1. Publication Nº *INPE-2416-PRE/124*	2. Version *2nd**	3. Date *May, 1982*	5. Distribution ☐ Internal ☒ External ☐ Restricted
4. Origin *DGA/DII*	Program *IONOSFERA*		

6. Key words - selected by the author(s)
PLASMA BUBBLE VELOCITY
ELECTRIC FIELD
SPREAD F
IONOSONDE

7. U.D.C.: *523.4-853*

8. Title *INPE-2416-PRE/124*

SPREAD F PLASMA BUBBLE VERTICAL RISE VELOCITIES DETERMINED FROM SPACED IONOSONDE OBSERVATIONS

10. Nº of pages: *26*

11. Last page: *25*

12. Revised by

Ivan J. Kantor

9. Authorship
M.A. Abdu
R.T. de Medeiros
J.H.A. Sobral
J.A. Bittencourt

Responsible author

13. Authorized by

Nelson de Jesus Parada
Director

14. Abstract/Notes

Systematic time differences in the onsets of spread F events in the ionograms are observed between the magnetic equatorial station Fortaleza (4°S, 38°W, dip latitude 1.8°S) and the low latitude station Cachoeira Paulista (23°S, 45°W, dip latitude 14°S), two stations in Brazil, located close to a common magnetic meridional plane. On the assumption, justified from different experimental observations, that the spread F irregularities occur in strongly field aligned plasma bubbles extending several degrees on either side of the magnetic equator, we have related the observed time differences in the onsets of spread F events at the two stations, to the plasma bubble vertical rise velocities over the magnetic equator. The vertical rise velocities of the plasma bubble so determined are found to be well within the values measured by VHF radar and satellite techniques, and further show, at times, good correlation with the amplitude of the prereversal peak in the vertical drift velocities and the heights of the evening equatorial F-layer. Possible implications of these results are discussed.

15. Remarks *This work was partly supported by the "Fundo Nacional de Desenvolvimento Científico e Tecnológico" under contract FINEP-537/CT.*
This work is being submitted to JGR.
**Revised version, november 1982.*

SPREAD F PLASMA BUBBLE VERTICAL RISE VELOCITIES DETERMINED FROM SPACED IONOSONDE OBSERVATIONS

by

M.A. Abdu, R.T. de Medeiros, J.H.A. Sobral, J.A. Bittencourt

Abstract

Systematic time differences in the onsets of spread F events in the ionograms are observed between the magnetic equatorial station Fortaleza ($4^{O}S$, $38^{O}W$, dip latitude $1.8^{O}S$) and the low latitude station Cachoeira Paulista ($23^{O}S$, $45^{O}W$, dip latitude $14^{O}S$), two stations in Brazil, located at close by magnetic meridional planes (actually some 12^{O} of magnetic longitude apart). On the assumption, justified from different experimental observations, that the spread F irregularities occur in strongly field aligned plasma bubbles that extend several degrees on either side of the magnetic equator, and rise up in vertically elongated columns over the magnetic equator, we have related the observed time differences in the onsets of spread F events at the two stations, to the plasma bubble vertical rise velocities over the magnetic equator. The vertical rise velocities of the plasma bubble so determined are found to be well within the values measured by VHF radar and satellite techniques, and further show, at times, good correlation with the amplitude of the prereversal peak in the vertical drift velocities and the heights of the evening equatorial F-layer. Possible implications of these results are discussed.

INTRODUCTION

Equatorial ionospheric spread F irregularities have been investigated using HF ionosonde, VHF radars, satellite beacon scintillation techniques, airglow photometers and in-situ measurements from space vehicles. The meter scale size irregularities producing plumes in the VHF backscatter radar maps, the decameter sizes that give rise to the spread F echoes in the ionograms, and the hectometer to kilometer sizes that produce VHF and UHF radio wave scintillation are all known to coexist during,at least, the development phase of an irregularity event (Farley et al., 1970; Woodman and La Hoz, 1976; Morse et al., 1977; Basu et al., 1978; Rastogi and Woodman, 1978; Tsunoda, 1980; Tsunoda and Towle, 1979; Aarons et al., 1980). Much of our knowledge on the dynamical characteristics of these irregularities have emerged from VHF radar studies. In particular, from measurements using the ALTAIR VHF steerable radar Tsunoda (1980, 1981) and Tsunoda and Towle (1979) have shown that these irregularities are colocated within plasma density depletions or "bubbles" in the equatorial ionosphere (Hanson and Sanatani,1973; McClure et al., 1977) that occur strongly aligned along the magnetic flux tubes, extending several degrees to either side of the magnetic equator. Further evidences on the field aligned characteristics of the bubble and the associated irregularities have been provided from the AE-C ion density measurements (McClure et al., 1977), the observations of 6300 Å and 7774 Å airglow emission patches (Weber et al., 1978, 1980; Moore and Weber,1981), the all sky images and scanning measurements of 6300 Å emission (Mendillo and Baumgardner,1982; Sobral et al. 1980a, 1980b), topside sounder results (Dyson and Benson, 1978) and multistation scintillation measurements (Aarons et al., 1980).

