Richardson, Texas, USA

coverages by the low-inclined ROCSAT-1 orbit will provide us many exciting new observations. In this first report of the IPEI preliminary results, we shall present examples of longitudinal variations of the vertical flow in the dawn sector, together with a couple of the new observations of the Equatorial Spread F event on the transitional scale (10 to 100 m).

2. IPEI DATA PRESENTATIONS

ROCSAT-1 is a three-axis stabilized spacecraft with the z-axis pointing toward the Earth's center, the y-axis pointing to the negative direction of the orbital angular momentum, and the x-axis along the velocity direction in a circular orbit. The normal of the IPEI sensor plane is directed along the x-axis with the two DM sensors aligned in the horizontal plane. Figure 1 depicts the relationship between the spacecraft coordinate system and the Earth-centered inertia (ECI) coordinate system. The IPEI data plotted in the Quick-Look display format for public browsing is in the spacecraft coordinate system. Figure 2 shows an example of such a plot. Data of every 8 seconds of drift velocities, V_z and V_y, and the ion density, N, directly obtained from VDM, HDM, and IT sensors, are plotted in the first three panels, respectively, in Fig. 2. The O^+ temperatures derived from the measurements of the RPA sensor are plotted in the fourth panel in Fig. 2. The satellite time in universal time (UT) and local time (LT), as well as the satellite's geographic latitude (Lat) and longitude (Lon) are listed at the bottom of the figure. Each Quick-Look display has 90 minutes of data which almost equals one ROCSAT-1 orbital period of 96.7 minutes. The data is plotted for the purpose of monitoring the IPEI performance and surveying geophysical phenomena. The offsets in drift velocities and a small error from ROCSAT-1 spacecraft attitude misalignment have not been corrected yet, and the scatters in RPA-derived data have not been altered.

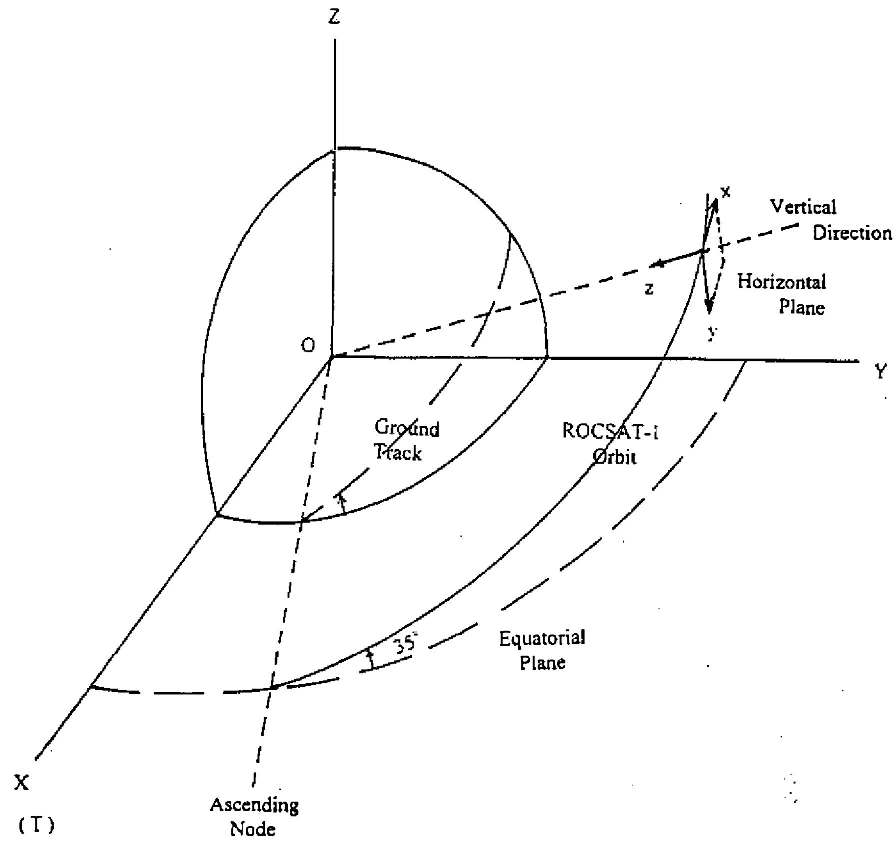
The offset in V_z is obtained by averaging all the V_z data in local times within the $\pm5°$ geomagnetic latitudes during the quiet periods of $Kp < 3$. The overlays of such V_z data for the first 180 days (Day 71 through Day 250) of IPEI operation are shown in Fig. 3. The average of V_z in Fig. 3 is 87.4 m/s, which for the time being is assumed to be the offset of V_z.

The offset of V_y is somewhat more complicated to obtain. First we notice that V_y contains the projection of a corotation flow velocity which has a value given by

$$
\begin{aligned}
(V_y)_{cor} &= \pm\omega_{\oplus} r\,(\cos^2 L - \cos^2 i)^{1/2} \\
&= \pm 510.52(\cos^2 L - \cos^2 i)^{1/2}\ \mathrm{m/s} \qquad (1)
\end{aligned}
$$

where $\omega_{\oplus}$ is the Earth's angular velocity and r is the radial position of ROCSAT-1 from the Earth's center. L and i represent, respectively, the ROCSAT-1 geocentric latitude and orbital inclination ($i = 35°$). The positive sign in Equation (1) for $(V_y)_{cor}$ is chosen when ROCSAT-1 moves northbound from L=-35° to L=35° and the negative sign, southbound from L=35° to L=-35°. The $(V_y)_{cor}$ value given in Equation (1) dominates the HDM measurements as seen in the second panel in Fig. 2. This reference value provides a check for the HDM performance. Analysis of deviations from this reference value may resolve the offset in V_y. However, many

Earth-Centered Inertia (ECI) Coordinate



Spacecraft Coordinate System

y: opposite to angular momentum

z: toward the Earth Center

x: $\hat{y} \times \hat{z}$ direction

Fig. 1. The orientation of the ROCSAT-1 spacecraft coordinate system (xyz) in relation to the Earth-centered inertia (ECI) coordinate system.

quiet-time data are needed to carry out such an analysis. We postpone the analysis until a later report. The offset in V_y does not hinder our study in the following sections.

The spacecraft is found to be quite stable so that the attitude angles of roll, pitch, and yaw have values in fractions of one degree which almost result in no changes in the corrected flow velocities in V_z and V_y. Only when the spacecraft was in a rocking motion, will the flow

