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EAST-WEST PLASMA BUBBLE IRREGULARITY MOTION DETERMINED FROM SPACED VHF POLARIMETERS: IMPLICATIONS ON VELOCITY SHEAR IN THE ZONAL F-REGION BULK PLASMA MOTION

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14. Abstract/Notes VHF electronic polarimeters were used to monitor Faraday rotation angle and amplitude of geostationary satellite (GOES-3) beacon signals, simultaneously at two station, Cachoeira Paulista (22°41'S, 45°W) and São José dos Campos (23°12'S, 45°55'W), separated by 110km exactly in the magnetic East-West direction in Brazil. The analysis of the data for a few months in 1981-82 period, carried out in this paper, shows TEC fluctuations correlated with range type spread F events in the local ionograms and amplitudes scintillation in the satellite beacon signals, thereby identifying themselves as plasma bubbles and associated structures in the equatorial ionosphere. The spaced polarimeter system has permitted determination of the East-West velocities of these plasma bubble structures whose nighttime variation pattern is in excellent agreement with those of the eastward bulk plasma measured by Jicamarca radar and with those of the plasma irregularities obtained from different radio and optical measurements carried out in the equatorial and low latitude regions. There exist, however, significant differences in the magnitude of the velocities in the different measurements, our results over low latitude locations showing highest values of all. These differences are interpreted as suggesting the possibility of a latitudinal variation in the plasma zonal velocities, consistent with the already known existence of vertical shears in the bulk plasma zonal flow over the equator.

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East-west plasma bubble irregularity motion determined from spaced VHF polarimeters: Implications on velocity shear in the zonal F region bulk plasma motion

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VHF electronic polarimeters were used to monitor Faraday rotation angle and amplitude of geostationary satellite (GOES 3) beacon signals, simultaneously at two stations, Cachoeira Paulista (22°41'S, 45°W) and São José dos Campos (23°12'S, 45°55'W), separated by 110 km exactly in the magnetic east-west direction in Brazil. The analysis of the data for a few months in the 1981-1982 period, carried out in this paper, shows TEC fluctuations correlated with range type spread F events in the local ionograms and amplitudes scintillation in the satellite beacon signals, thereby identifying themselves as plasma bubbles and associated structures in the equatorial ionosphere. The spaced polarimeter system has permitted determination of the east-west velocities of these plasma bubble structures whose nighttime variation pattern is in excellent agreement with those of the eastward bulk plasma measured by Jicamarca radar and with those of the plasma bubble irregularities obtained from different radio and optical measurements carried out in the equatorial and low-latitude regions. There exist, however, significant differences in the magnitude of the velocities in the different measurements, our results over low-latitude locations showing highest values of all. These differences are interpreted as suggesting the possibility of a latitudinal variation in the plasma zonal velocities, consistent with the already known existence of vertical shears in the bulk plasma zonal flow over the equator.

INTRODUCTION

Ionization depletions in plasma bubbles that occur during an equatorial ionospheric irregularity event often cause detectable effects in the integrated columnar ionization contents (TEC) in the transionospheric propagation paths, so that an electronic polarimeter monitoring the Faraday rotation angle of VHF beacons from geostationary satellites could provide an effective and rather simple way of investigating the equatorial ionospheric dynamics during such events. Klobuchar et al. [1978] and Yeh et al. [1981] have demonstrated that polarimeter technique could indeed be used for observing ionospheric plasma depletions associated with amplitude scintillation of transionospheric radio signals. Strong Faraday rotation angle fluctuations, in the presence of amplitude scintillations, of geostationary satellite signals have been reported from low latitude stations located in the equatorial anomaly crest region, namely, over Ascension Island (31°S dip) by Klobuchar and Aarons [1981] and over Calcutta by Das Gupta and Maitra [1980]. Earlier, Kaushika and de Mendonça [1974] had reported scintillation (or fluctuation) in the Faraday rotation angle occurring in the presence of large and long-period disturbances in the Faraday rotation angle, and spread F in the ionograms, over São José dos Campos (23°12'S, 45°55'W, 25.5° dip).

Since 1972, regular monitoring of TEC by using VHF electronic polarimeters has been carried out over São José dos Campos. Recently, a second polarimeter was installed at Cachoeira Paulista (22°41'S, 45°W, 25.5° dip), located at 110 km magnetically eastward of São José dos Campos. These polarimeter sites are shown in Figure 1. Analyses of simultaneous polarimeter data registered over these stations, together with the ionosonde data from Cachoeira Paulista, have permitted determination of the east-west velocities of the propagating disturbances in the TEC and their identification with plasma bubble events. Results of analyses for the 1981-1982 summer months are presented in this paper.