The irregularities are generated in the equatorial ionosphere following the rapid rise of the evening F-layer (Farley et al., 1970) associated with the pre-reversal enhacement in the F-region bulk plasma vertical drift (Fejer et al., 1979; Woodman,1970; Abdu et al., 1982a).With the resulting large heights, the steep gradient region of the bottomside F-layer gets into conditions propitious for different irregularity generation mechanisms to operate.

The present consensus on the generation mechanism of the plasma bubbles is that they are generated primarily through the Rayleigh-Taylor plasma instability mechanism originally suggested by Dungey (1956) and elaborated by Haerendel (1973) and Balsley et al. (1972), and also by the gradient drift ($\underset{\sim}{E}x\underset{\sim}{B}$) instability process (Reid, 1968) operating on ionization perturbations, introduced by a seeding mechanism, at the bottomside electron density gradient region. The steep ionization gradients that develop with the formation of a bubble, subsequently provide conditions favourable for secondary plasma instability processes to operate, leading to the generation of smaller and smaller size irregularities, as described by Haerendel (1973). Begining with the generation and growth phase, the bubble nonlinearly rises up by polarization $\underset{\sim}{E}x\underset{\sim}{B}$ motion, and also drifts (mostly) westward relative to the ambient ionosphere. The associated velocities (especially the upward component) determined from numerical simulation of the Rayleigh-Taylor mechanism (Scannapieco and Ossakow, 1976; Ossakow et al.,1979) have been found to be in agreement with the velocities observed by VHF radar (Woodman and La Hoz, 1976; Tsunoda, 1980, 1981) and by the retarding potential analyzer on board tha AE-C satellite (McClure et al., 1977), which are of the order of 150 m s^{-1} upward and 60 m s^{-1} westward with large variations around these values. From numerical simulation based on the field line integrated quantities of Pedersen conductivity and ion density gradients, Anderson and Haerendel (1979) have shown that the bubble rise velocities are strongly dependent on the F-region ambient east-west electric field.

Radar mapping of the two-dimensional shape of the plasma bubbles in the equatorial plane transverse to the magnetic field has been carried out by Tsunoda (1981) and Tsunoda et al. (1982). They have shown that the plasma bubbles are vertically elongated depletions that extend upward from the bottomside of the F-layer in the form of wedges, and having well defined "head" and "neck" regions. Further they develop with their axes of depletions tilted somewhat westward of the vertical. The rise velocities were found to vary from 75 to 350 m s^{-1} (Tsunoda, 1981). As the field-aligned plasma bubble and associated irregularities rise in the equatorial ionosphere, the low latitude extremities of the bubble should propagate away from the equator in such a way that the upper height limit of the irregularities would define also the latitudinal limit of the irregularity occurrence associated with a given event. Thus the occurrence of spread F events over a low latitude station in the early hours of the post-sunset period could be produced by the poleward passage of the low latitude footprint of the head region of a developing bubble. Poleward propagating 6300 Å airglow depletion patches observed (especially in the early hours of the post sunset period) over Cachoeira Paulista by meridional scan photometers (Sobral et al., 1980a, 1980b; Nakamura et al., 1982) were found to be consistent with this picture of the plasma bubble dynamics. (It should be pointed out, however, that the low latitude spread F observed at later hours of the post sunset period could be caused also by the eastward passages of the neck regions of north-south elongated and westward tilted depletion patches corresponding to the plasma bubble generations that took place at longitudes well westward of that of the ionosonde. These cases will be excluded from considerations here since only the first onsets in the early sunset hours are analyzed).

Therefore, a certain time delay could be expected in the onset of the spread F events over a low latitude station with respect to that over an equatorial station, located in close by magnetic meridional planes, in proportion to the time plasma bubbles take to extend upward from the bottomside F-region over the magnetic equator to the apex of the field line that meets the subpeak F-region over the low latitude station. Systematic time differences in the local times of the onset of spread F events are observed between the magnetic equatorial station Fortaleza (4°S, 38°W; dip lat. 1.8°S) and the low latitude station Cachoeira Paulista (23°S, 45°W; dip lat. 14°S). In a comparative study carried out recently of the spread F occurrences at these two stations, Abdu et al. (1983) have presented evidence that suggested that the spread F irregularities observed over Cachoeira Paulista could indeed be resulting from flux tube extension of the plasma bubbles whose generation could have occurred primarily over the magnetic equator. The following additional points seem to be worth mentioning. During the months of frequent spread-F occurrences, namely, equinoctial and southern solstice months, the post-sunset spread-F onsets on most of the nights occur just before the pre-reversal maximum in the F-layer bulk plasma vertical velocity (usually from 1900 to 1930 LST, or 1830-1900 LT; see Abdu et al., 1981a and 1981b). Further, all the spread-F onsets over Cachoeira Paulista were preceded by onsets of spread F at Fortaleza (the time differences varied from a few minutes to a few tens of minutes). Many cases of spread-F over Fortaleza were not, however, accompanied by such events over Cachoeira Paulista. We have attributed this latter observation to the possibility that either plasma bubbles did not develop in these cases or the bubble rise velocity was so low that it did not rise to the apex altitude of the magnetic field line before the reversal, to downward, of the F-layer bulk plasma velocity (that usually occurs by about 2000 LST).