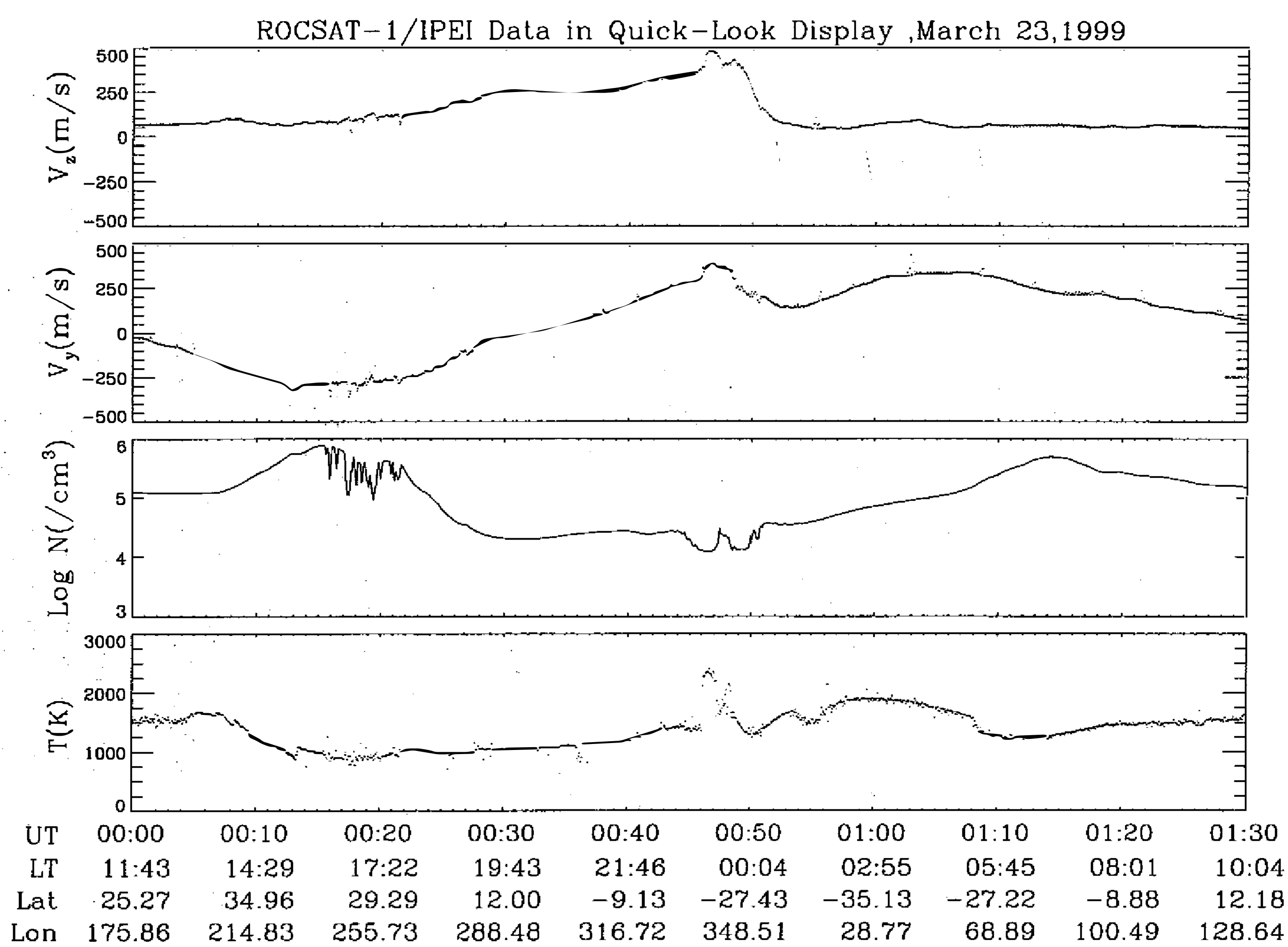


Fig. 2. The IPEI data of the first 90 minutes on March 23, 1999 plotted in the Quick-Look display format.

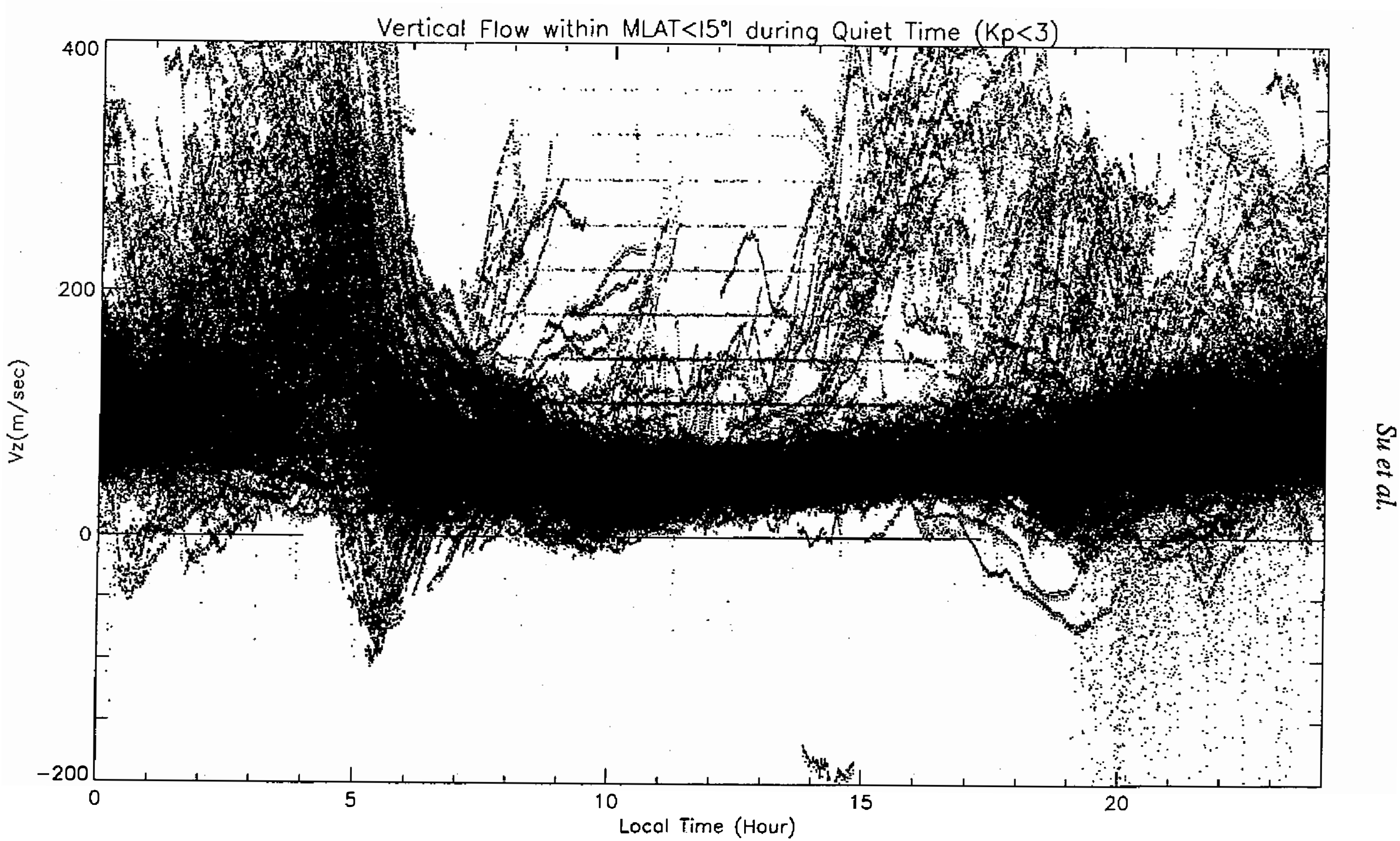


Fig. 3. The local-time variation of the vertical drift velocity V_z from Days 71 to 250 of 1999 when the ROCSAT-1 orbit lies within ±5° geomagnetic latitude during the geomagnetic quiet time of Kp < 3.

velocity V_z and V_y indicate superficial wave motion in Quick-Look display data which warrants correction.

3. THE LONGITUDINAL AND LATITUDINAL/LOCAL-TIME VARIATIONS OF VERTICAL FLOW

The plot of V_z data in Fig. 3 by itself is very interesting. First of all, we notice that the amplitudes of the variations in V_z are quite large and they are not due to the offset in V_z. Apart from many outliers, the dominant part (dark part) of the variation in V_z from dawn to midnight is rather featureless. The prereversal enhancement of the post sunset effect has been masked out and become obscure. However, when the seasonal effect is separated out, the prereversal enhancement does stand out from the average (Yeh et al., 1999b).