EXPERIMENTAL RESULTS

Fluctuations in the Faraday rotation angle of a few percent (mostly, 1-5 percent) having periods of the order of a few (usually ~5-20) minutes invariably appear in the postsunset period in the equinoctial and summer months. Very often these fluctuations are superimposed upon, or develop into, much stronger (and steeper) TEC changes of longer periods, as seen in the examples of Faraday rotation angle records presented in Figures 2a and 2b for December 24, 1980, and December 11, 1981, respectively. These were registered on GOES-3, which has subionospheric points at 350 km of -21.4° latitude and -50.3° longitude for reception from São José dos Campos. In the early phase of the events the small-scale fluctuations are clean and well defined, but in the later stages they are accompanied by fast and steep fluctuations (or scintillations) to the point of causing uncertainty in the relative Faraday rotation angle values (TEC) at these hours. The tracings of the records for the two stations on December 11, 1981, shown in Figure 2b is a typical example of this depolarization effect [Lee et al., 1982]. Figure 2c, which represents recordings on SIRIO on the night of January 6-7, 1983 (subionospheric points at 350 km, from São José dos Campos, being -21.5° latitude, -43.5° longitude), presents also the amplitude scintillation intervals on this night, that demonstrates the concurrent occurrences of Faraday rotation angle fluctuations and the VHF amplitude scintillation. (Simultaneous Faraday rotation and amplitude scintillation measurements were carried out only since January 1983.)

Although the association between VHF scintillation events and range type spread F in the ionograms is well known [Huang, 1970; Rastogi et al., 1981; Medeiros et al., 1983], and hence we expect good correlation between the Faraday rotation angle fluctuations and range type spread F, we have tried to establish this relationships more specifically in our present data by providing in Figure 3 a statistics of the occurrences of the Faraday rotation angle fluctuations recorded at our two stations and range type spread F over one of these stations, namely, over Cachoeira Paulista, for December 1981. In Figure 3 the correlations among the occurrences of these events appear to be very good indeed. However, since GOES 3 subionospheric points for these stations (for example, 20.7°S and 50°W for the beacon reception at Cachoeira Paulista) could be 200-300 km westward of the region covered by the ionosonde at Cachoeira Paulista (and since an ionosonde is sensitive to the bottomside irregularities only), some apparently uncorrelated events are also present. The tendency for the TEC fluctuations onsets to be somewhat earlier than the range type spread F onsets, on many of the evenings, is due to eastward movements of the disturbances from longitudes westward of these stations, where they are generated on these evenings.

In Figures 2a, 2b, and 2c we have marked A, B, C, etc., and A', B', C', etc., to represent the corresponding maxima and minima points in the TEC fluctuations at the two stations. Well-defined correlation time delays between the two TEC curves can be noted, such that a given feature in the TEC fluctuations is first seen over São José dos Campos before its detection over Cachoeira Paulista after a time Δt. The same time delay was present also in the case of the associated scintillation patches observed at the two stations. We have determined this time difference, Δt, as a function of local time for all clear events registered during November and December 1981 and January 1982, when we had a reasonably good coverage of useful data. Mean time delays, $\overline{\Delta t}$, for local time intervals n to n + 1 (where n varied from 1800 LT to 0600 LT), were calculated by using the Δt values within each time interval for the entire period of study. These mean time delays were then converted to velocities by using the mean subionospheric point separation for the two stations. The local time variations in the mean velocities of the TEC fluctuations thus obtained for the summer months of 1981-1982 is presented in Figure 4. In the early postsunset hours this velocity is around 215 ms^{-1}. The velocity reaches a maximum around 2100 LT of 230 ms^{-1}, from where it monotonically decreases to around 80 ms^{-1} in the early morning hours. The standard deviations of these values for different local times together with the mean velocities are presented in Table 1. (The velocities given in Table 1 were actually calculated as mean of the individual velocities obtained from individual Δt values, whereas the mean velocities plotted in Figure 4 were obtained, as explained above, by using $\overline{\Delta t}$. The difference between them is very small indeed). Yeh et al. [1981] measured velocities of VHF scintillation producing irregularities by monitoring 257.55 MHz Marisat signals using two antennas separated by 278 m over Natal. The velocity measured on the night of March 9, 1978, is reproduced in Figure 4. It should be noted that the irregularity scale sizes observed by Yeh et al. were of the order of 800 m, whereas the scales sizes represented by the TEC fluctuations analyzed here are of much larger sizes (of a few tens of kilometers). The local time decrease in the irregularity velocity observed by Yeh et al., after 2100 LT on this night, is in excellent agreement with the behavior at these hours in our results, with an important exception that our velocities are always significantly higher than those of Yeh et al. In Figure 4 we have plotted also the eastward bulk plasma motion measured by Jicamarca radar, reproduced from the work of Fejer et al. [1981], representing the mean behavior for the 1970-1971 period, a sunspot maximum epoch (see also Woodman [1972]). Our present results refer to the descending phase of the recent sunspot maximum epoch. Fejer et al. [1981] noted that the east-west velocities did not depend much on the season, solar activity, or magnetic disturbances.