In this paper we have analyzed the systematic differences observed in the onset times of spread-F at these two stations, in order to deduce the plasma bubble rise velocities that best explain the observed time differences. The analysis is carried out for the months of the more frequent spread-F incidence rates,usually the equinoctial and southern solstice months,during the period starting from January 1978 to February 1980.

DETERMINATION OF THE PLASMA BUBBLE RISE VELOCITY

In considering the time differences between the onsets of spread F events at Fortaleza and Cachoeira Paulista we should keep in mind that these two stations are located at close magnetic meridional planes. Their locations are shown in Figure 1. The magnetic meridian over Cachoeira Paulista, in fact, passes through the point A at the magnetic equator as shown in the figure, which is about 12° westward in longitude from Fortaleza. Based on the considerations presented below we have assumed that the onset time of the first spread-F event on any evening, over the longitudinal range extending from Fortaleza up to the point A, and in the vicinity beyond, would be practically the same as those observed over Fortaleza.

The spread F onset usually occurs, as mentioned before, very close to the time of the prereversal peak in the F-layer vertical drift in the evening hours (see, for example, Woodman, 1970; Farley et al., 1970; Rastogi, 1978; Abdu et al., 1981a; Fejer et al., 1979), and an important factor that determines the times and widths of the prereversal peak in V_z seems to be the magnetic declination angle (Abdu et al., 1981b), which for the point A (16°W), is reasonably close to that for Fortaleza (21°W). The monthly average onset times (in local solar time) of range type spread F events read from ionograms over Fortaleza and Huancayo over the magnetic equator, and Cachoeira Paulista over low latitude, are presented in Figure 2 for the period October to February (the months of highest spread F occurrence) during 1978-79. Similar results hold also for the rest of the periods analyzed here for Fortaleza and Cachoeira Paulista (in the case of Huancayo this point has not been verified). Judging from the onset times at Fortaleza and Huancayo, on the basis of the difference in the magnetic declination angles at these sites, we do not expect any significant difference in the onset times to arise from differences in the vertical rise velocity of the F-layer at Fortaleza and the longitude of the point A. The other factors such as the F-layer base height and its electron density gradient, and the relevent neutral atmosphere parameters could be assumed to have very similar local time dependence within the longitudes covered by the two places. The spread-F occurrence over Fortaleza site on a given evening could, therefore, be taken as indication that conditions were conducive to spread-F occurrences, in the form of several successive and independent plumes in the neighbouring region along the magnetic equator as long as an atmospheric seeding source is present to cause the required initial perturbation in the ambient ionization uniformly in these regions, an assumption that is perfectly justified due, again, to the small longitudinal separation involved. Such seeding sources seem to be present regularly (on all evening) in the ionosphere over this region as our published results (and unpublished data) on spread F occurrence suggest. For instance, spread-F was present in the early hours of the post sunset period on almost all magnetically "quiet" nights of the equinoctial and southern solstice months (Abdu et al., 1981a). Further, the spread-F occurrence in 97 percent of the cases, considered throughout the year, occurred when the Rayleigh-Taylor instability condition determined from ionograms was satisfied,whereas all the cases of non-occurrences of spread-F were found to be accompanied by negative growth rate (Abdu et al., 1982b). The irregularities, causing backscatter plumes, develop as shown by Tsunoda (1981),from the west wall of an altitude modulated bottomside F-layer, presumably caused by a seeding source which might be atmospheric gravity waves (Röttger, 1978) in the presence of an eastward neutral wind (see also Fejer et al., 1981). Therefore, the precise local times of the post-sunset onset of the irregularity patches, over any site along the equator,could vary somewhat from day-to-day depending upon the phase of the atmospheric wave, in relation to the local onset times of the instability conditions, over that site. Our study on the statistics of the onset times during the spread-F season over Fortaleza (see,for example,the Figure 2 of Abdu et al., 1981a), shows that under "quiet" magnetic conditions the variation in onset times could be reasonably small (of the order of 15-30 minutes) if we consider groups of a few days, so that the mean onset times for such groups could be almost independent of longitude, at least,within the longitude region covered in the present analysis. We are, therefore, justified in assuming that the local times of spread-F onset, on an average, over the vicinity regions of point A will be practically the same as those over Fortaleza. In other words, we are justified in treating the results of spread-F at Fortaleza and Cachoeira Paulista as if these two stations were situated in close by magnetic meridional planes, especially, for determining the statistical trends, on a few-day basis, of the plasma bubble vertical rise velocities.