The variation of V_z around dawn in Fig. 3 is quite variable. When many consecutive ROCSAT-1 orbits are examined, the variation of V_z around dawn shows a dramatic longitudinal and latitudinal/local-time dependence. This is demonstrated as follows. The orbit of ROCSAT-1 is fixed in an inertia coordinate system except that the oblate Earth together with the Sun's motion around the Earth will cause the orbit to displace westward 0.46 hour per day in local time. Thus, for practical purposes, every data point in the 15 orbits of ROCSAT-1 per day can be assumed to be fixed at a certain local time and latitude. However, the longitudinal location along the orbit varies as the Earth rotates under the ROCSAT-1 orbit so that the IPEI data can be used to study the longitudinal variations of the ionospheric plasma and flow in one day. The local-time effect is then derived after many days' data are examined.

We select March 23, 1999 to start such a study. This day is a geomagnetically quiet day with Kp = $1^-, 1^-, 1^-, 2^-, 2, 2, 2, 2^+$ for each 3-hour slot. The first 360 minutes of data are shown in Fig. 4. The plot utilizes the Quick-Look display data except that the offset in V_z is removed and the corotational value in V_y is added as the dot-dashed line in the second panel for reference. The V_z, V_y, O^+ temperature and O^+ concentration percentage (newly added data) have undergone 16-second running averages to reduce scatter.

The general feature of diurnal variations in ion density N, and O^+ temperature can be easily recognized. The ion density changes from $10^4/cm^3$ at midnight to $10^6/cm^3$ around local noon and again around 2000 LT in the equatorial anomaly region. The equatorial spread F events of density depletion near the equator are conspicuously noticeable. The O^+ temperature drops to 1000 K in the night and rises to 2000 K during the daytime.

The diurnal variations in the ion density and temperature seem to be more or less universal and appear to be longitude dependent, as reported in the literature (Anderson, 1981; Su et al., 1996). On the other hand, the drastic variations in V_z, V_y and O^+ concentration percentage around the dawn sector is very prominent, as seen in Fig. 4. Around 0500 LT at dawn, the VDM detects a large downward flow in V_z at ~400 m/s when ROCSAT-1 is at latitude 30° S and longitude 30° E, a location near the South Atlantic Anomaly region. V_y also deviates strongly from the corotational reference value. The O^+ temperature shows a large fluctuation and the O^+ concentration percentage reaches the minimum dip of about 25%. The other ion species, most likely H^+, rises to 75%, as the data implies. These drastic changes subside

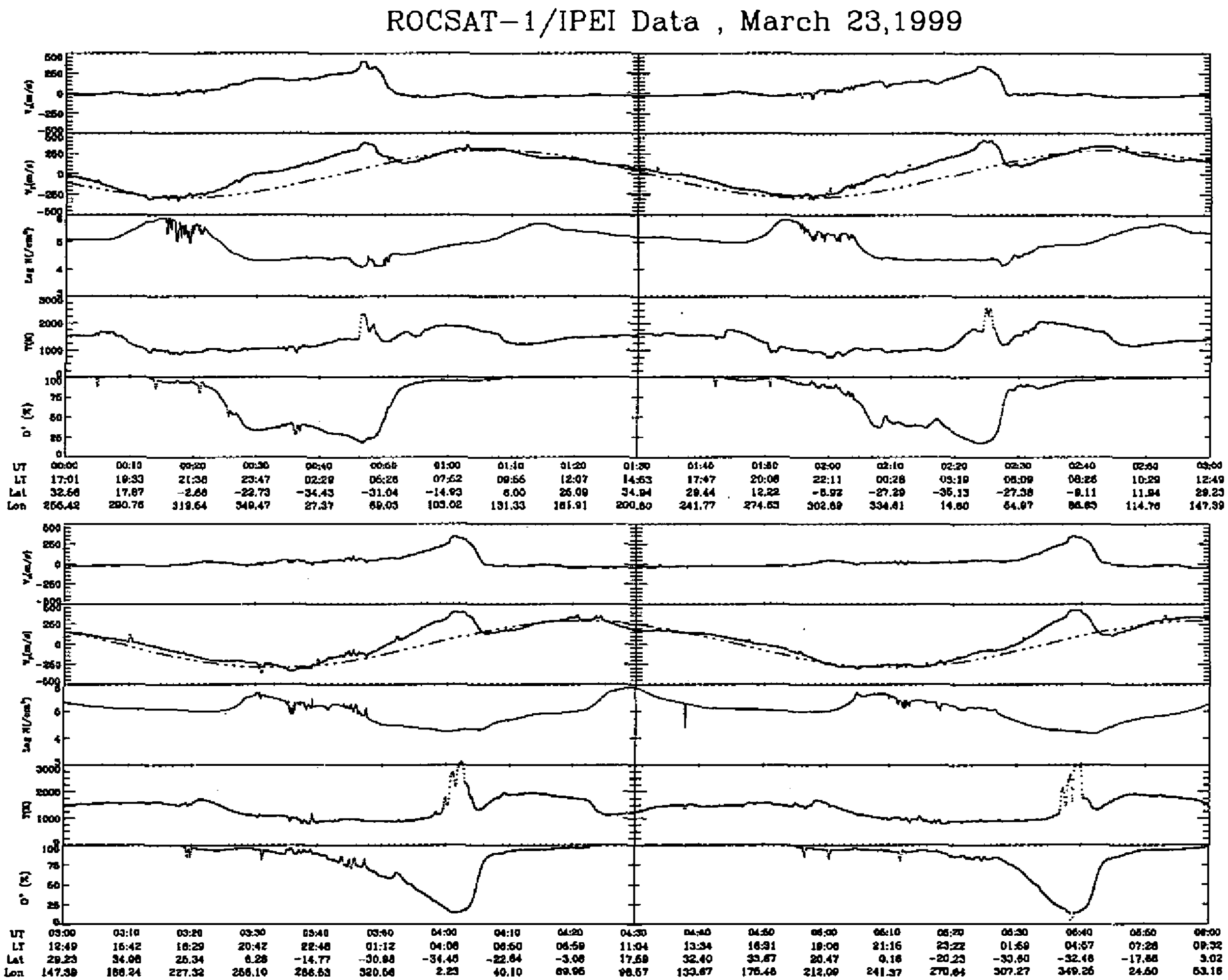


Fig. 4. The diurnal variations of the low-latitude ionospheric plasma flow, density, temperature, and O^+ concentration percentage observed from the ROCSAT-1/IPEI payload during the first four orbits on March 23, 1999.

shortly after sunrise as ROCSAT-1 moves away from the Anomaly region.

The longitudinal dependence of these variations can be reconfirmed from further study of the IPEI data 12 hours later, when the ROCSAT-1 orbit drifts in longitude to about 180° away from longitude 30° E. Figure 5 displays data from such an observation. Notice that the local dawn terminator remains at latitude 30° S, but falls on longitude 220° E. The diurnal variations in ion density and O^+ temperature are much flatter but retain similar patterns, as seen in Fig. 4. However, the variations in V_z, V_y and O^+ concentration percentage around 0500 LT, the dawn terminator seem to be diminishing.

