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GPS phase fluctuations in the equatorial region during the MISETA 1994 campaign

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Abstract. In this paper we present the first coordinated use of Global Positioning System (GPS) multisite and multisatellite observations with ground based radar and optical diagnostics to investigate equatorial irregularity patterns. Thirty second samples of total electron content (TEC) obtained from GPS phase differences between 1.2- and 1.6-GHz signals are used to study phase fluctuations at several stations. Comparisons were made with various types of ground measurements during the multi-instrument studies of the equatorial thermosphere aeronomy (MISETA) period. Depletions of 6300Å airglow emission from Arequipa, Peru, correlated with phase fluctuations recorded at the same site. Phase fluctuations at Arequipa occurred at the times when the Jicamarca radar backscatter returns from plumes were noted but were also seen on other nights when there were no radar returns from plumes. Levels of phase fluctuations noted at Arequipa varied considerably on nights when only thin layers of irregularities were observed by the Jicamarca radar. Differences of ionospheric conditions between the two sites, separated by only 5.5° geographic longitude, may account for the different behavior patterns of irregularities noted. Similar differences in the general behavior pattern of phase fluctuations were shown when data from Arequipa and Fortaleza, Brazil, were compared. These stations, 33° apart, but at the same dip latitude had different patterns for some days. During a magnetic storm a very high altitude plume was observed by the radar and by phase fluctuations noted at Santiago at 18° dip latitude. This correlation of high plume altitude during some periods of magnetic activity was validated by additional examples of phase fluctuations from three other magnetic storms in the solar minimum years of 1994 and 1995.

1. Introduction

F layer irregularity studies stem from the scientific community's interest in the physics of plasma instabilities and from the technical interest in the effects of the ionosphere on radio signals. A relatively new data source has been available for these studies, the observations of the International GPS Service for Geodynamics (IGS). To explore this resource, a program of studies of phase fluctuations and total electron content (TEC) has been developed at the Center for Space Physics of Boston University.

Available literature concerning amplitude scintillation in the equatorial region has shown that during both sunspot minimum and sunspot maximum, plumes of irregularities develop at the equator. The plume development, predominantly showing backscatter irregularities to 800 km, produce amplitude scintillations. Within plus and minus 5° of the magnetic equator 6-7 dB peak to peak fluctuations at 1.5 GHz occur [*Aarons*, 1993].

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In the equatorial anomaly region, these levels are only occasionally reached [*Basu et al.*, 1988] in sunspot minimum years. The equatorial anomaly region shows enhanced electron density compared to that at the magnetic equator and peaks 12°-18° dip latitude north and south of the magnetic equator. During sunspot maximum years the enhanced electron density produces amplitude scintillations in the anomaly region of over 20 dB peak to peak for hours. While phase fluctuations do not follow in detail amplitude scintillations, it has been found in these studies that during periods when amplitude scintillations are received at both high and equatorial latitudes, both show similar trends.

Measurements of satellite beacon differential phase scintillations were made at high latitudes by *Kersley et al.* [1995]. In those studies, the phase differences between 150 and 400 MHz were used with the NNSS series of satellites at 1000 km to determine the occurrence patterns of phase scintillation. Their data were digitized at rapid rates, thus allowing the spectrum of phase scintillations to be determined. Phase fluctuations reported in this paper were obtained by examining total electron content variations. Thirty second values of phase differences between the 1.2-GHz and the 1.6-GHz signals of each GPS satellite were recorded. The rate of change of the 30-s values is the source of the phase fluctuation study. With the data set consisting of 30-s samples, thus limiting spectral characteristics, we have chosen to call our data "phase fluctuations." The use of these relatively long samples means that we are studying irregularity structures of the order of several kilometers. It should be noted that amplitude scintillations result from scattering from irregularities of the order of several hundred meters to a kilometer. Jicamarca radar backscatter returns result from probing 3-m irregularities. From the cascading properties during the development of irregularities, it is expected that the general morphology of the phase fluctuations will be similar for a range of irregularity sizes.

2. The Database

From the IGS database, routine observations of TEC are available from a number of observatories throughout the world. The aim of this paper is to study phase fluctuations at equatorial latitudes during the multi-instrumented studies of the equatorial thermosphere aeronomy (MISETA) period of September 24 to October 7, 1994. Other series of days, in 1994 and 1995, are used to validate some of the results from the September-October period. This will be the first application of GPS phase fluctuation data used to understand dynamic ionospheric morphologies.

In the analysis, the phase fluctuation data emerge in the form of Figure 1; the data are observations at Arequipa, Peru. The propagation path in dip latitude of the satellite at 400 km is calculated. The data that emerges are the rate of change of total electron content per minute (TECU per minute) where the TEC unit is 1×10^{16} el/m^2.

The analysis then followed several paths. The filter employed in the rate of change analysis (P. Fougere, personal communication, 1993) eliminates changes in TEC which occur on time scales larger than 25 min. Thus very large scale changes of irregularities are eliminated. In addition dTEC/min values were computed only where the elevation of the satellite was greater than 15°. This was done in order to avoid problems of tropospheric fluctuations on the signal as well as to minimize the effects of physical obstacles in the propagation paths.

Figure 2 is a map of the sites involved and their positions as a function of dip latitude. Table 1 gives site coordinates. A plot of *Kp* and *Dst* is shown in Figure 3 for the period of the anlaysis.

3. Comparison of Radar Returns, Depletions, and Phase Fluctuations for 2 Days

We now examine several case study events that occurred during the MISETA campaign period.

October 3

The most spectacular plume that developed in this period was that of October 3; irregularities reached altitudes over 1400 km (Figure 4). At Jicamarca, the plume development started in a classical manner with a thin layer at 200 km at 2000 local standard time (LST) (0100 UT). The irregularity layer height rose to almost 400 km by 0300 UT. Just before 0300 UT, a fully developed structure appeared. The structure was maintained at intense levels until 0500 UT and remained strong at high altitudes until the end of the radar observations at 0700 UT.

Figure 5 shows the all-sky (150°) field of view for simultaneous airglow imaging and GPS observations from Arequipa on the night of October 3, 1994. The imager records the depletion of nightglow emissions arising from recombination processes. The depletion of airglow denotes a depletion of electron density near the 300-km level [*Mendillo et al.*, 1996]. At 0048 UT (1948 LST), Figure 5 shows a clearly outlined depletion region as observed at Arequipa. This image, taken close to sunset, shows the depletion region extending to the limits of the field of view of the 6300-Å all-sky imager. The satellite passes which were outside of the