In the following, we will use definitions of the magnetic apex coordinate systems after VanZandt et al. (1973) to describe the parameters used for deriving the plasma bubble rise velocity. The spread F onset time at Cachoeira Paulista corresponds, according to the flux tube extension of the plasma bubble and the associated irregularities, to the time of occurrence of the irregularities at the apex of the field line meeting the base of the F-layer (h'F) over Cachoeira Paulista. We shall denote the height of the apex as P_{eq} which could vary, of course, depending upon the h'F over Cachoeira Paulista. It would be of the order of 600 km for an h'F of 250 km which we have found to be the approximate average value in the post-sunset hours. Since the irregularities rise in the equatorial ionosphere with an associated eastward (in the corotating frame) velocity, the irregularities that occur at P_{eq}, are, in fact, those that had their onset at the base of the F-region somewhat westward of the point A, namely, over the point marked C in Figure 1. Thus the time required for the irregularities to propagate from their onset region over the point C, to P_{eq}, should be the same as the time that elapses between the onset of spread F over the point C and that over Cachoeira Paulista (both times being referred to a common reference longitude). We shall denote this elapsed time as Δt. Based on the discussion in the previous paragraph we can assume that the local times of the spread F onset over the point C are the same as those over Fortaleza. Thus, we can show that:

$$\Delta t = (t_{oCP} - t_{oFz} - T_{\Delta L})/(1 + 2.14 \times 10^{-3} V_x),$$

where t_{oCP} and t_{oFz} are the local solar times of spread F onsets over Cachoeira Paulista and Fortaleza respectively, $T_{\Delta L}$ is the local solar time difference between Cachoeira Paulista and the longitude of A, V_x is the eastward velocity, in m s^{-1}, of the plasma bubble, and the factor 2.14×10^{-3} represents the change of local time, in seconds, per unit longitudinal distance.

The vertical bubble rise velocity, V_B, is then determined knowing the virtual height of the F-layer base at the onset of the spread F in the ionograms of Fortaleza, or, over the point C, (denoted as the height hF_{oe}) at which the bubble starts getting formed with associated vertical growth. The apex height at which the plasma bubble will be located at the end of the time Δt, was then determined from the h'F at the onset of the spread F over Cachoeira Paulista with the help of magnetic B-L charts representing the field lines as functions of altitude and latitude, prepared by Harrison et al. (1963). Thus the vertical rise velocity of the bubble, V_B, will be given by:

$$V_B = (P_{eq} - hF_{oe})/\Delta t$$

Value of V_B was calculated for each day during the months of January and February 1978, October 1978 to February 1979 and October 1979 to February 1980, since these are the months when spread F occurrence had highest frequency during the interval considered. In general, the individual V_B values present large scatter, varying from a few m sec^{-1} up to a few hundreds of m sec^{-1}. Therefore, ten-day running means ($\overline{V}_B$) were calculated during each of these periods and the results for January and February 1978 are presented in Figure 3. These mean values (and even most of the individual values, though not shown here) are well within the bubble vertical velocities obtained previously from different techniques (see, for example, Woodman and La Hoz, 1976; McClure et al., 1977; Ossakow et al., 1979; Tsunoda, 1981; Nakamura, 1981). In Figure 3 we have plotted also 10-day running means of the amplitudes of the prereversal peaks (denoted by $\overline{V}_{zp}$) of the evening F-layer vertical velocities calculated as d(h'F)/dt (Bittencourt and Abdu, 1981; and Abdu et al., 1981b). It may be noted that a good degree of correlation between the bubble rise velocities and the bulk plasma velocities is evident in the mean trends of these parameters. The h'F values, obtained from ionograms over Fortaleza, are also plotted in the same figure. The gross characteristics seen in this figure are that the bubble velocity is small (or large) when the $\overline{V}_{zp}$ is small (or large), and both the parameters vary roughly in phase with the $\overline{h'F}$

values. Results for October 1978 to February 1979 and for October 1979 to February 1980 are presented in Figures 4 and 5. The correlation among the three parameters seems to be poor for most part of the interval shown in Figure 4. But trends suggesting varying degrees of positive relationship between $\overline{V}_B$ and the other two parameters are evident in the results presented in Figure 5, during October and a major part of November 1979, and for February 1980. It is interesting to note that during most part of the intervals in all these figures (3, 4 and 5) there seems to be present a consistent tendency for a good correlation between variations in $\overline{V}_{zp}$ and $\overline{h'F}$ over Fortaleza.