ROCSAT-1 drifts westward 0.46 hour per day in local time so that 26 days after March 23, 1999 the dawn terminator of ROCSAT-1 falls on the northern hemisphere. Figure 6 shows the first 360 minutes of data on April 18, 1999. Kp values for this day are 3^-, 2^0, 1^-, 2^-, 2^0, 1^+, 2^0, and 1^0. Notice that no drastic changes in V_z, V_y and O^+ concentration percentage are observed around local dawn. Similar observation of flat variations is noticed (not shown here) 12 hours later on the same day when ROCSAT-1 moves to the opposite longitude, around the South Atlantic Anomaly longitude but in a northern latitude.

Another 26 days later, the ROCSAT-1 orbit repeats the track of March 23. Data shown in Fig. 7 from May 16, 1999 (because data from May 14 and May 15 are not available) again revealed drastic variations in V_z, V_y and O^+ concentration percentage near local dawn, as was seen in Fig. 4. May 16 is an extremely quiet day with Kp not over 1^+ all day. These drastic change in V_z variations between 0300 and 0500 LT for March 23, April 18, and May 16, 1999 are displayed in Fig. 8. The longitudinal and latitudinal/local-time dependences of V_z variation are clearly noticed. Since the large downward flow of V_z occurs around local dawn when ROCSAT-1 emerges from the nightside ionosphere in the southern hemisphere, the cause could be related to a large H^+ flow from the protonsphere to ionosphere (Hanson and Ortenburger, 1961) or inter-hemispheric transport phenomenon. Some detailed statistical study of the hemispheric asymmetry on the vertical flow is reported by Yeh et al. (1999b).

Incidentally, a surge spike in the downward flow of V_z observed at sunrise, for example at 0514 LT (0046 UT) in Fig. 4, has been ruled out as was caused by the ROCSAT-1 spacecraft potential changes at sunrise. Since the spike is also related to the spike in the decrease of the O^+ percentage, it is very likely to be related to the H^+ flow surge from the higher altitude region of the protonsphere where the Sun's light arrives earlier than the lower part of the protonsphere-ionosphere boundary where ROCSAT-1 is orbiting.

4. FLOWS IN EQUATORIAL SPREAD F

Another prominent feature noticed in Figs. 4 and 5 is the frequent occurrence of the bubbles and blobs in equatorial spread F (ESF) events. The expanded plots of data from 1440 to 1500 UT for March 23, 1999 are shown in Fig. 9. The ESF events have been observed by spacecraft for many years (see e.g., Hanson et al., 1973; Dyson et al., 1974; Oya et al., 1986; Kil and Heelis, 1998). However, the IPEI data shown in Fig. 9 can provide a better understanding of the microscopic features of an ESF event with the simultaneous measurements of V_z, V_y, N, O^+ temperature and O^+ concentration percentage. We shall first study the flow pattern in Fig. 9

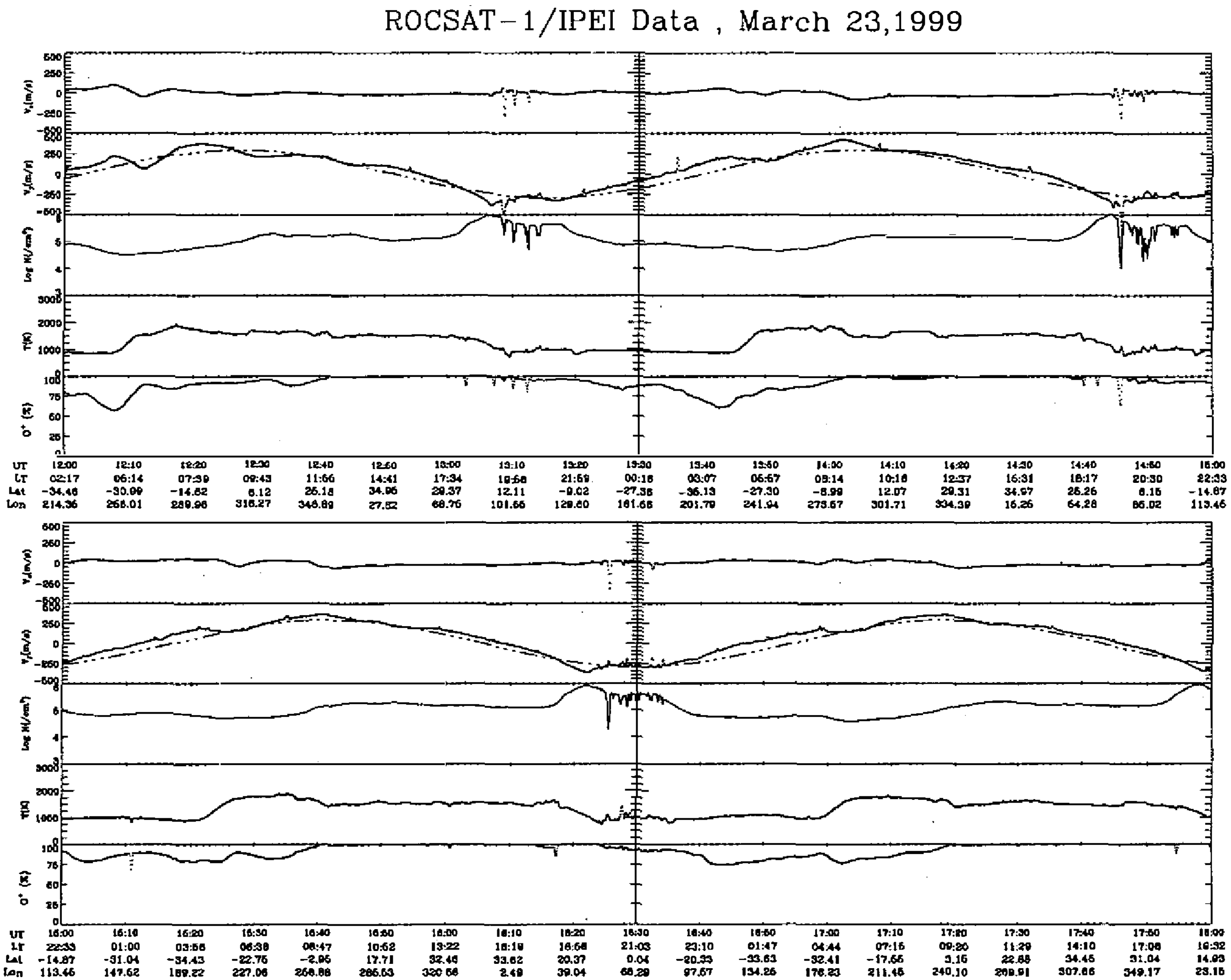


Fig. 5. As in Figure 4 except the orbit is 12 hours later.