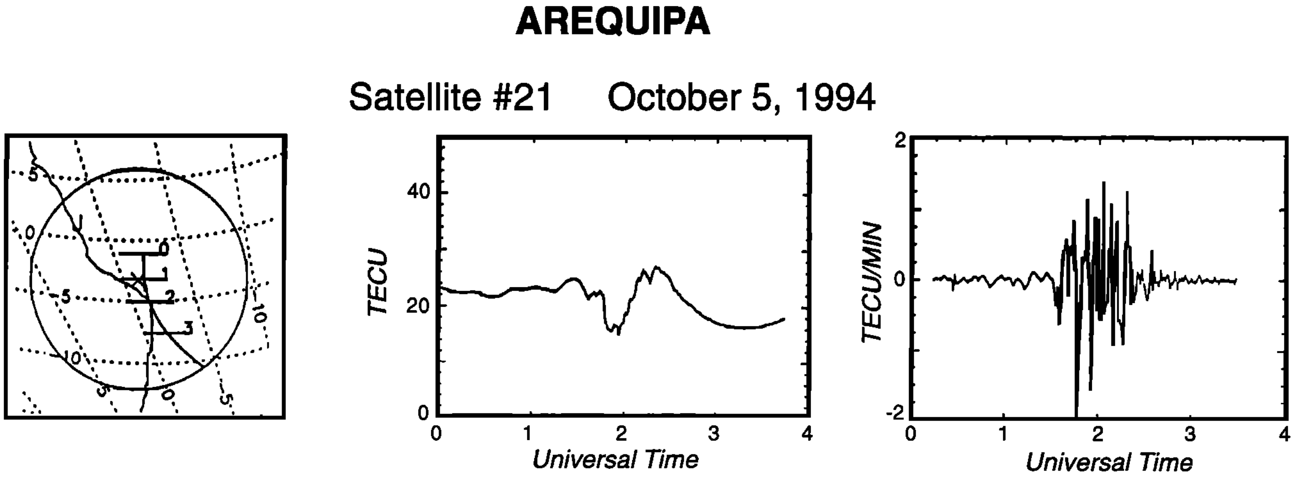


Figure 1. The data available from International GPS Service (IGS) are used with orbital elements to plot the ionospheric propagation path of satellite 21 for October 5, 1994, as observed from Arequipa, Peru. The total electron content in units of 1×10^{16} el/m^2 is shown as a function of universal time. The rate of change of total electron content (TEC) per minute is then determined as a measure of phase fluctuation. In the case illustrated, there is a drop in TEC when the phase fluctuations occur. In the diagram the 15° elevation circle is shown. Arequipa is at the center of the diagram (marked by a cross) with J marking the position of the Jicamarca radar. Positions of the propagation path are calculated using 400 km heights.

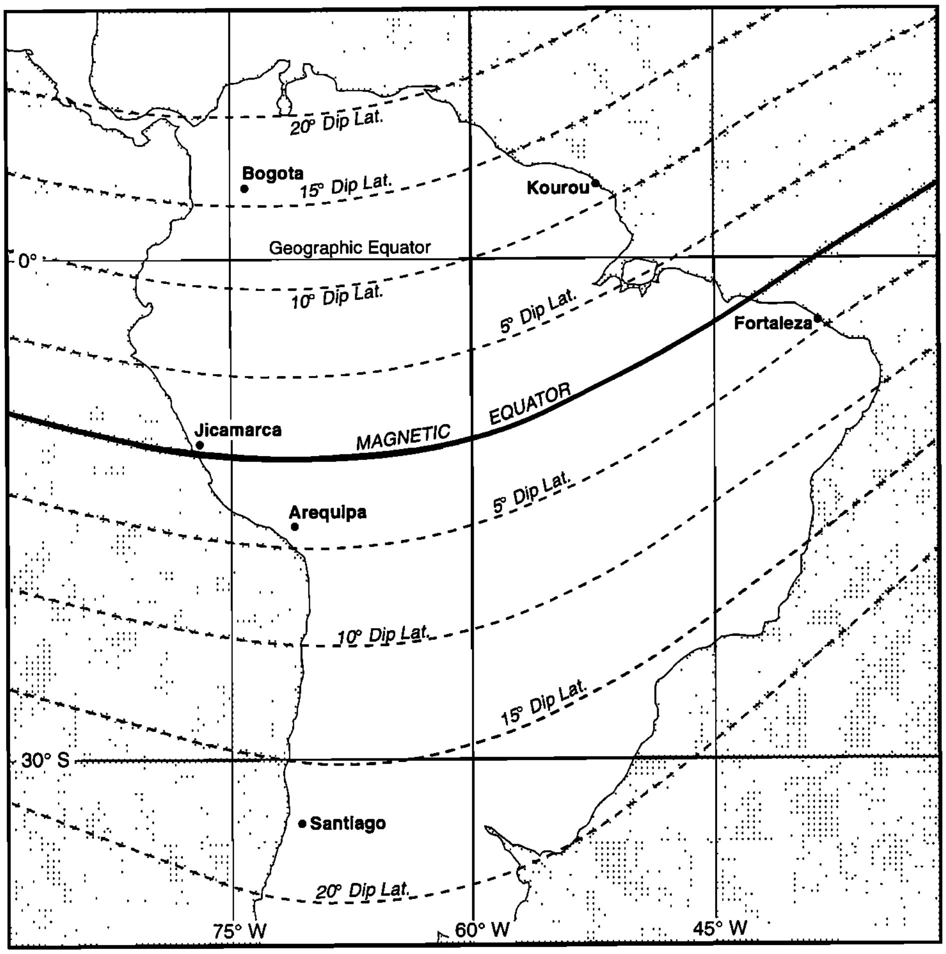


Figure 2. Map of the various observation sites referred to in the text.

depletion region in this time period did not experience fluctuations (22, 28). Those at the walls of the depletion region (1 and 21) and passing thru the depletion region (17) showed strong to medium rate of change of TEC.

The Jicamarca radar failed to show plume returns at 0048 UT and only started to develop a thin backscattered layer at 0100 UT. The indications from this Arequipa image at 0048 UT are that early irregularities developed at or near the longitude of the postsunset line of Arequipa (71.5° W). Corresponding irregularities did not occur at the longitude of Jicamarca at 77° W. Later, along the Jicamarca meridian there was a single plume and accompanying phase fluctuations. It might be noted that scintillation data from a site close to the Jicamarca site in Ancon, Peru, (C. E. Valladares, private communication, 1995) did not indicate the existence of irregularities at 0048 UT. This further validated the point that development of the depletion at 0048 UT was along the longitude of Arequipa. After the development, these early Arequipa irregularities moved eastward and thus could not be observed at the Jicamarca meridian.

Table 1. Locations of GPS, Airglow, and Radar Sites Used in This Study

	Geographic Latitude	Geographic Longitude	Dip Latitude
Arequipa, Peru	16° S	71.5° W	3.7° S
Jicamarca, Peru	12° S	77° W	0.8° N
Santiago, Chile	33° S	71° W	17.7° S
Fortaleza, Brazil	4° S	38° W	5° S
Kourou, French Guiana	5° N	53° W	11.3° N
Bogota, Colombia	4.6° N	73° W	16.7° N

Figure 6 presents GPS phase fluctuation data over the full 0000-0600 UT period on October 3 (right) as well as for a quiet (nonphase fluctuation) night, October 2 (left). For October 2 when no evidence of *F* layer irregularities were noted on the radar and no depletions were observed by the Arequipa imager, no phase fluctuations were noted. From the October 3 Arequipa phase fluctuation data shown in Figure 6, it is apparent that before the development or arrival of the 03 UT plume, there was an earlier development at Arequipa's meridian. This took place independently of what was happening at Jicamarca. Figure 6 indicates that phase fluctuations could be noted from 0015 to 0200 UT.

We now turn to Arequipa observations during the time of the spectacular plume at Jicamarca on October 3. The longitudinal separation between the overhead field line at Jicamarca and the overhead field line at Arequipa is 5.5°; the distance between field lines is ~600 km at 400 km. Most of the GPS data available were close to overhead observations with little on longitudes to the east or west of Arequipa. Using a zonal plasma drift of 150 m/s which can take place in the early evening [*Yeh et al.*, 1981], it would take approximately an hour to bring irregularities developed at the longitude of