Excellent agreement is present between the local time velocity variation pattern deduced from the polarimeter data and that of the bulk plasma velocity measured by the Jicamarca radar, especially in the occurrence of the maximum around 2100 LT. The result of Yeh et al. [1981] that shows a rather faster local time decrease in the drift velocities may not in fact indicate a significant departure from our results, since it represents only one night of data as compared to the statistical mean from a large number of measurements that our results represent. The most striking feature in Figure 4 is that the velocities obtained from the TEC fluctuations are significantly higher than the bulk plasma velocities measured by the Jicamarca radar, the difference being of the order of 80-90 percent near 2100 LT decreasing to around 30 percent near 0330 LT. This difference cannot be explained by possible errors in the respective measurement techniques which are less than 10 percent in our data (caused by the reading resolution permitted by the speed of the chart paper), and about 12 ms^{-1} in the Jicamarca data [Fejer et al., 1981]. The average scintillation patch velocities determined by Aarons and Whitney [1980] for 13 nights in March 1977 over Ancon, Peru, have similar local time variation although the values are somewhat less than ours. Our velocities are also significantly higher than the eastward thermospheric neutral wind velocities over Kwajalein Atoll obtained from Fabry-Perot interferometer by Sipler et al. [1980, 1983]. However, the trends of their velocities decreasing with local time after 2100 LT are in good agreement with ours. Weber et al. [1978] have reported 6300Å airglow depletion patch drift speeds of 50-100 ms^{-1} eastward, lasting for several hours over Ascension Island. Mendillo and Baumgardner [1982] have presented local time variation of eastward drift velocities of 6300Å airglow depletion patches over Ascension Island that decreased from 190 ms^{-1} at 2100 LT to 80 ms^{-1} at 0100 LT. Though the Ascension Island measurements corresponds to nearly the same magnetic dip latitude as ours, they represent a location very much closer to the geographic equator (7.5°S) than ours (22°S). Possible implications of the differences in the eastward velocities manifested in these different results, especially the difference between our results and the results from Jicamarca radar, will be briefly discussed below.

DISCUSSION

The Faraday rotation angle (or TEC) fluctuations presented here are manifestations of plasma bubble dynamics in the equatorial ionosphere, since they are strongly correlated with range type spread F and amplitude scintillations, as shown in Figures 2c and 3. Their eastward propagation represents another known characteristic of the plasma bubble structures. The different scale sizes producing the TEC fluctuations are supposed to drift with the same east-west velocity, since they are all collocated within a plasma depletion [Tsunoda and Towle, 1979; Szuszczewicz et al., 1980; Basu et al., 1978]. We have attempted to determine the important periods in the TEC fluctuation spectra by subjecting each of the data sets in Figures 2a, 2b, and 2c to a maximum entropy spectrum analysis using filter lengths of different percentages of data points (up to 90 percent) taken at 2-min intervals. We found periodicity intervals (reasonably similar in the three data sets) as 134-165 min., 81-86 min, 43-49 min, 30-32 min, 18-24 min, and several lower periods between 8 and 20 min. The higher periods, namely, 145-165 min, must be due to the background TEC changes (data samples extending for 1 or 2 hours more than those shown in these figures were used for the analysis). The structured depletions, such as those seen from ~2100 LT to ~2150 LT and again from ~2210 LT to ~2300 LT in Figure 2b and from ~2130 LT to ~2230 LT in Figure 2c seem to correspond to the 43-49 min period interval, which is similar to the periods found by Kaushika and de Mendonça [1974] from a few 1972 data sample. From the present preliminary spectral analysis we find that plasma bubble structures to at least 70 km, representing 8-min period and assuming 150 ms^{-1} eastward drift (if we use the frozen-in concept to relate spatial behavior to temporal behavior; Yeh et al. [1981]), within depletion regions of larger east-west structures of the 43-49 min periods, or more, are detectable with the present polarimeters setup.

Before proceedings further it is worthwhile to demonstrate that the Δt that we have interpreted as representing the plasma bubble zonal velocities are not in any significant way influenced by the vertical motions important in the growth phase of a plasma bubble event. Such a possibility might be expected, since the satellite propagation paths were not aligned even approximately with the magnetic meridian of the midpoint of the two polarimeter sites, but made significant angles either eastward or westward of it. But such a possibility seems to be very remote from the following considerations:

1. The TEC depletions detected at our low-latitude locations should represent bubble structures vertically extending up to 600-700 km above the equator (namely, up to the apex of the field line connecting the low-latitude F-layer peak considering the flux tube alignment of the depletions; Tsunoda [1980], Weber et al. [1982], Abdu et al. [1983a]), and hence those that are at the end of their growth phases, when their vertical velocities are usually very small compared to the dominating eastward velocity [Tsunoda, 1981; Woodman and La Hoz, 1976].