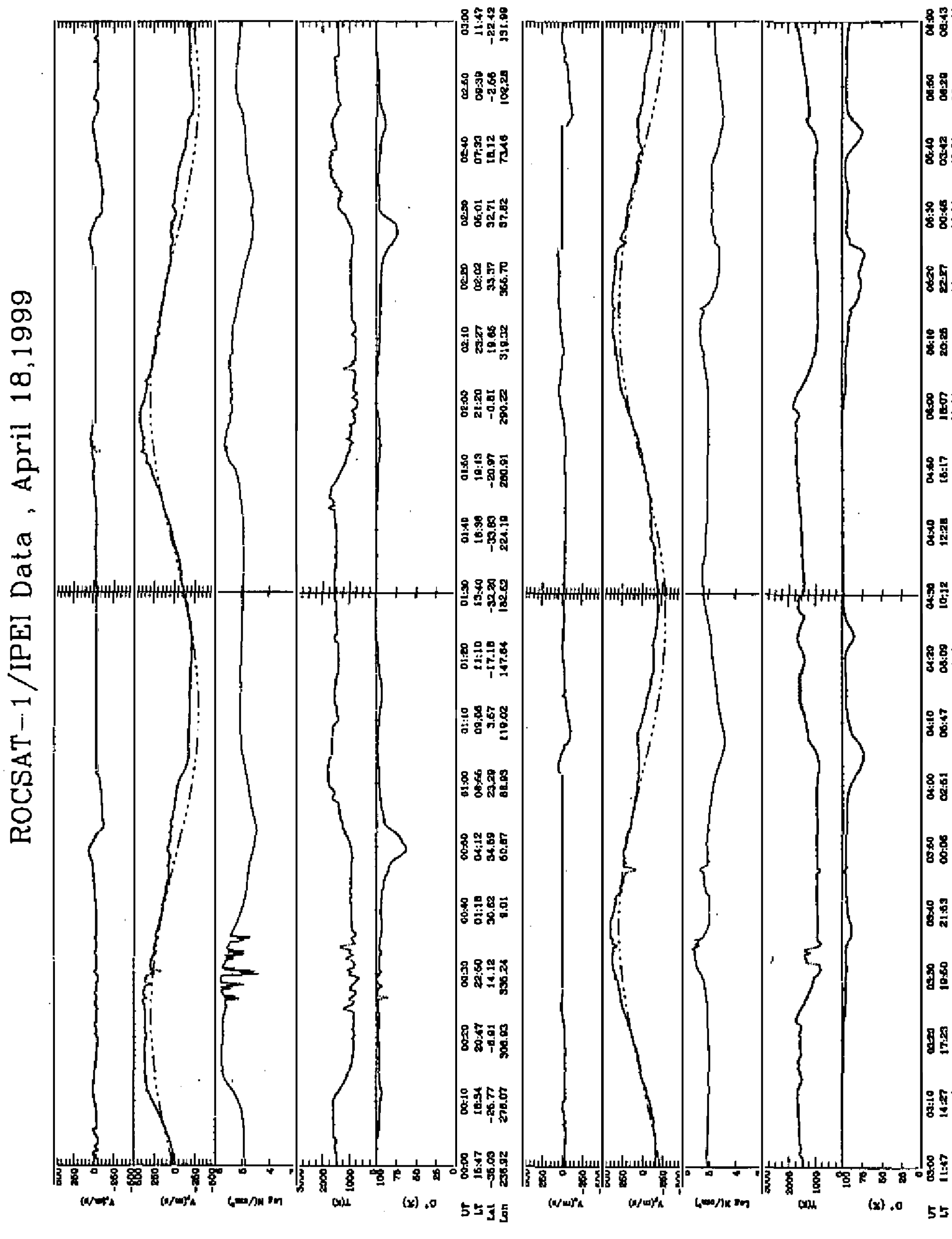


Fig. 6. As in Figure 4, but on April 18, 1999.

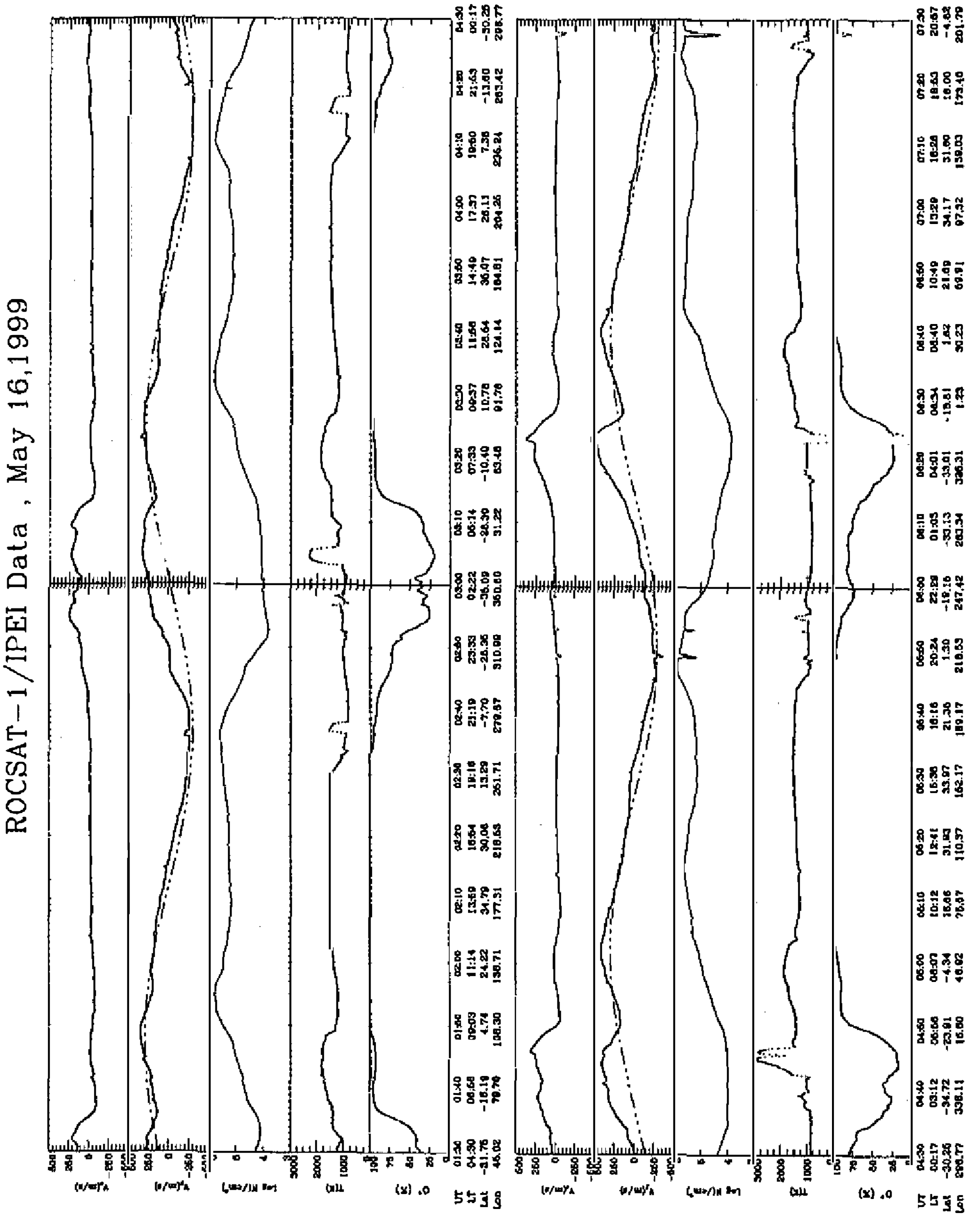


Fig. 7. As in Figure 4, but on May 16, 1999.