DISCUSSION

The individual V_B values obtained from the present analysis could have large uncertainty at times, due to the fact that the corresponding Δt was determined from ionosonde observations that are taken simultaneously both at Fortaleza and Cachoeira Paulista, but at 15 minutes intervals. The onset of a spread F event could have actually taken place before its detection in the ionogram. Thus, Δt values that are close to 15 minutes could have large errors, whereas the error will decrease for higher Δt values. Consequently, the scatter will be higher for higher V_B values and smaller for smaller V_B values. We have estimated that the individual velocities of the order of 300 m s^{-1} could be in error by as much as 100 percent, whereas the error would be 10 percent only for the velocities of the order of 30 m s^{-1}. However, if we assume that the distribution function of the occurrence of spread F onset times, before their detection in the ionograms, are the same for two stations, the error in Δt is expected to be small when the mean of a large number of Δt's are considered and hence also in the $\overline{V}_B$ values obtained as the running mean of several points (ten in the present case). Thus, the $\overline{V}_B$ values presented in Figures 3, 4 and 5 seem to be reliable since they fall also within the values for the bubble rise velocities measured by back-scatter radar (Woodman and La Hoz, 1976; Tsunoda, 1980, 1981) by satellites (McClure et al., 1977), from airglow photometer techniques (Nakamura et al., 1982; Weber et al., 1980) and those predicted from theoretical modelling (Ossakow et al., 1979; Anderson and Haerendel, 1979). Another possible error could be due to variations in the eastward velocity, V_x, which we have taken as 100 m s^{-1} in all our calculations. A 100 percent change in V_x could introduce about 20 percent error in the individual V_B values. Another source of systematic error that could cause significant scatter in the individual values mentioned above, is related to the fact that the ionosondes are so widely separated that they are not monitoring the progress of individual bubble but only the first appearence of any bubble induced signature at the two locations. For reasons mentioned before the error due to this factor should be insignificant in the mean trends, obtained by taking the running means, of the bubble velocities.

In analyzing the relationship between $\overline{V}_B$ and $\overline{V}_{zp}$ we should consider the diverse factors that control the plasma bubble generation and its subsequent vertical growth velocities. From theoretical modelling, taking into account field line integrated plasma properties, Anderson and Haerendel (1979) showed that the bubble rise velocities are in general always small (or large) when the F region ambient electric field or the $\underset{\sim}{E}\times\underset{\sim}{B}$ vertical drift velocity is small (or large). Our results in Figure 3 and in parts of Figures 4 and 5, showing positive relationship between $\overline{V}_B$ and $\overline{V}_{zp}$, is in good agreement with these results of Anderson and Haerendel (1979). VHF radar measurements by Tsunoda (1981) has shown a decrease in the plume rise velocity towards the end of a bubble development phase which might be caused by a similar decrease in the bulk plasma vertical motion at those times. The bubble generation and vertical growth, according to the Rayleigh-Taylor mechanism, depend also upon the presence of an initial perturbation in the ionization, ion-neutral collision frequency and the ionization gradient at the base of the F-layer. Two-dimensional simulation of the collisional Rayleigh-Taylor mechanism by Ossakow et al. (1979) has shown strong dependence of the ionization depletion in the bubble,and consequently of the bubble rise velocity, on the height of the F-layer (arising from the upward decrease in the ion-neutral collision frequency), which is in agreement with the positive relationship between $\overline{V}_B$ and $\overline{h'F}$ observed in parts of the present results. If the degree of the depletion in the bubble is a measure of the spread-F irregularity strength, then the recent results (Abdu et al., 1982a), showing a positive correlation between V_{zp} and range type spread F indices in the post sunset hours, seems to be a complementary evidence supporting the positive relationship between $\overline{V}_B$ and $\overline{V}_{zp}$ obtained from the present analysis. The in-phase variations in $\overline{V}_B$, $\overline{V}_{zp}$ and $\overline{h'F}$, present in part of our results, in fact, suggest that the east-west F-region ambient electric field influences the bubble rise velocity in two ways: (a) through polarization changes resulting from the difference in the conductivity between the bubble and its vicinity regions, in the presence of the ambient electric field (Anderson and Haerendel, 1979); and (b) through changes in the ion-neutral collision frequency at F layer heights (Ossakow et al., 1979) when variations in these heights are produced by the ambient electric field.