2. The depletion magnitudes observed by the two polarimeters are nearly the same in most of the cases, whereas they could be consistently different if vertical rise velocity of a growing bubble is recorded in the two path.

3. Perhaps the most important argument in favor of the eastward velocity is the following. The presence of a vertical velocity component should be detected as eastward or westward component on satellite ray paths situated westward or eastward, respectively, of the magnetic meridian of the polarimeters. However, the velocities obtained on the Sirio beacon, namely, on an eastern path, during the summer months of 1982 (not shown here) and

those obtained from the western GOES 3 path (Figure 4) were both eastward and of approximatley the same magnitude (in fact, the velocities obtained from the Sirio path were slightly higher than those from the GOES 3 path), and had exactly the same local time variation pattern, a result that could rule out any significant vertical velocity contribution.

4. Yet another important point is the occurrence of velocity peak around 2100 LT coinciding almost exactly with the eastward velocity peak from Jicamarca radar and other measurements mentioned earlier. If vertical velocity component were important, one should expect the peak shifted toward 1900 LT, the time of the evening prereversal enhancement in the F-layer vertical drift over Fortaleza [Abdu et al., 1981], since the plasma bubble rise velocity could often be dependent on the ambient F-layer electric field as predicted from numerical modelling by Anderson and Haerendel [1979] and as experimentally deduced from ionogram analysis by Abdu et al. [1983b]. Thus we may conclude that the velocities of plasma bubble structures determined from our east-west spaced polarimeter setup do represent the zonal motion of these structures, and as mentioned earlier, it should represent the velocities at heights around 700 km over the equator. Further, since they are part of developed, or mature, and vertically extended structures, their motion, in fact, would be almost the same as that of the ambient plasma. This comes about because of the very weak vertical electric field sustained by these vertically elongated structures [Ossakow and Chaturvedi, 1978, Tsunoda et al., 1981]. Thus the zonal velocities measured by us could be taken as the zonal bulk plasma motion of the ambient plasma near the F-layer peak over the low-latitude sites, or equivalently, near 600-700 km height above the magnetic equator.

We have noted in Figure 4 that our mean zonal velocities are higher (by 80-90 percent near 2100 LT) than the plasma zonal velocities in the 300-400 km height range obtained from Jicamarca radar. Possible factors contributing to this difference will be briefly discussed below. The Jicamarca velocities refer to the previous sunspot maximum epoch (1970-1971), whereas our measurements were carried out during the early descending phase of the recent activity maximum (1981-1982). The measurements over Jicamarca during the recent activity maximum have shown individual nights of significantly larger velocities (of the order of 180 ms^{-1}; B.G. Fejer, private communication, 1984) which, however, seems inadequate to explain the difference with our mean velocities. Further, we note that the difference in the mean velocities from solar activity minimum to maximum as presented by Fejer et al. [1981] was of the order of 25 percent during the evening-premidnight hours. Another relevant point seems to be that the Jicamarca velocities were obtained for conditions without spread F irregularity generation, and it might be thought that on evening of plasma bubble occurrences the eastward ambient plasma drift could be higher than that reported by Fejer et al. Such differences, however, have not been established yet. Further, considering the meter scale irregularity eastward velocities measured by Kudeki et al. [1981], also over Jicamarca, and by Tsunoda et al. [1981] over Kwajalein, such differences seems to be very small at least in the height region of 300-400 km, and therefore seem also inadequate to explain the differences in Figure 4.

We suggest that the differences in the zonal velocities presented in Figure 4 and in the other results mentioned before, might be a manifestation of possible existence of a latitudinal variation in the zonal velocities. The equivalent picture in the equatorial plane, corresponding to such a latitudinal velocity gradient, would be a height gradient in the velocities arising from the flux tube alignment of the plasma bubble. This interpretation would seem to be consistent with the already known phenomenon of the vertical shears in the zonal plasma flow. Haerendel [1980], from analyses of vapor cloud tracers, have deduced westward plasma flow in the lower F region which reverses to eastward at higher levels (see also Heelis et al. [1974]), where radar measurements of plasma irregularities by Kudeki et al. [1981] and Tsunoda et al. [1981] have determined positive shears, velocity increasing with altitude. The eastward velocity continues to increase with altitude till around 500-600 km. The precise nature of the velocity height dependence at still higher levels is not yet known from radar measurements. In order to explain the often observed westward tilts of mature plasma bubbles [Woodman and La Hoz, 1976; Tsunoda, 1981; Weber et al., 1980; Mendillo and