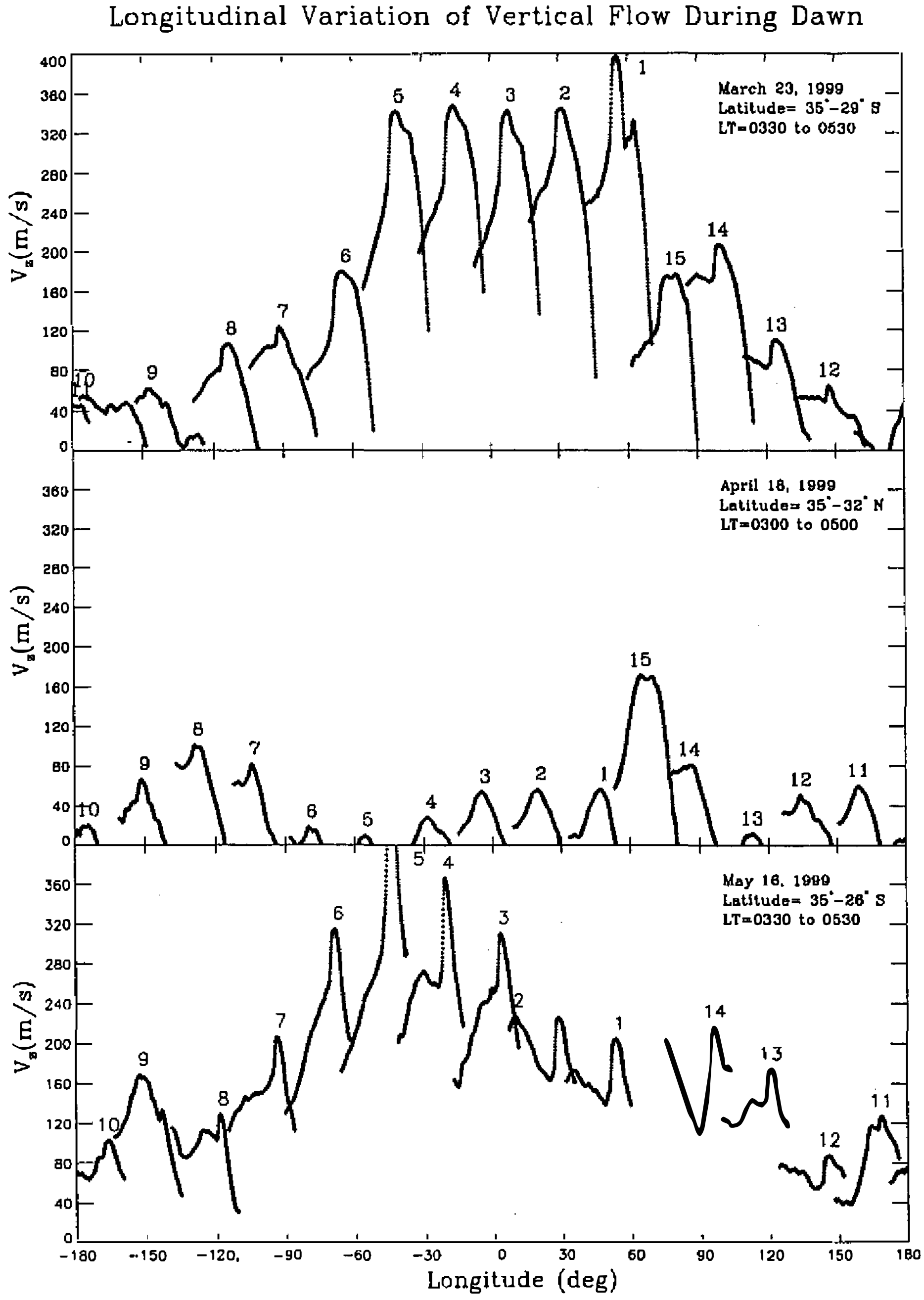


Fig. 8. The longitudinal variations of the vertical flow V_z between ~3:00 to ~5:00 LT for March 23, April 18, and May 16, 1999. The numerical digits attached to the V_z values indicate the orbital sequences of observation.

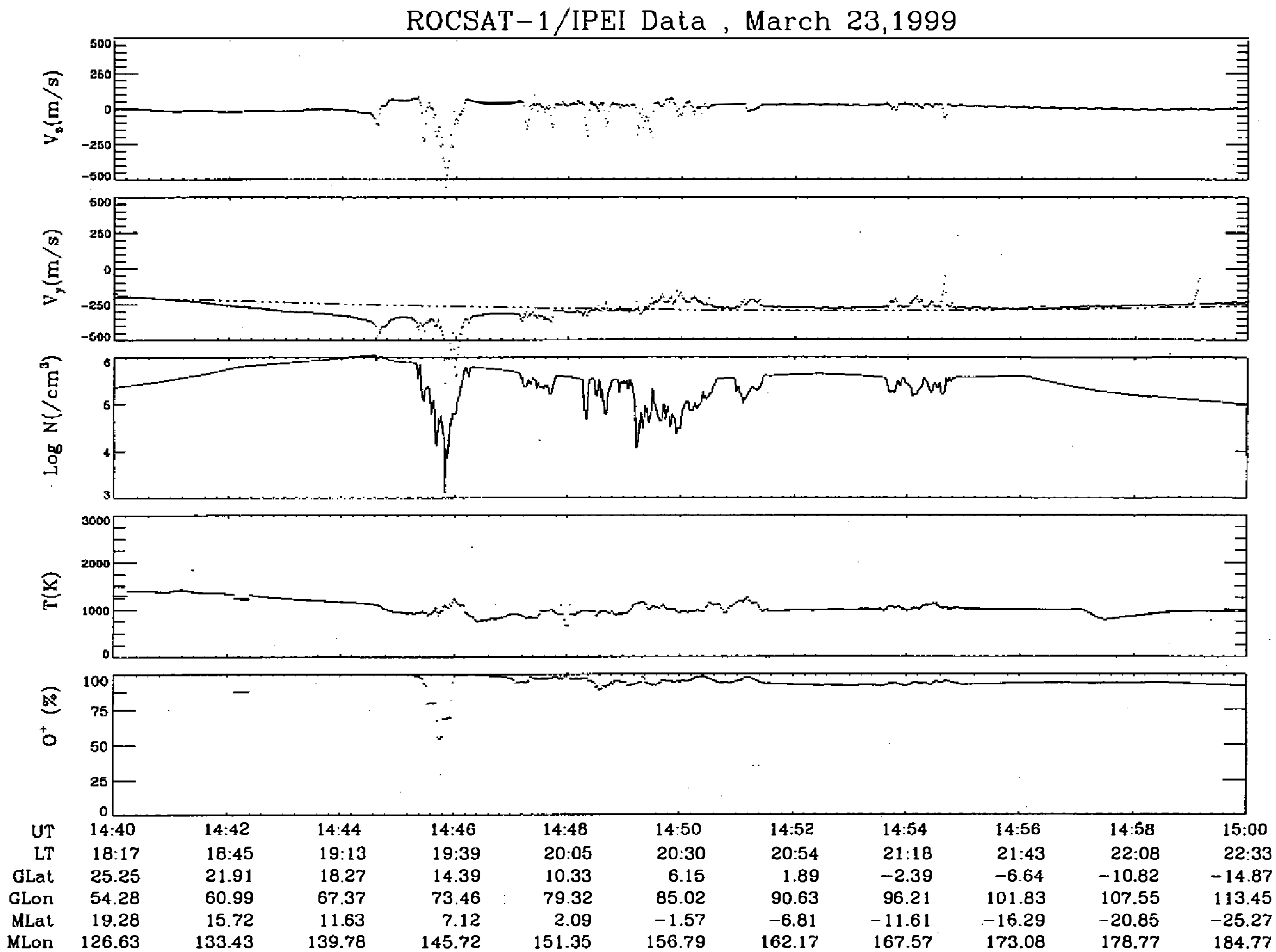


Fig. 9. The expanded plots of the IPEI data between 14:40 and 15:00 UT for March 23, 1999.

for the gross feature of the ESF events.