The good degree of correlation that is present among $\overline{V}_B$, $\overline{V}_{zp}$ and $\overline{h}$'F, though restricted to some periods only, could be explained as due to the dominating influence of the F-region ambient east-west electric field in the bubble development phase. The absence of any significant correlation seen on many other occasions, therefore, seems to warrant a discussion in terms of the other different parameters that also control, or influence, the bubble development. It should be noted that the dominating influence of an F-region ambient electric field could be identified through a positive correlation between $\overline{V}_B$ and $\overline{V}_{zp}$ only because variations in the other controlling factors were not sufficient to mask this influence. One of the most important of these factors seems to be the amplitude of the initial perturbations in the ambient ionization upon which the instability processes operate. Two-dimensional numerical simulation of the collisional Rayleigh-Taylor instability mechanism, of the type carried out by Ossakow et al. (1979) has been used by Nakamura (1981) to study the bubble height and rise velocity characteristics as a function of the amplitude of the initial perturbations, and the results show strong dependence between them. In a typical calculation (Nakamura, 1981),an initial perturbation of one percent of the ambient ion density gave rise to a bubble vertical velocity of 60 m s^{-1} at a height of 340 km, whereas an initial perturbation of 10 percent resulted in a velocity of 170 m s^{-1} at a height of 400 km, at the end of 700 s from the onset of the instability process in both cases. Therefore, variabilities in the factors that determine the amplitude of the initial perturbations, such as possibly a gravity wave spectrum that could be regularly present in the evening equatorial ionosphere (Röttger, 1978; Booker, 1979) should be sufficient to mask any possible dependence of the plasma bubble rise velocity on the F-region ambient electric field. Variations in the ionization gradient scale length at the F-layer base, variations in eastward neutral winds and changes in the ion-neutral collision frequency (caused by magnetic activity, for example) are the other factors that could contribute to ambiguous relationships of $\overline{V}_B$ with $\overline{V}_{zp}$ and $\overline{h'F}$. Detailed investigation into these different problems is beyond the scope of the present work, which has its main purpose to demonstrate that reasonable estimates of the plasma bubble rise velocities in the equatorial ionosphere could be achieved from simultaneous observations of spread F events by spaced ionosondes located, preferably, along or in the vicinity of a common magnetic meridional plane, covering the magnetic equator and low latitudes.

CONCLUSIONS

We have analyzed the systematic differences in times of the first onsets of the range type spread F, in the post sunset period, observed over the equatorial station, Fortaleza, and over the low latitude station, Cachoeira Paulista, to determine the equatorial plasma bubble rise velocities. The derivation of the individual velocities, as referred to a selected bubble event, has involved some assumptions on the physical and dynamical bubble characteristics, that are realistic and based on the well-known results from VHF radar observations, airglow and satellite measurements, widely cited above, and on the comparative studies of spread F statistics over the two stations, carried out by us recently.

The irregularities giving rise to range type spread F in the ionograms have their onset usually in the early hours of the post sunset period. They constitute part of the wide spectrum of the irregularities, from meter to kilometer sizes, that is generated during an equatorial plasma bubble event. The generation of the bubble and the associated irregularities occur simultaneously along magnetic flux tube, extending several degrees to either side of the equator. The depleted regions rise up over the equator in elongated columns extending upward from the bottomside F-layer in the form of westward tilted wedges as described by Tsunoda et al. (1982). The field line footprint of the "head" region of the bubble, during its resulting poleward motion, causes spread F events over low latitudes sites, which could account for (at least) the first spread F events occuring in the early sunset period over low latitude. If a spread F event in the equatorial ionosphere is not associated with a growing bubble event then, according to this picture, no spread F will be observed over low latitude sites.

Hence,the time delay observed in the onsets of spread F events was attributed to the time that plasma bubble takes, from its development at the bottomside F-layer, to rise up to the apex of the magnetic field line linking the low latitude F-layer base. The rise velocity of a selected bubble, derived in this way, has significant dispersion due, mainly, to the longitudinal separation of the two stations and to some extent to the 15-minutes time resolution used in the measurement. The dispersion in the derived velocities from these factors are, however, significantly reduced in the running means of the velocities, as evident from the excellent agreement obtained with the bubble rise velocities determined from several other different techniques (cited before), and from the very good correlation observed, on many occasions, with the pre-reversal peak in the F-layer bulk plasma vertical drift. The latter point also corroborate the theoretically expected dependence of the bubble rise velocity on the ambient F-region electric field shown by Anderson and Haerendel (1979). Possible causes for not observing such a correlation on many other occasions have been discussed. Better precision and confidence in the individual bubble velocities could be achieved from observations taken with better time resolution, say every 1 to 5 minutes, and operating the ionosondes closer to a common magnetic meridional plane than is done at present. Such studies are being planned for the near future.

ACKNOWLEDGEMENTS

The authors wish to thank B.G. Fejer for his helpful comments on the original manuscript.

This work was partially supported by the "Fundo Nacional de Desenvolvimento Científico e Tecnológico" under Contract FINEP-537-CT.