Baumgardner, 1982], it seems to be necessary that the eastward ambient plasma drift should present a negative gradient at higher levels. This requirement, of course, would depend upon whether the very developments of plasma bubbles occur with a westward tilt [Tsunoda, 1983] or the tilt develops later as happens to a passive structure in the presence of an appropriate plasma flow pattern [Woodman and La Hoz, 1976]. From numerical simulation of plasma bubble development using constant eastward neutral wind and field line integrated background conductivity, Zalesak et al. [1982] obtained plasma drift profile having a positive shear up to an altitude of h_{max}, the height of maximum equatorial plane Pederson conductivity, and then a negative gradient, which according to these authors could qualitatively explain the C shapes and tilted structures seen by Woodman and La Hoz [1976] and Tsunoda [1981]. However, Anderson and Mendillo [1983] used a latitude dependent neutral wind (velocity decreasing away from the equator) in their model to obtain a negative height gradient in the eastward plasma drift (above ~550 km) required to explain the westward tilts of airglow depletion patches observed by Mendillo and Taylor [1983] and Weber et al. [1980]. The precise nature of the latitudinal distribution of the neutral wind, however, seems to be far from being understood. An important factor controlling such a distribution should be, in our view, the position of the subsolar point relative to the geographic equator and hence the season of the observation.

From the discussion above, the general consensus seems to be that the eastward velocity should be decreasing at altitude above approximately 500-600 km. Our low-latitude zonal velocities mapped on to vicinity of 700 km in the equatorial plane, therefore, should fall on the negative slope region of an eastward velocity height distribution, thus implying somewhat higher velocities at the peak of the distribution.

Our suggestion of a possible latitudinal gradient has been based largely on the comparison of our results with those of Fejer et al. [1981]. An additional justification for such a comparison comes from the fact that the positive shear in the 2000-2200 LT window obtained by comparing our velocities (interpolated on a reasonable slope down to the altitude of 500 km) with the Jicamarca results yielded a positive shear in the 350 km (mean height for the radar measurements for this case) to 550 km range of ~0.6 ms^{-1} km^{-1}, which is very reasonable compared to the velocity shear for the same local time window deduced from the results of Tsunoda et al. [1981], namely, ~0.6 ms^{-1} km^{-1} between 375 km and 600 km and ~08. ms^{-1} km^{-1} between 375 km and 500 km. The results of Kudeki et al. [1981] yielded ~1 ms^{-1} km^{-1} between 400 and 500 km, and theoretical model results by Anderson and Mendillo [1983] yielded ~0.8 ms^{-1} km^{-1} between 350 km and 500 km. The existence of such shears might explain also the higher scintillation patch velocities reported by Aarons and Whitney [1980] over Ancon, Peru, as compared to the Jicamarca velocities if we assume that the scintillation producing irregularities during those measurements might have occurred at higher levels than those sampled in the radar measurements.

CONCLUSIONS

We have shown that an east-west spaced VHF polarimeter set up over a low-latitude location can be used to determine the zonal movements of plasma bubbles and structures within them. Observations carried out during the summer months of 1981-1982 were used to determine an average nighttime variation pattern in these velocities, which compare very well with the velocities reported from different other techniques. Plasma bubble structures of the order of 70 km were observed within larger sizes of the order of 450 km or more.

Based on well-established magnetic flux tube aligned characteristics of the plasma bubbles and associated irregularities, we have projected our velocities onto magnetic equatorial apex heights of the field lines in which the low-latitude measurements were carried out. Due to the large axial ratio of these vertically extended structures, we have considered the measured velocities as representing the ambient plasma velocities at these heights. These velocities were, however, generally higher than other measurements widely cited above. By using the bulk plasma velocities measured by Jicamarca radar, over the equator, for reference (based on the reasonings explained before), the higher eastward velocities measured by our polarimeter system over 12^{o}S dip latitude have been interpreted as possible indication of a latitudinal variation in the zonal plasma flow consistent with the already known existence of vertical shears in the equatorial F region. Based on recent radar measurements [Tsunoda et al., 1981; Kudeki et al., 1981] and theoretical model results [Zalesak et al., 1982; Anderson and Mendillo, 1983] on velocity shears, we have placed our velocities on the negative slope region of the eastward velocity vertical profile, which (for explaining the often observed westward tilts of mature plasma bubbles) has a maximum in the region of 500-600 km. The positive shear flow below this maximum estimated by us, comparing our results with those of Fejer et al. [1981], yielded shears well in agreement with those observed from radars and obtained from theoretical models. Our results, however, suggest that such shear distribution in the F-layer plasma continues well past the 2000 LT window observed by radars, decreasing in intensity toward later hours. It should be emphasized that the precise nature of the latitudinal variation necessary to determine the nature of the plasma velocity shears in the equatorial ionosphere is very poorly known. Thus further verification of our suggested interpretation of the data could only be possible by more experimental investigations in the future. A carefully selected latitudinal and longitudinal polarimeter network is being planned for the near future for investigating this problem further.