In the ion depletion region where low ion density (bubbles) occurs, such as that which started at 1444 UT when V_z is seen to flow upward. On the other hand, V_y is southward until 1448 UT but turns northward afterwards. However, when the occurrence of ESF events is related to the geomagnetic location of the ROCSAT-1 orbit, we conclude that the V_y flow is poleward along the field line at locations both before and after 1448 UT. The accompanying O^+ temperature fluctuates and so does the O^+ concentration percentage. The detailed ion motions inside the bubbles have been reported by Yeh et al. (1999c).

5. POWER SPECTRUM OF FLUCTUATIONS INSIDE A BUBBLE

The 1024 Hz sampling rate for density, V_z and V_y fluctuations inside a bubble will enable us to study, for the first time from a spacecraft observation, the dynamics of bubble structure on the transitional scale range (10 -100 m). An example of such observation is shown in Fig. 10 for data from 0325 to 0327 UT on March 28, 1999. This example is chosen from when the IPEI operated at Fast Mode to sample data at 1024 Hz during the passage of bubble events. Following a procedure similar to Kil and Heelis (1998), we take a 2-second data segment and linearly detrend the data. A Hanning window is then applied to the detrended data before the fast Fourier transform (FFT) is performed to obtain the power spectral density (PSD). To reduce the fluctuations in PSD, two 2-second spectra are averaged before fitting the PSD with a function form of $P \propto f^n$. The frequency abscissa is further converted to the wavenumber ($=\lambda^{-1}$) by $f=V_{s/c}(\lambda^{-1})$, where $V_{s/c}$ is the orbital velocity of ROCSAT-1. Figure 11 illustrates the procedure for the spectral analysis. The first panel in the figure is the linear fitting to detrend a two-second slice of data. The second panel indicates the data after the Hanning window has been applied to the detrended data in the first panel. The third panel shows the result of the power spectral density of data after FFT. The fourth panel is the averages of two 2-second PSDs from the third panel and the spectral indices from the data fitting.

The power spectral density in the fourth panel in Fig. 11 has been broken into three sections, as discussed by Kelley et al. (1982) -medium scale (10 -1000 km), intermediate scale (0.1 -10 km), and transitional scale (10 -100 m) -to fit $P \propto f^n$ separately to obtain the spectral indices, n_1, n_2, and n_3. The values of n_1 and n_2 have been reported from previous spacecraft observation (Kil and Heelis, 1998). The n_3 value has only been obtained by rocket observation (Kelley et al., 1982). The value n_3=-4 seen in the fourth panel is a new result and is similar to those reported by the rocket observations in a slightly lower ionospheric region. However, the fluctuations in ΔV_z and ΔV_y on the transitional scale have not been reported from any space-borne instruments. Detailed analysis of the fluctuation in the ESF events has been reported by Su et al. (1999).

6. CONCLUSIONS AND DISCUSSION

The low-inclination of the ROCSAT-1 orbit enables us to examine the local-time/ latitudinal dependence of the longititudinal variation of the low-latitude ionospheric plasma elec-

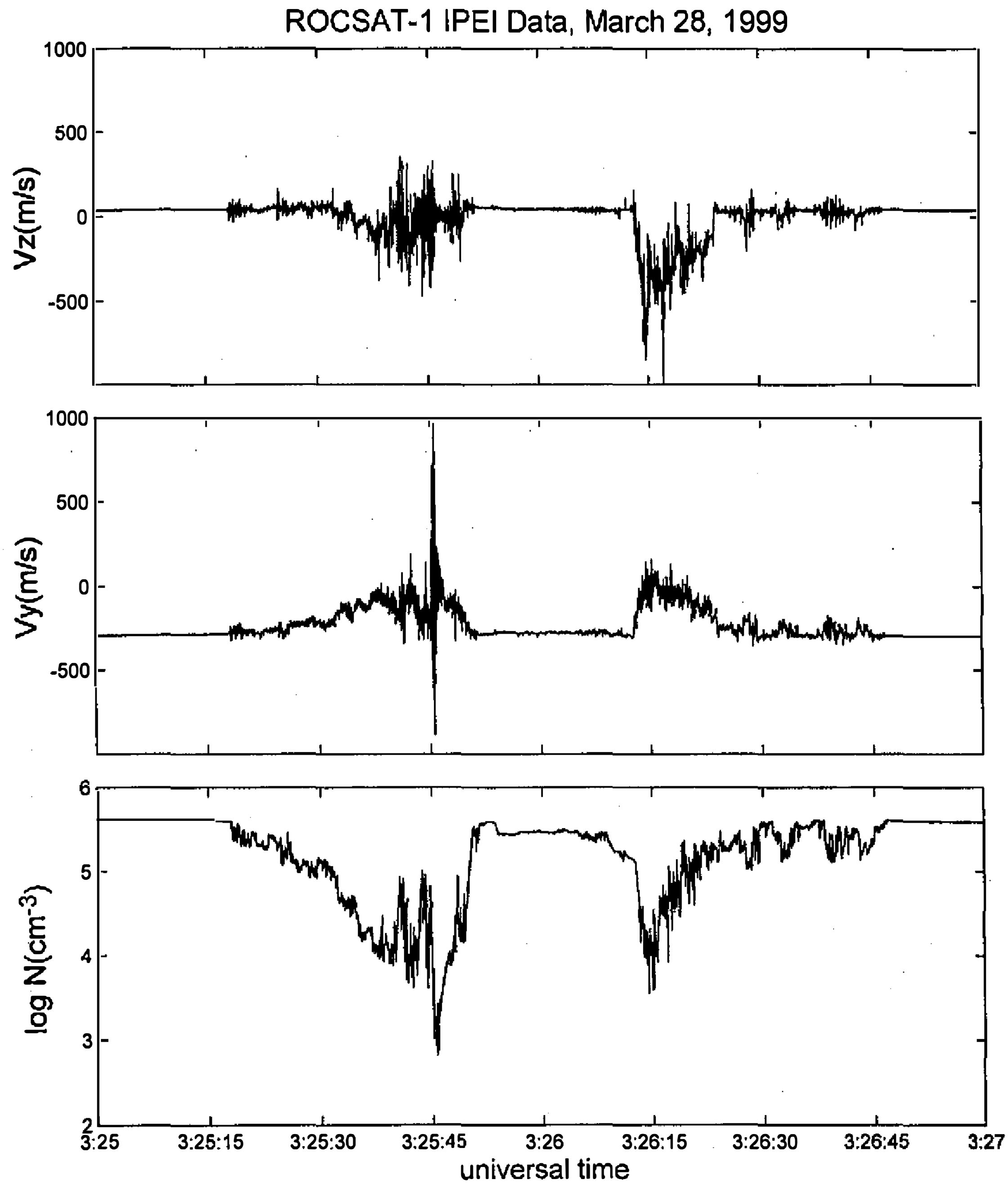


Fig. 10. The expanded plots of the IPEI data between 3:25 to 3:27 UT for March 28, 1999. The data are obtained during the Fast mode operation of IPEI.