FIGURE CAPTIONS

Figure 1 - Locations of the ionosonde stations, Fortaleza and Cachoeira Paulista, relative to the magnetic and geographic equators. Dip latitudes at $20^{o}S$ and $30^{o}S$ are shown. Also shown are the geographic and magnetic meridians over Cachoeira Paulista and their intersections with the magnetic equator (see the text for further details).

Figure 2 - Monthly mean spread F onset times in local solar times plotted during October 1978 to February 1979, for Fortaleza (——), Huancayo (----) and Cachoeira Paulista (....).

Figure 3 - Ten-day running means of the vertical bubble rise velocity $\overline{V}_B$, for January and February 1978, plotted together with the corresponding running mean values of the amplitudes of the prereversal enhancements in the F-layer vertical rise velocities in the evening hours, $\overline{V}_{zp}$, and with those of the heights of the base of the F-layer $\overline{h'F}$.

Figure 4 - Same parameters as in Figure 3, plotted for October, November and December, 1978,and for January and February, 1979.

Figure 5 - Same parameters as in Figure 3 and 4, plotted for October, November and December, 1979, and for January and February, 1980.

REFERENCES

Aarons, J., J.P. Mullen, J.R. Koster, R.F. da Silva, J.R. Medeiros, R.T. Medeiros, A. Bushpy, J. Pantoja, J. Lanai, and M.R. Paulson, Seasonal and geomagnetic control of equatorial scintillations in two longitudinal sectors, J. Atmos. Terr. Phys., 42, 861-866, 1980.

Abdu, M.A., I.S. Batista, and J.A. Bittencourt, Some characteristics of spread F at magnetic equatorial station Fortaleza, J. Geophys. Res., 86, 6836, 1981a

Abdu, M.A., J.A. Bittencourt, and I.S. Batista, Magnetic declination control of the equatorial F region dynamo electric field development and spread F, J. Geophys. Res., 86, 11443-11446, 1981b.

Abdu, M.A., R.T. de Medeiros, J.A. Bittencourt and I.S. Batista, vertical ionization drift velocities and range type spread F in the evening equatorial ionosphere, J. Geophys. Res., in press, 1982a.

Abdu, M.A., R.T. de Medeiros and J.H.A. Sobral, Equatorial spread F instability conditions as determined from ionograms, Geophys. Res. Lett., 9, 692-695, 1982b.

Abdu, M.A., R.T. Medeiros, and Y. Nakamura, Latitudinal and flux tube extension on the equatorial spread F irregularities, J. Geophys. Res., in press ,1983.

Anderson, D.N., and G. Haerendel, The motion of depleted plasma regions in the equatorial ionosphere, J. Geophys. Res., 84, 4251-4256, 1979.

Balsley, B.B., G. Haerendel, and R.A. Greenwald, Equatorial spread F: recent observations and a new interpretation, J. Geophys. Res., 77, 5625-5628, 1972.

Basu, S., J. Aarons, J. P. McClure, and M.D. Cousins, On the coexistence of kilometer and meter-scale irregularities in the nighttime equatorial F-region, J. Atmos. Terr. Phys., 83, 3219-4226, 1978.

Bittencourt, J.A., and M.A. Abdu, A theoretical comparison between apparent and real vertical ionization drift velocities in the equatorial F-region, J. Geophys. Res., 86, 2451-2454, 1981.

Booker, H.G., The role of acoustic gravity waves in the generation of spread F and ionospheric scintillations, J. Atmos. Terr. Phys., 41, 501-515, 1979.

Dungey, J.W. Convective diffusion in the equatorial F-region, J. Atmos. Terr. Phys., 9, 304-310, 1956.

Dyson, P.L. and R.I. Benson, Topside sounder observation of equatorial bubbles, Geophys. Res. Lett., 5, 795-798, 1978.

Farley, D.T., B.B. Balsley, R.F. Woodman, and J.P. McClure, Equatorial spread F: implications on VHF radar observations, J. Geophys. Res., 75, 7199-7216, 1970.

Fejer, B.G., D.T. Farley, R.F. Woodman, and C. Calderon, Dependence of equatorial F region vertical drifts on season and solar cycle, J. Geophys. Res., 84, 5792-5796, 1979.

Fejer, B.G., D.T. Farley, C.E. Gonzalez, R.F. Woodman and C. Calderon, F region east-west drifts at Jicamarca, J. Geophys. Res., 86, 9087, 1981.

Haerendel, G., Theory of equatorial spread F, report, Max Plank, Inst. für Phys. und Astrophys., Munich, 1973.

Hanson, W.B., and S. Sanatani, Large Ni gradients below the equatorial F2-peak, J. Geophys. Res., 78, 1167-1173, 1973.