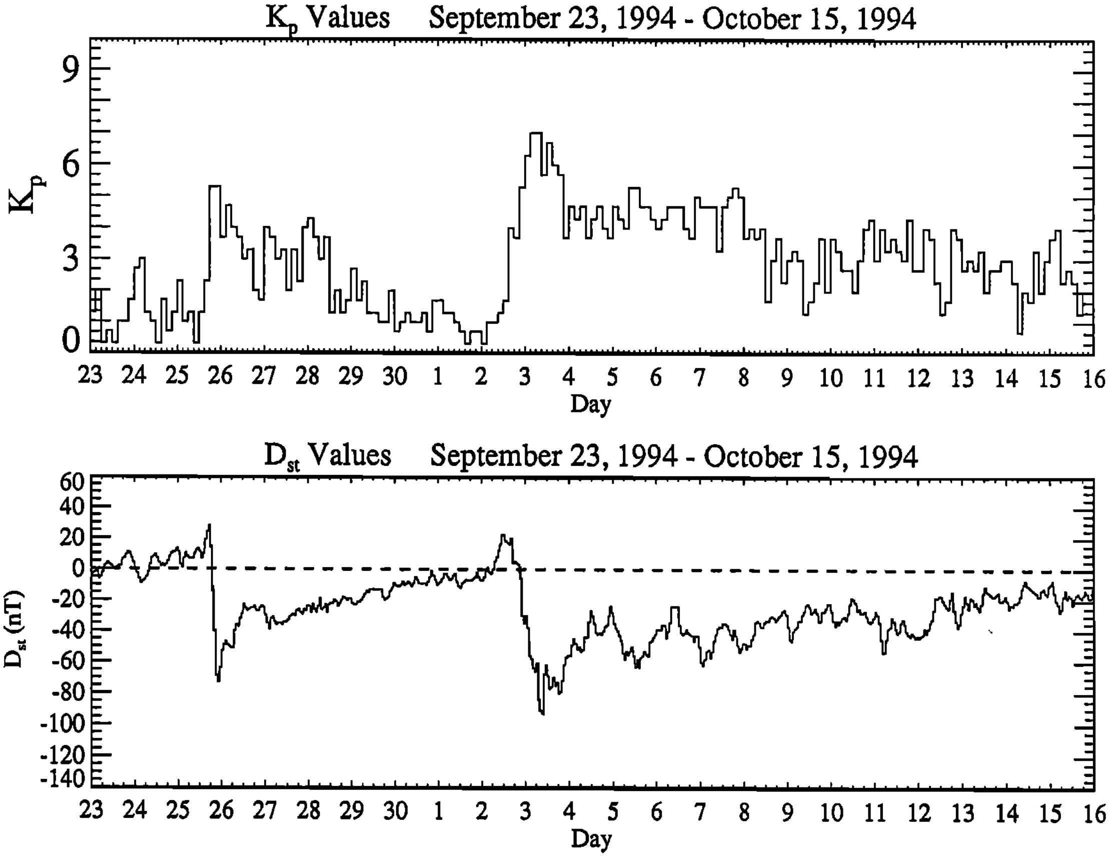


Figure 3. *Dst* and *Kp* values for the overall period examined. Magnetic storms commenced on September 25 and October 2. The data for the October 4-7 period showed relatively high values of *Kp* and a slow release of ring current ions as evidenced by prolonged negative *Dst* values.

Jicamarca to the field line of Arequipa. The October 3 radar plume at 0300 UT would be expected to arrive at the field line from Arequipa at 0400 UT, if the origin of the development of the plume was only at Jicamarca's longitude. At 0230 UT the propagation paths observed from Arequipa showed low levels of fluctuations. However, at 0300 UT higher levels can be noted.

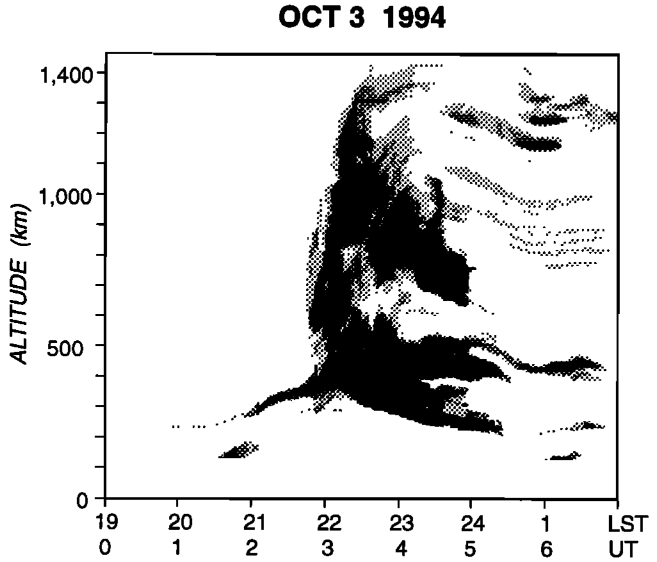


Figure 4. A sketch of Jicamarca relative backscatter power for the high altitude plume of October 3. Blackened areas are backscatter levels of higher value than the hatched regions.

The development time was brief as was indicated by the simultaneous appearance of phase irregularities at Arequipa and backscatter on the Jicamarca radar. It is probable that the plume developed over a relatively large range of longitudes which included both Jicamarca and Arequipa. The large range of affected longitudes is also indicated by the radar plume lasting over 2 hours. While the sunset line moves westward at a velocity of approximately 500 m/s, the rapid development of plumes after sunset has been measured in a limited number of cases to be of the order of 160-300 m/s westward [*Aarons et al.*, 1980].

In examining a site south of Jicamarca, we found that the GPS data from Santiago, Chile, at 17.7° dip latitude, showed evidence of phase fluctuations between 0250 and 0400 UT on October 3. These were noted on paths equatorward of the station. For the MISETA period this was extremely rare; only on October 5 were fluctuations observed which reached a very high altitude and could be traced along a field line to the higher latitude of Santiago. Figure 7 contrasts the phase fluctuations at Arequipa and those at Santiago for the MISETA period. These are plots of 15 min averages of the rate of change of TEC data at the two GPS sites. Each dot is a 15 min sample with no phase fluctuations > 0.5 TECU/min. Excursions are between 0.5 and 1 TECU/min (triangles), 1-2 TECU/min (squares) and greater than 2 TECU/min (solid dots). The symbols denote two or more 1 min samples of phase fluctuations of the levels denoted on the diagram.

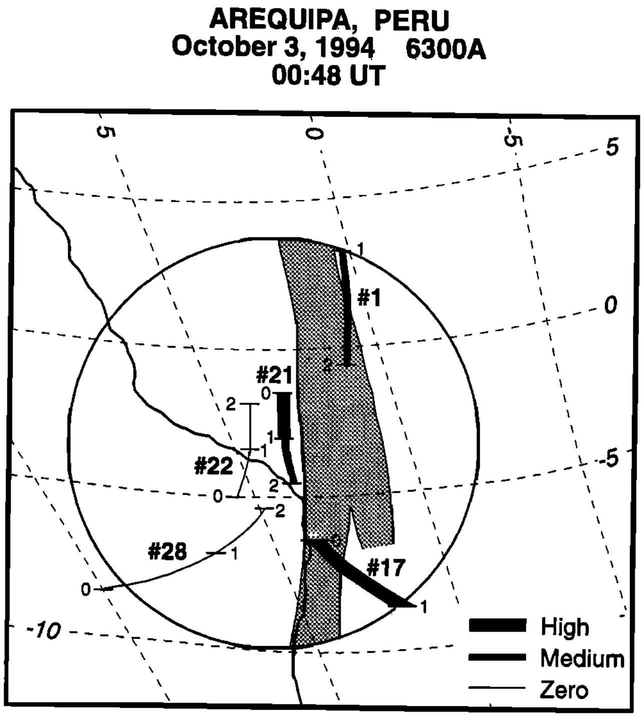


Figure 5. A depletion image (shaded) for 0048 UT on October 3 as observed from Arequipa, Peru. The individual satellites with their relative phase fluctuations are shown. The satellite paths over a relatively long period of time are shown while the depletion image is instantaneous.

Clearly, phase fluctuations are much more common at the lower latitude site, implying a higher occurrence of irregularities or plumes that do not extend to heights near 1200 km, the altitude where geomagnetic field line mapping indicates is overhead at Santiago.

Kourou, French Guiana, at 11° N dip latitude, showed phase fluctuations on October 3, another indication that the high altitudes reached by the 0300 UT plume affected fluctuations at latitudes close to the anomaly region. We shall return to storm related high-altitude effects in a later section.