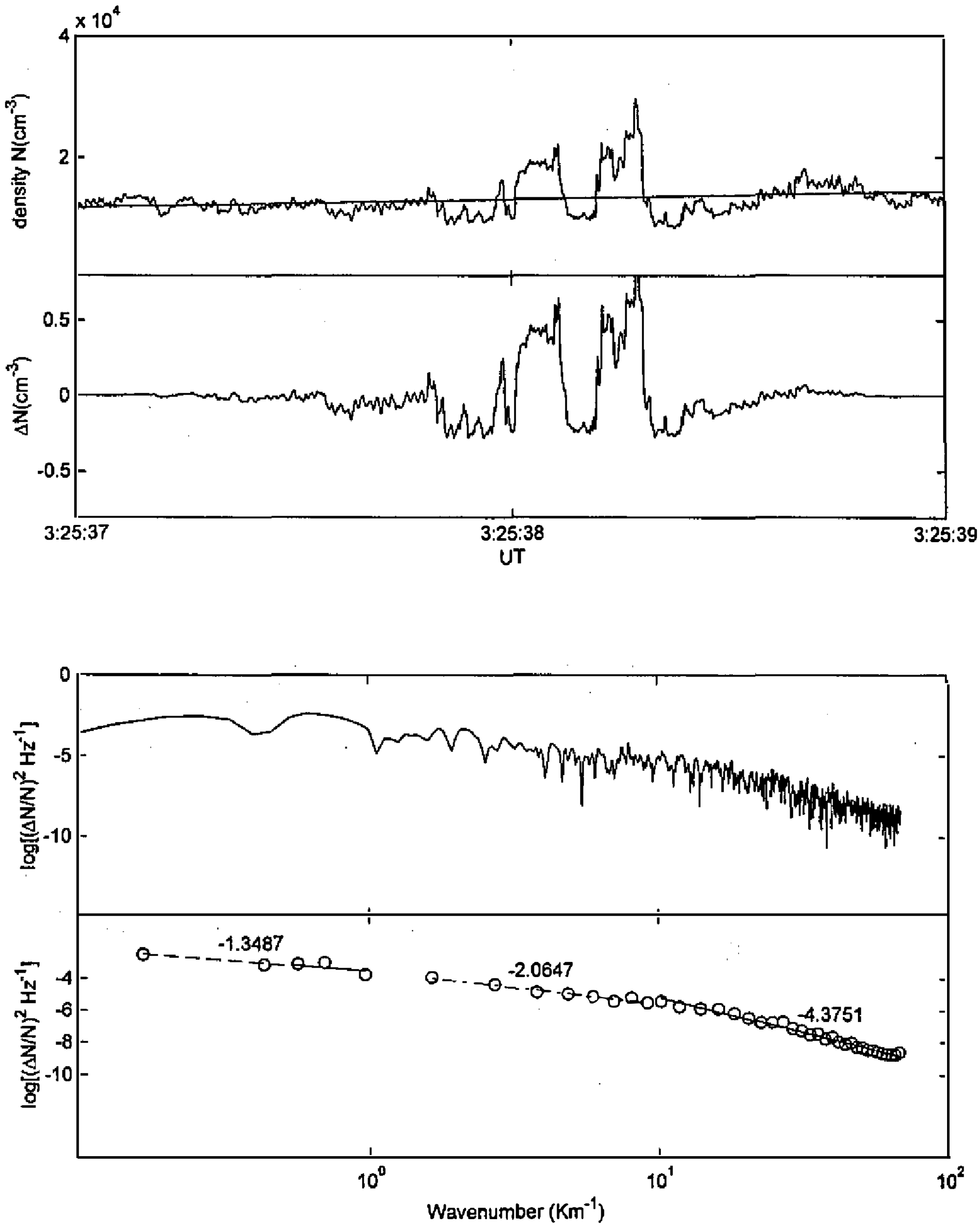


Fig. 11. The analysis procedure to obtain the spectral power density (SPD) and the spectral index.

trodynamics. In this first report of the preliminary results, strong hemispheric asymmetry of the enhanced downward flow at dawn has been observed. Although the mechanism for the flow of 300 meters per second or more could be related to the protons (as inferred from IPEI/

RPA data) rushing down along the field line to the ionosphere at dawn, detailed analysis is still needed to support this.

Furthermore, this report is to fulfill the design goal of the IPEI payload to be the first spacecraft to observe the equatorial spread F (ESF) event on the transitional scale (10 - 100 m). The spectral index of the power spectral density for the density fluctuation in the ESF event is found to be about -4, which is very close to the rocket observation made in the early 80s.

The purpose of this preliminary report is to demonstrate the fine quality of IPEI data such that they can be readily used for new ionospheric study inferred from data published in the Quick-Look display plots in the Website. This report shall encourage scientists to utilize the IPEI data.

Acknowledgements We would like to thank many dedicated scientists, engineers, and administrators in the National Space Program Office, the W. B. Hanson Center for Space Sciences at the University of Texas at Dallas, and National Central University for the success of the ROCSAT-1 IPEI payload. The report has been supported by National Space Program Office Operation Contract NSC89-NSPO(A)- PDD-008-STP01 and by National Science Council Research Project NCS89-2111-M-008-027-AP9.

REFERENCES

Anderson, D. N., 1981: Modeling the ambient, low latitude F-region ionosphere - a review. *J. Atm and Terr. Phys.*, **43**, 753-762.

Chang, Y. -S., W. -L. Chiang, S. -Y. Ying, B. J. Holt, C. R. Lippincott, and K. -C. Hsieh, 1999: System architecture of the IPEI payload on ROCSAT-1. *TAO supplementary issue*, 7-18.

Dyson, P. L., J. P. McClure, and W. B. Hanson, 1974: In situ measurement of the spectral characteristics of F region ionosphere irregularities. *J. Geophys. Res.*, **79**, 1479-1502.

Hanson, W. B. and I. B. Ortenburger, 1961: The coupling between the protonsphere and the normal F region. *J. Geophys. Res.*, **66**, 1425-1435.

Kelley, M. C., R. Pfaff, K. D. Baker, J. C. Ulwick, R. Livingston, C. Rino, and R. Tsunoda, 1982: Simultaneous rocket probe and radar measurements of equatorial spread F—Transitional and short wavelength results. *J. Geophys. Res.*, **87**, 1575-1588.

Kil, H. and R. A. Heelis, 1998: Equatorial density irregularity structures at intermediate scales and their temporal evaluations. *J. Geophys. Res.*, **103**, 3989-3981.

Oya, H., T. Takahashi, and S. Watanabe, 1986: Observation of low latitude ionosphere by the impedance probe on board the Hinotori satellite. *J. Geomag. Geoelectr.*, **38**, 111-123.

Yeh, H. C., S. Y. Su, Y. C. Yeh, J. M. Wu, R. A. Heelis, and B. J. Holt, 1999a: Scientific mission of the IPEI payload onboard ROCSAT-1. *TAO suppl.*, 19-42.

Yeh, H.C., S.-Y. Su, R. A. Heelis, and J. M. Wu, 1999b: The IPEI preliminary results: vertical ion drift statistics. *TAO*, December.

Yeh, H. C., S.-Y. Su, R. A. Heelis, Y. C. Yeh, and J. M. Wu, 1999c: The cross-spectral analysis of ion motion in equatorial bubbles, to be submitted to Geophys. Res. Lett..

Su, S.-Y., H. C. Yeh, R. A. Heelis, and S. L. Chen, 1999: ROCSAT-1 IPEI observation of equatorial spread F æ transitional scale results, submitted to J. Geophys. Res., Lett..

Su. Y. Z., K.-I. Oyama, G. J. Baily, S. Fukao, T. Takahashi, and H. Oya, 1996: Longitudinal variations of the topside ionosphere at low latitudes: Satellite measurements and mathematical modelings. *J. Geophys. Res.*, **101**, 17191-17205.