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Fig. 1. Locations of the São José dos Campos and Cachoeira Paulista polarimeters relative to the geographic coordinates and isodip lines.

Fig. 2a. Tracings of the Faraday rotation angle measurements on the satellite GOES 3 VHF signals received by polarimeters at São José dos Campos (solid line) and at Cachoeira Paulista (broken line) for December 24, 1980. The corresponding phases (maxima or minima) in the Faraday rotation angle fluctuations in the two records are shown A, A', B, B', C, C', etc., for São José dos Campos and Cachoeira Paulista, respectively.

Fig. 2b. Tracings of the Faraday rotation angle records similar to Figure 2a for December 11, 1981. Note the fast fluctuation of the Faraday rotation angle is often rendered unreliable.

Fig. 2c. Tracing of the Faraday rotation angle measurements similar to Figure 2a and 2b, for January 6-7, 1983, on the beacon from satellite Sirio. Also shown, in the lower part of the figure, are the amplitude scintillation intervals. Note that the degree of the scintillation is not shown here.

Fig. 3 A statistical representation of the occurrences of Faraday rotation (TEC) fluctuations registered at São José dos Campos and Cachoeira Paulista on GOES 3 VHF beacon and range type spread F over Cachoeira Paulista for all days of December 1981, plotted as function of local time between 1800 LT and 0600 LT. The wavy solid line represents oscillation in clean TEC traces (namely, without rapid fluctuations or scintillations). The wavy dashed line represents oscillations in TEC superimposed with rapid fluctuations of small amplitude, the straight dashed line represents small-amplitude fluctuations in Faraday rotation angle without well-defined oscillations in TEC, and the straight solid line represents strong fluctuations in the Faraday rotation angle. The lowermost (solid) line for each day represents occurrence of range type spread F. The letter C represents failure of data. (Note that on December 26, the events over Cachoeira Paulista are not marked owing to uncertainty in time.).

Fig. 4. Mean eastward velocities of Faraday rotation angle fluctuations, namely, structures in plasma bubbles, presented as a function of local time, representing the summer months of 1981-1982 (triangles). Also shown are the F-region bulk plasma eastward velocities measured by Jicamarca radar [Fejer et al., 1981] (circles) and eastward velocities of VHF scintillation patches measured using closely spaced antennas over Natal [Yeh et al., 1981] (dashed line). The numbers written at the top end of the figure are those of data points used to obtain the mean velocities presented here.

TABLE 1. Mean Eastward Velocities Obtained From Spaced Polarimeter for Summer Months of 1981-1982 and Their Standard Deviations as a Function of Local Time

	Local Time								
	1900–2000	2000–2100	2100–2200	2200–2300	2300–0000	0000–0100	0100–0200	0200–0300	0300–0400
Mean Velocities ms^{-1}	219	237	234	178	176	164	126	120	90
σ ms^{-1}	33	58	39	32	50	55	26	26	13

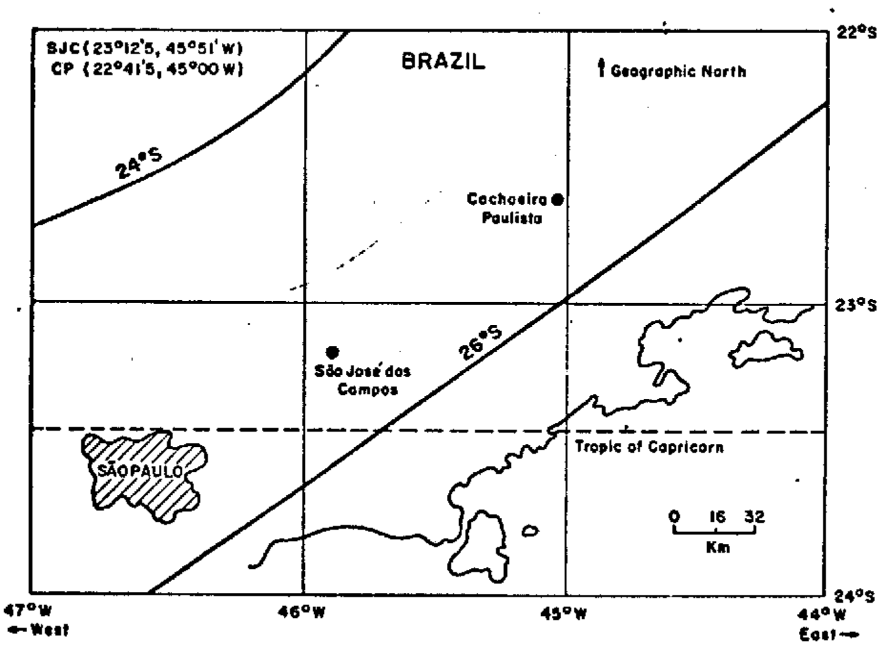
SJC (23°12'S, 45°51'W)
CP (22°41'S, 45°00 W)
BRAZIL
Geographic North
24°S
26°S
Cachoeira Paulista
São José dos Campos
SÃO PAULO
Tropic of Capricorn
0 16 32
Km
22°S
23°S
24°S
47°W
← West
46°W
45°W
44°W
East →