October 5

On October 5, a thin layer of irregularities was detected between 0100-0330 UT (2000-2330 LST) by the backscatter radar at Jicamarca (Figure 8); plumes were not observed in this time period. At Arequipa, the GPS observations showed very high values of *d*TEC/*dt* in the 0115 to 0315 UT time period. Depletions were observed extending over the field of view. The phase fluctuations plus the depletion images indicated that plumes did develop at the Arequipa longitude. Lending weight to this hypothesis is that phase fluctuations were observed at Santiago; it is suggested that high-altitude effects of a plume produced these fluctuations. Figure 9 shows phase fluctuations on the satellites visible during the night hours of October 5. In Figure 9, fluctuations can be readily seen when contrasted with the phase fluctuation data observed on another "thin layer" night, October 4.

On the backscatter radar at Jicamarca there was a low-altitude plume structure (to 500 km) observed at 0410 UT; in all likelihood this plume developed in the west and moved eastward. The indications from the early time period on this night are that the development of irregularities differed between Jicamarca and Arequipa.

4. Overview of Full MISETA Period

We have analyzed data of each day of the MISETA '94 Campaign (September 24 to October 7, 1994) for sites near the west and east coasts of South America in order to assess longitude differences in night by night irregularity development patterns. The GPS results from Arequipa and Fortaleza (see Figure 2) are presented in Table 2, along with a brief description of Jicamarca radar returns for the night. The characterization of GPS data was arrived at in a partly subjective manner, tagging perceptible phase fluctuations

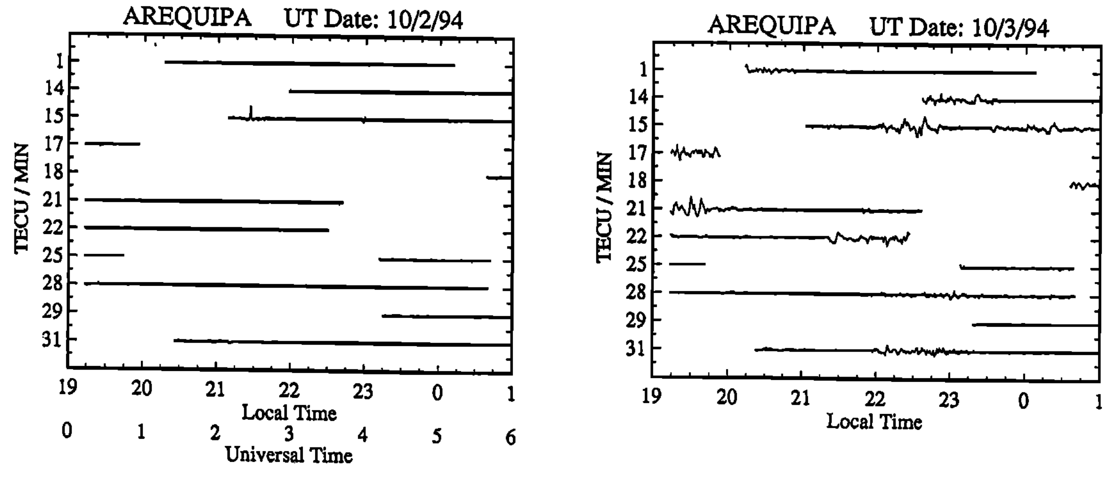


Figure 6. Phase fluctuation for individual satellite signals received during the 1900-0100 LST period (0000-06 UT). (Left) October 2 was a quiet night for this parameter, but (right) October 3 data indicated moderate levels of phase fluctuations. Early evening phase fluctuations were seen on October 3 from 0000 to 0100 UT (1900 to 2000 LST). In addition, the 0300 UT irregularities correlated with the 0300 UT plume noted on the Jicamarca radar. Satellite vehicle numbers are shown on the vertical scale. On that scale each satellite number is distanced 2 TECU/min from the next satellite number.

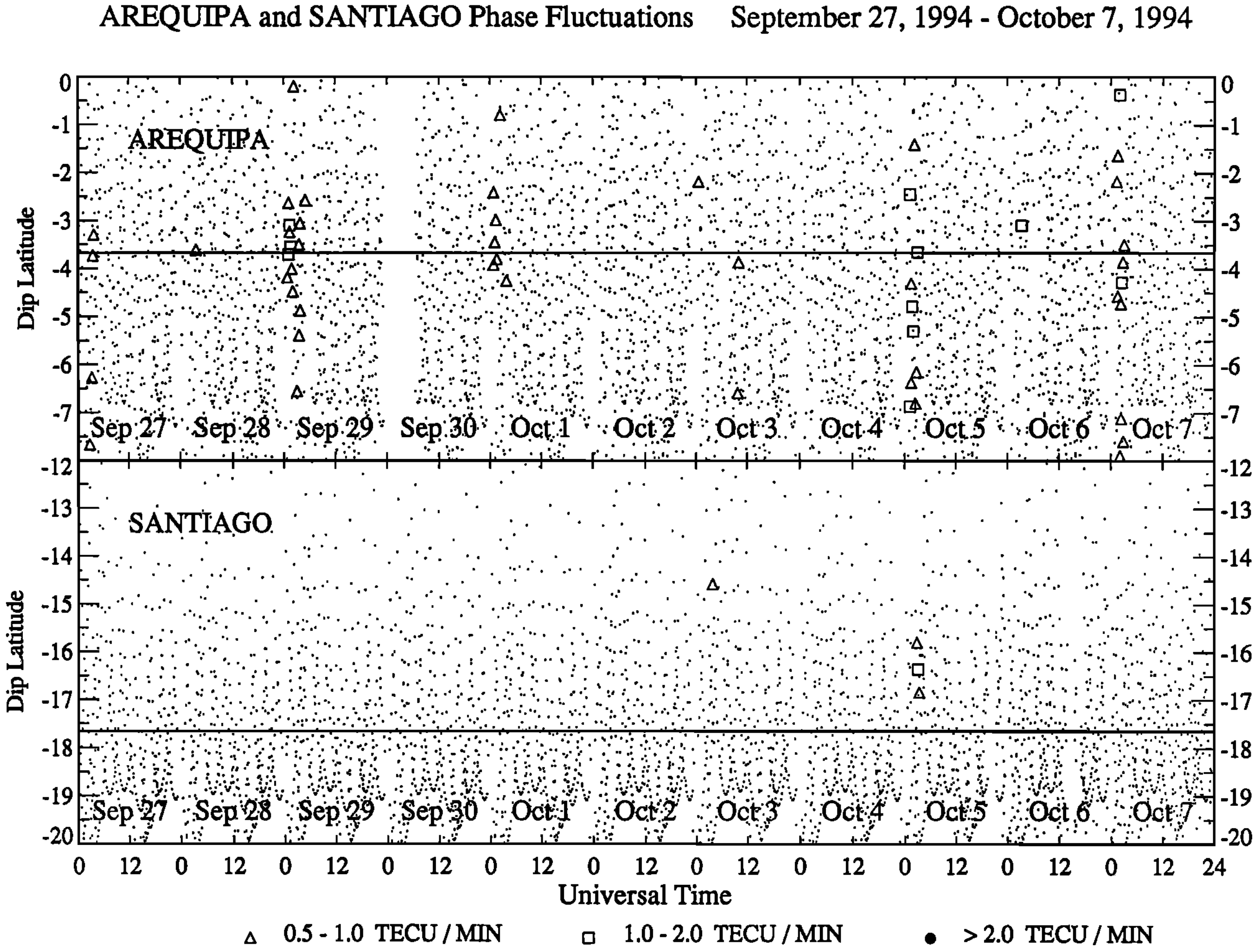


Figure 7. General phase fluctuation occurrence pattern for the period for Arequipa and Santiago data. The symbols denote two or more 1-min values of *d*TEC/*dt* in a 15-min period. Each dot is a 15-min period summary with less than two one minute phase fluctuation values greater than 0.5 TEC/min. The triangle symbol denotes two or more 1-min phase fluctuations in a 15-min period with two or more excursions of 0.5-1 TECU/min. The square symbol denotes excursions between 1 and 2 TECU/min and the solid dot >2 TECU/min.

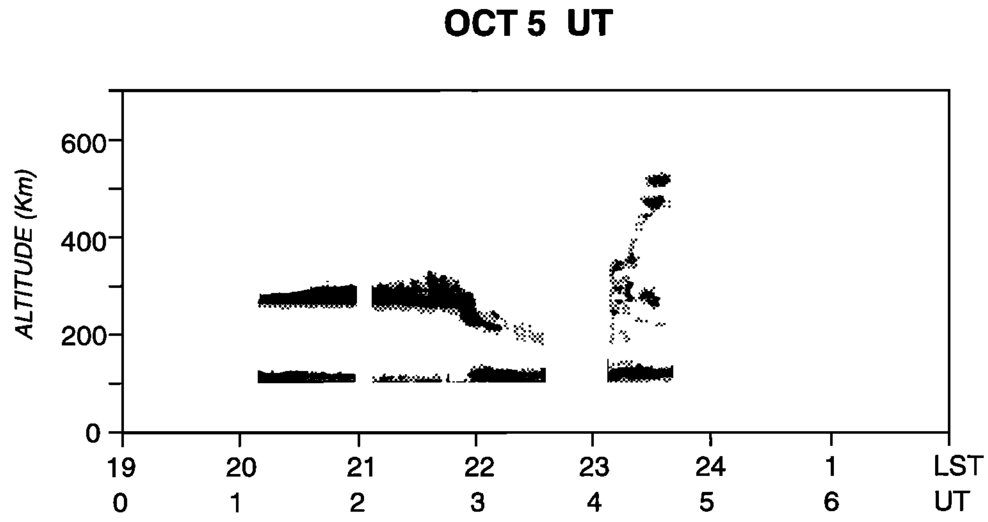


Figure 8. Tracing of Jicamarca relative backscatter power for October 5. In the early evening only thin layers were observed. At 2300 LST a plume extending to 600 km was observed.

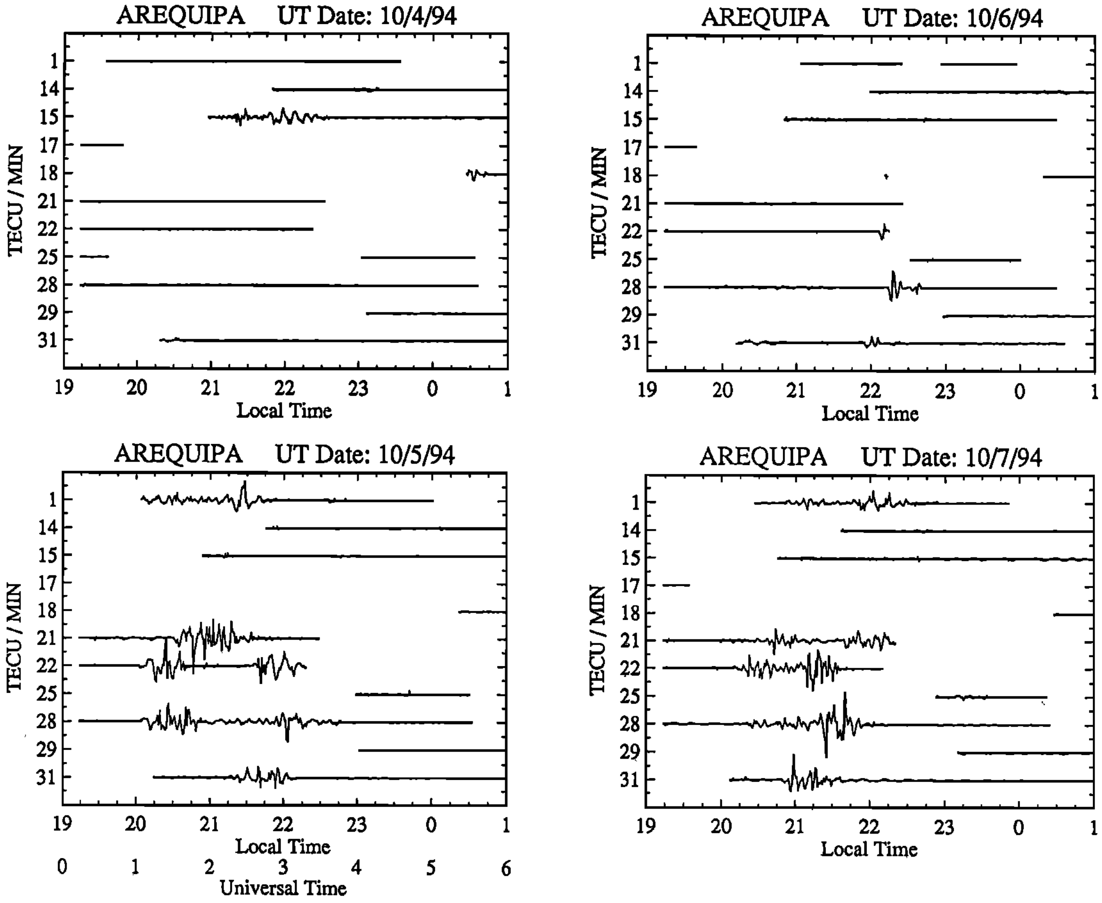


Figure 9. Phase fluctuations for October 4,5,6, and 7 when the Jicamarca radar observed predominantly thin layers.

below 0.5 TECU/minute as low level and data from several satellites of the order of 0.5 TECU/minute as moderate level.

The results of this comparison of Jicamarca radar returns and Arequipa phase fluctuations are that the Jicamarca radar returns at times are not well correlated with intense phase fluctuations overhead at a site 5.5° of longitude away. However, when no radar returns were noted on October 2, no phase fluctuations were noted at Arequipa.

During the October 4-7 period, the Jicamarca radar detected only thin layers. Two of the days, October 4 and October 6, had clear skies, and no airglow depletions were noted; during these 2 days, only minor phase fluctuations were noted. Two other days, October 5 and 7, when primarily thin layers were detected by the radar, showed both depletions and phase fluctuations.

It is evident from Table 2 that there is a considerable difference in irregularity structure as measured by phase fluctuations between Arequipa and Fortaleza, two ground stations 33° apart in geographic longitude but at almost the same dip latitude. In the comparison of Arequipa and

Table 2: Comparison of Jicamarca Radar Returns and Arequipa and Fortaleza Phase Fluctuations (*f*)

Ut Date	Radar Fluctuations	Arequipa Fluctuations	Fortaleza Fluctuations
Sept. 24	200-400 km plumes	low level *f*	low level *f*
Sept. 27	low altitude plume 0150 UT high plume 0305-06 UT	low level *f*	moderate *f* activity
Sept. 28	two plumes	moderate level	no *f*
Sept. 29	thin layer	high *f* activity	high *f* activity
Sept. 30	no returns	no data	moderate *f* activity
Oct. 1	thin layer	high f activity	no *f*
Oct. 2	no returns	no *f*	high *f*
Oct. 3	high plume to 1400 km	low to moderate level *f*	low *f*
Oct. 4	thin layer	no *f*	no *f*
Oct. 5	thin layer low-alitude plume at 0410 UT	high *f*	low to moderate *f*
Oct. 6	thin layer 200-300 km	very low f	low f
Oct. 7	thin layer	high f	high f

Fortaleza phase fluctuations shown in Table 2, Fortaleza showed no phase fluctuations on September 28, while Arequipa showed moderate levels. On October 1, Arequipa had high level phase fluctuation activity, but Fortaleza showed no phase fluctuations. On October 2, Fortaleza recorded high-level fluctuations, Arequipa showed no fluctuations. Yet there were days when the GPS phase fluctuation data showed similar patterns such as September 29, October 6, and October 7 with one day, October 4, when no fluctuations were observed at either ground station.

One hypothesis for necessary conditions for the development of plumes that has been set forth is that *F* layer electron densities be symmetrical north and south of the magnetic equator [*Cohen and Bowles*, 1961] and [*Maruyama and Matuura*, 1984]. To show that symmetry is correlated with plume development, Maruyama and Matuura have utilized satellite data on electron densities at the 1100 km level. We suggest that total electron content data could be used to study the day-to-day variations of the degree of symmetry in the F region plasma spanning the anomaly region.