Fig. 1

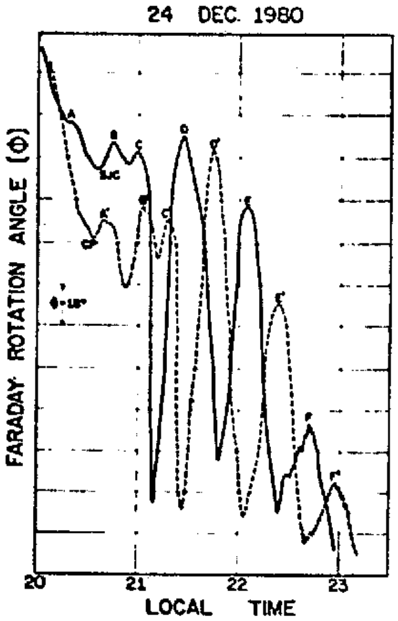
24 DEC. 1980
FARADAY ROTATION ANGLE (Φ)
LOCAL TIME
20
21
22
23
A
B
C
D
E
F
SJC
CP
K'
C'
D'
E'
F'

Fig. 2a

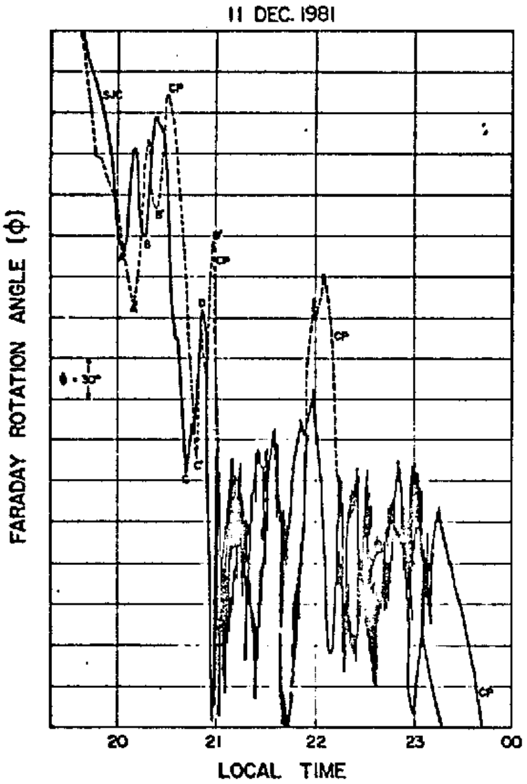
11 DEC. 1981
FARADAY ROTATION ANGLE (Φ)
Φ = 30°
SJC
CP
A
B
B'
C
C'
D
D'
20
21
22
23
00
LOCAL TIME