In an attempt to fully utilize the GPS data, we have developed three-dimensional maps of total electron content as a function of local time and latitude. An example is shown in Figure 10 for October 5, 1994, which was produced by combining TEC measurements for two contiguous stations,

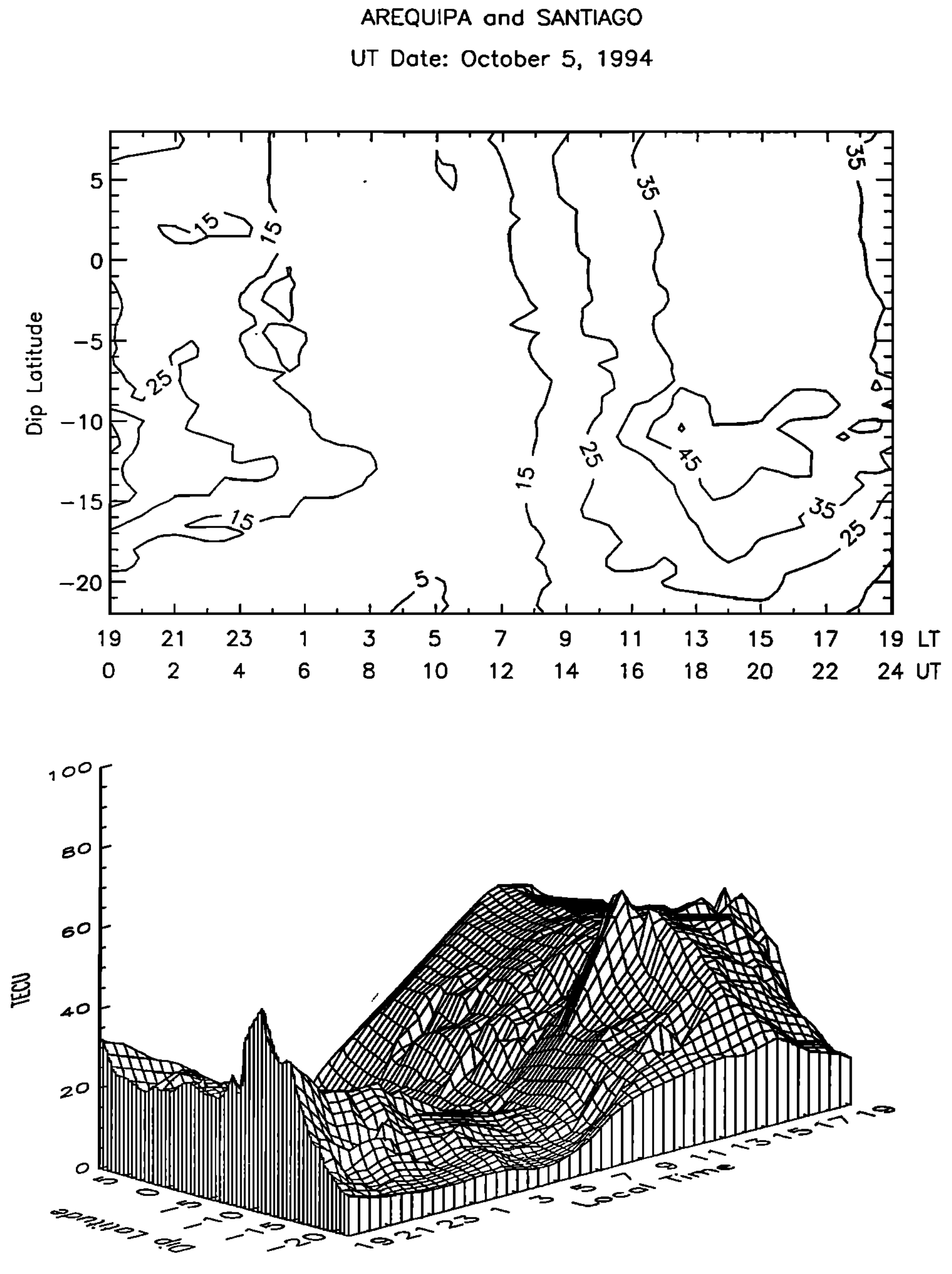


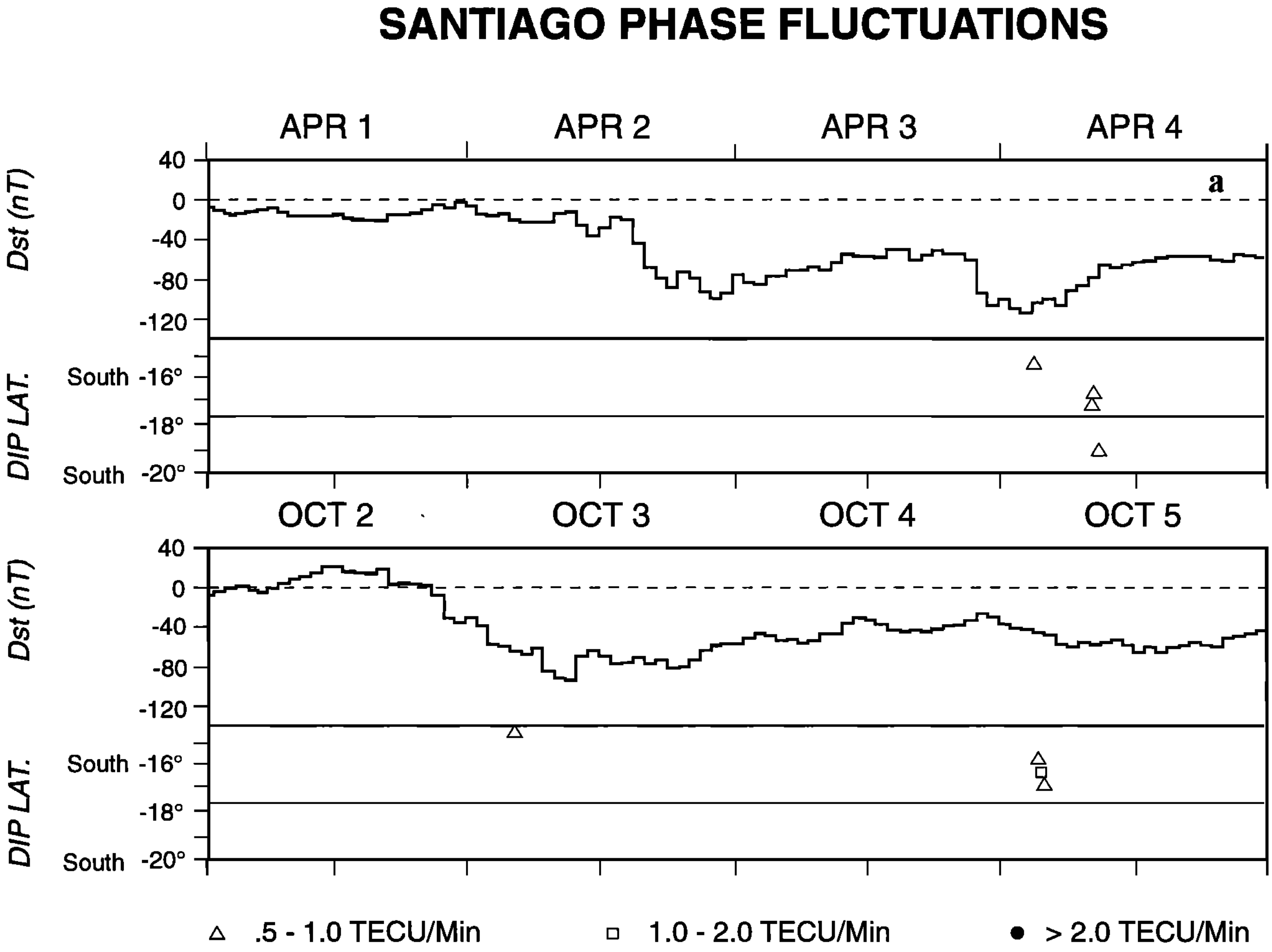
Figure 10. Contours and a three-dimensional picture of total electron content of the equatorial and anomaly regions for October 5, 1994. Data from Arequipa and Santiago were combined. Offset values of both satellites and ground stations were used.

Arequipa and Santiago. Offsets for both stations were used as were offsets for each satellite; the offset data were supplied by A. Manucci (private communication 1995). The equatorial anomaly of electron density is evident on this figure with higher total electron content noted in the 9°-15° dip latitudes for this night and with high TEC particularly noted in the sunset to midnight time period at these latitudes when irregularities developed. As shown in Figures 7 and 8, this was a night of phase fluctuations at both Arequipa and Santiago and a night of prolonged geomagnetic activity (see Figure 3). While use of only two stations cannot capture the full characteristics of the transequatorial TEC behavior, it can address night-to night formation of the anomaly (and thus the strengths of the E x B drifts conducive to instability development). This technique will thus allow us to study many parameters of the equatorial anomaly region including width, time development at a range of latitudes, and absolute values once the full multisite low-latitude GPS network is established.

5. Very High Altitude Plumes

The October 3 plume took place during the development of a magnetic storm. Most of the studies on magnetic storm activity [*Dabas et al.*, 1989 and *Aarons*, 1991] have been done for high solar flux years. During those years it was clear that the sunset rise of the F layer was the determining factor in the development of plumes. During the years of high solar flux and in the months of irregularity activity, magnetic storms can produce various effects on the generation of plume irregularities. The time of the magnetic storm maximum determines whether the storm will not affect the generation of plumes or whether it might inhibit or generate irregularity plumes.

In analysis of other magnetic storm periods in 1994 and 1995, it was found that the only phase fluctuations observed at Santiago occurred during high levels of magnetic activity. When magnetic activity was low there were no phase fluctuations at the dip latitude of 17.7°. Magnetic storm case



Figures 11. Plots of Santiago phase fluctuations for four storm periods in (a) 1994 and (b) 1995 similar to that of Figure 7. The phase fluctuation activity depicted shows the contrast between magnetically quiet days and days of high excursions of *Dst*. (c) Bogota phase fluctuation data are shown for January 17 and 18, 1995; the magnetic storm occurred on January 18 as shown in Figure 11b. As noted in the text, phase fluctuation data were available for this storm period from both Santiago at 17.7° S dip latitude and Bogota at 16° N dip latitude; on January 18 both showed strong phase fluctuation. Very short interference pulses in the Bogota data were noted at both days but the slower phase fluctuations can be readily noted on the January 18 observations when compared to the January 17 records.

studies were developed with data taken over several days. For each case study, the magnetic storm period was chosen because of quiet days preceeding the onset of storm activity. Phase fluctuations observed at Santiago were observed on days of high magnetic activity, that is, April 4, 1994, January 18, 1995, and March 10, 1995, as well as October 3 and October 5, 1994 (Figures 11a and 11b). For this limited number of storms, high-altitude plumes were observed during large excursions of *Dst*. The extension of the lines of force above the magnetic equator to latitudes near the position of Santiago indicates that altitudes over 1200 km have been affected by the plumes generated during the days indicated.

In addition to the storms cited and illustrated, other storm periods (November 3-4, 1993, and July 17-18, 1995) showed phase fluctuations at Santiago during the early phases of the magnetic storm.

Identifying the phase fluctuations observed at the southern latitude of Santiago as due to a plume was validated in the following way. If a high altitude-plume had indeed developed, then the observations in the northern anomaly region should show evidence of activity as well on the Santiago propagation path. When Bogota, Colombia, came on line at a dip latitude of 16° N, the data for January 18, 1995, were examined in order to compare them with the simultaneous GPS observations from Santiago (Figure 11b). Although the data for Bogota during this period were plagued by pulsing interference, it can be seen in Figure 11c that the fluctuations were observed only on January 18; in this diagram, the phase fluctuations are of longer period than the pulses.

As noted above, each period of magnetic activity does not always produce high-altitude plumes. Equally large excursions of *Dst* (-100 nT) occurred and no high altitudes plumes were observed (April 2, 1994, in Figure 11a). For the gradual commencement magnetic storm of September 27-28, 1995 there were no phase fluctuations recorded at the stations of Santiago, Bogota, Brasilia, and Arequipa. The time of maximum *Dst*, 1500 - 1600 LST, in all likelihood prevented the layer height from rising. The effect of magnetic activity on the equatorial development of irregularities is a function of local time, magnetic storm characrteristics, and the ambient ionosphere before the onset of magnetic activity.

6. Discussion

In the years of low solar flux, thin layers of irregularities are frequently observed. *Basu and Aarons* [1977] showed that for two equinox periods, almost half the nights exhibited thin layer backscatter returns or returns from a layer of moderate thickness. These are common occurrences in years of low solar flux. The thin backscatter layers shown in the MISETA time period and those outlined by *Basu and Aarons* [1977] are in all probability not the basically summer thin layers