Fig. 2b

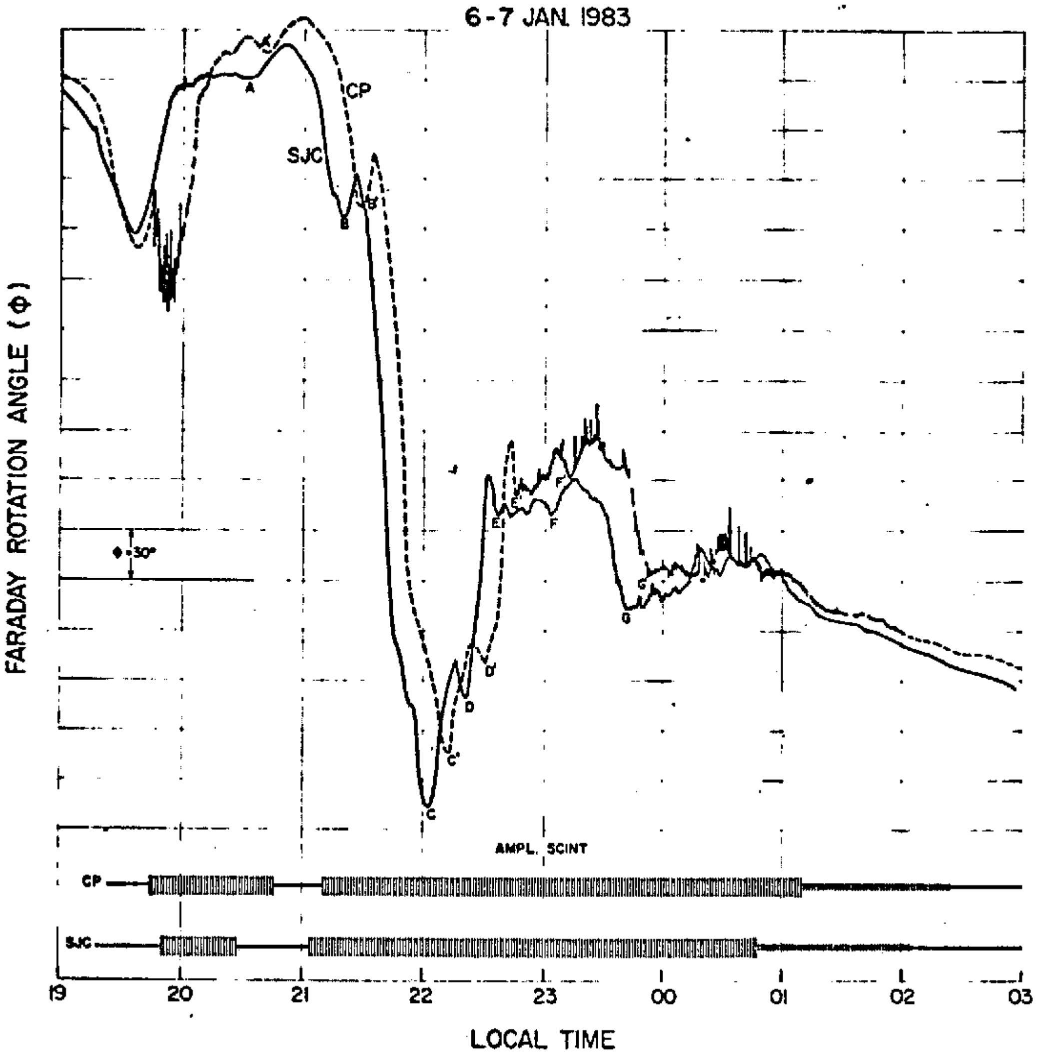
6-7 JAN. 1983
FARADAY ROTATION ANGLE (Φ)
Φ = 30°
CP
SJC
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
AMPL. SCINT
CP
SJC
19
20
21
22
23
00
01
02
03
LOCAL TIME

Fig. 2c

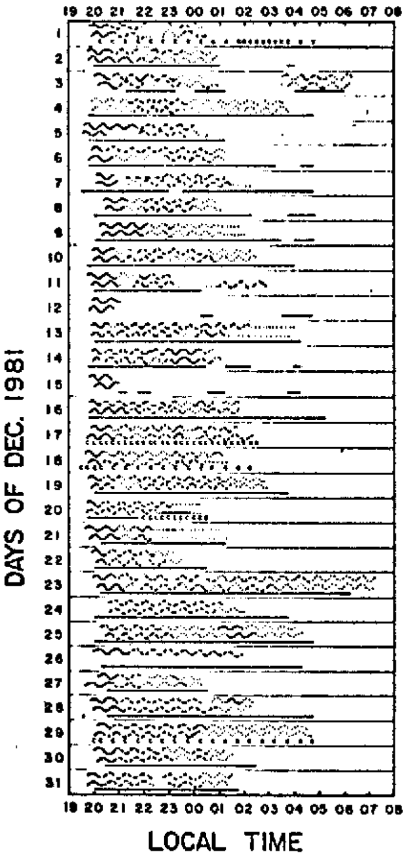
19 20 21 22 23 00 01 02 03 04 05 06 07 08
DAYS OF DEC. 1981
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
LOCAL TIME

Fig. 3

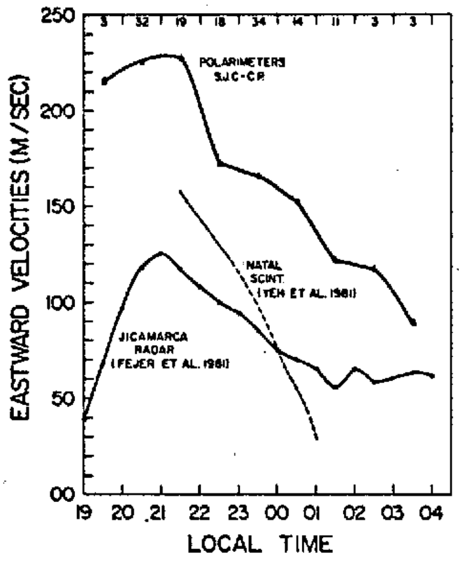
3 32 19 18 34 14 11 3 3
POLARIMETERS
SJC-CP
NATAL
SCINT.
(YEH ET AL. 1981)
JICAMARCA
RADAR
(FEJER ET AL. 1981)
EASTWARD VELOCITIES (M/SEC)
250
200
150
100
50
00
19 20 21 22 23 00 01 02 03 04
LOCAL TIME

Fig. 4