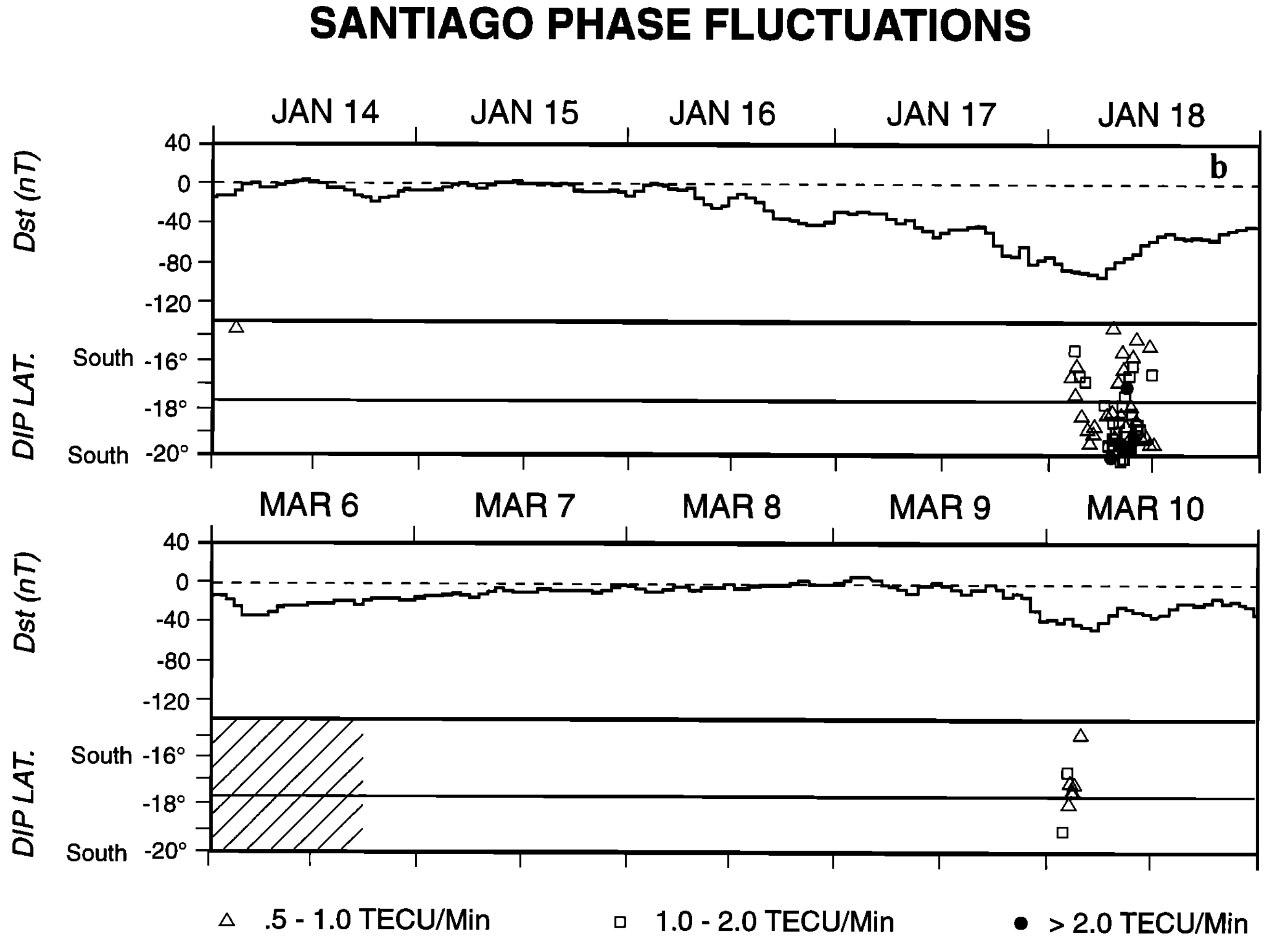


Figure 11. (continued)

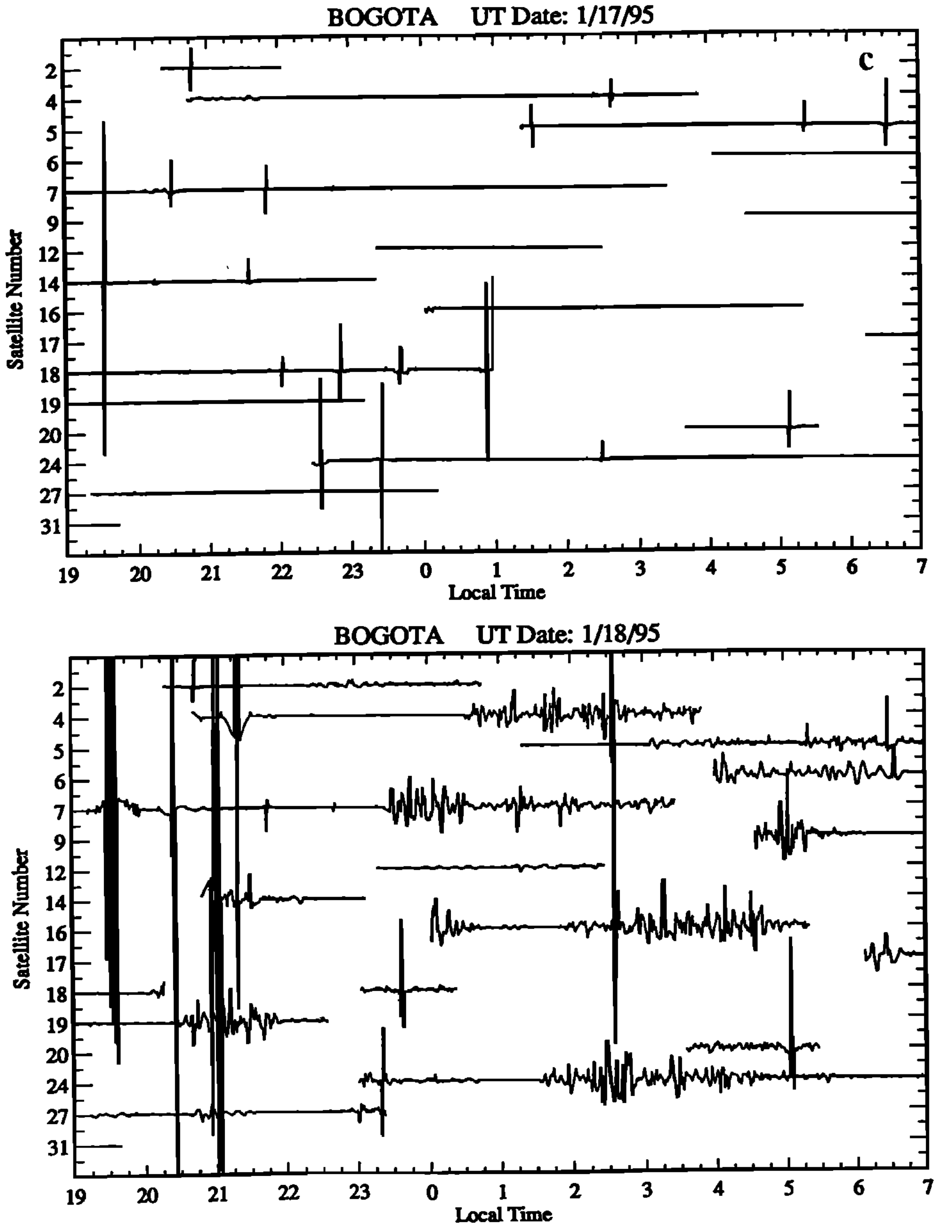


Figure 11. (continued)

described by *Valladares et al.*, [1983] and *Craigin et al.* [1985] and named bottomside sinusoidal layers (BSS). In a study of the amplitude scintillations observed during the existance of BSS layers *Basu et al.* [1986] found a value of only 1.5 dB peak to peak levels at 1.5 GHz [*Basu et al.*, 1986] for their limited observations. For amplitude scintillations at least, GPS in the same band should be minimumly affected by these irregularities. In addition, the MISETA observations were made in the equinox period, while BSS layers have maximum occurrence in the summer.

The irregularities that have been observed in the radar data move east and should appear later at the Arequipa longitude. Using typical zonal drifts, irregularities seen at Jicamarca should appear overhead at Arequipa after about an hour. Backscatter radar data indicated thin layers over Jicamarca on October 4 and October 6. No GPS phase fluctuations were found for the latitudes and longitudes observed from Arequipa for October 4 and 6; in addition no airglow depletions were observed during these 2 days. If thin layers existed over the magnetic equator at the longitude of the Arequipa field line, they failed to produce irregularities of intensity to develop phase fluctuations or depletions. On October 5 in the immediate postsunset time period, only thin layers were observed by the Jicamarca radar but at Arequipa there were strong phase fluctuations in this time period and strong phase fluctuations at Santiago, indicating a high-altitude - high-latitude region of irregularities.

7. Conclusions

In a paper describing amplitude scintillation activity as determined by measurements in 1981 at Ascension Island [*Aarons et al.*, 1983], the correlation of amplitude scintillation and airglow depletion regions was shown. We have shown here that phase fluctuations are similarly correlated with depletion images.

The development of plumes of extremely high altitudes has been described in previous studies of airglow depletion effects [*Sahai et al.*, 1994]. A particularly good example was noted on October 3 in the MISETA period. Analysis of other storms in periods of low solar flux revealed a similar pattern of production of turbulence. The January 18, 1995 storm was an even more dramatic example with phase fluctuations produced at dip latitudes of over 20° south.

In principle, it might be possible to use radar data and wind-induced plasma drift patterns to forecast irregularity activity for a particular location. For plumes the development follows the sunset line; once developed the wind pattern moves the irregularities eastward. The data set for the MISETA period indicates considerable differences not only from day-to-day but across relatively short longitudinal baselines. There are highly localized effects that may lead to gross differences between sites only 5.5 ° apart. The development of irregularities over 33° of longitude between Arequipa and Fortaleza indicated considerable day-to-day differences in activity during the same season of high irregularity occurrence.

Depletion images and GPS phase fluctuations have all-sky capabilities. The Jicamarca radar observations are limited to regions near the zenith. Within the field of view of a single station, the use of depletion images would be a good method of forecasting the effect of irregularities on various propagation paths. We note that each method has severe limitations. Clouds and the presence of the moon in the field of view restrict the use of depletion images while the radar returns may be a highly localized detection of *F* layer irregularities and hours of operation are limited. GPS sites may thus offer the best solution for forecasting requirements at all local times and seasons.

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