Harrison, R.E., K.W. Hubbard, F.L. Keller and J.I. Vette, Plots of constant B and constant L for various longitudes, Aerospace Corp., report nº TDR-169(3510)-TR 4, El Segundo, California, 1963.

McClure, J.P., W.B. Hanson, and J.F. Hoffman, Plasma bubbles and irregularities in the equatorial ionosphere, J. Geophys. Res., 82, 2650-2656, 1977.

Mendillo, M. and J. Baumgardner, Airglow characteristics of equatorial plasma depletions, J. Geophys. Res., 87, 7641, 1982.

Moore, J.G. and E.J. Weber, OI 6300 and 7774 Å airglow measurements of equatorial plasma depletions, J. Atmos. Terr. Phys., 43, 851, 1981.

Morse, F.A., B.C. Edgar, H.C. Koons, C.J. Rita, W.J. Heikkila, J.H. Hoffman, B.A. Tinsley, J.D. Winningham, A.B. Christensen, R.F. Woodman, J. Pomalaza, and N.R. Teixeira, Equion: an equatorial ionospheric irregularity experiment, J. Geophys. Res., 82, 578-592, 1977.

Nakamura, Y., J.H.A. Sobral and M.A. Abdu, A simulation of equatorial plasma bubble signatures on the OI 6300 Å nightglow meridional profile over Brazilian low latitude, submitted for publication in J. Geophys. Res., 1982.

Nakamura, Y., Irregularities ionosféricas em baixas latitudes no setor americano, Doctor Thesis, Instituto de Pesquisas Espaciais, INPE-2243-TDL/065, S.J.Campos, Brazil, 1981.

Ossakow, S.L., S.T. Zalesak, B.E. McDonald, and P.K. Chaturvedi, Nonlinear equatorial spread F: dependence on altitude of the peak and bottomside electron density gradient scale length, J. Geophys. Res., 84, 17-29, 1979.

Rastogi, R.G., On the equatorial spread F, Proc. Indian Acad. Sci., 87A, 115-131, 1978.

Rastogi, R.G., and R.F. Woodman, VHF radio wave scattering due to range and frequency types of equatorial spread F, J. Atmos. Terr. Phys., 40. 485-491, 1978.

Reid, G.C., The formation os small-scale irregularities in the ionosphere, J. Geophys. Res., 73, 1627-1640, 1968.

Röttger, J., Drifting patches of equatorial spread F irregularities: experimental support for the spatial resonance mechanism in the ionosphere, J. Atmos. Phys., 40, 1093-1102, 1978.

Scannapieco, A.J., and S.L. Ossakow, Nonlinear equatorial spread F, Geophys. Res. Letters., 3, 451-454, 1976.

Sobral, J.H.A., M.A. Abdu, and I.S. Batista, Airglow studies on the ionosphere dynamics over low latitude in Brazil, Ann. Geophys., 36, 199-204, 1980a.

Sobral, J.H.A., M.A. Abdu, C.J. Zamlutti, I.S. Batista, Association between plasma-bubble irregularities and airglow disturbances over Brazilian low latitude, Geophys. Res. Letters., 7, 980-982, 1980b.

Tsunoda, R.T., Magnetic field aligned characteristics of plasma bubbles in the nighttime equatorial ionosphere, J. Atmos. Terr. Phys., 42, 743-752, 1980.

Tsunoda, R.T. and D.M. Towle, On the spatial relationship of 1-meter equatorial spread F irregularities and depletions in total electron content, Geophys. Res. Letters, 6, 873, 1979-

Tsunoda, R.T., Time evolution and dynamics of equatorial backscatter plumes-1. Growth phase, J. Geophys. Res., 86, 139, 1981.

Tsunoda, R.T., R.C. Livingston, J.P. McClure and W.B. Hanson, Equatorial plasma bubbles: vertically-elongated wedges from the bottomside F-layer, J. Geophys. Res., 87, 9176, 1982.

Vanzandt, T.E., W.L. Clark, and J.M. Warnock, Magnetic apex coordinates: A magnetic coordinate system for the ionospheric F_2 layer, J. Geophys. Res., 77, 2406-2411, 1972.

Weber, E.J., J. Buchau, R.H. Eather, and S.B. Mende, North-south aligned equatorial airglow depletions, J. Geophys. Res., 83, 712-716, 1978.

Weber, E.J., J. Buchau, and J.G. Moore, Airborne studies of equatorial F-layer ionosphere irregularities, J. Geophys. Res., 85, 4631-4641, 1980.

Woodman, R.F., Vertical drift velocities and east-west electric fields at the magnetic equator, J. Geophys. Res., 75, 6249, 1970.

Woodman, R.F., and C. La Hoz, Radar observations of F region equatorial irregularities, J. Geophys, Res., 81, 5447-5466, 1976.

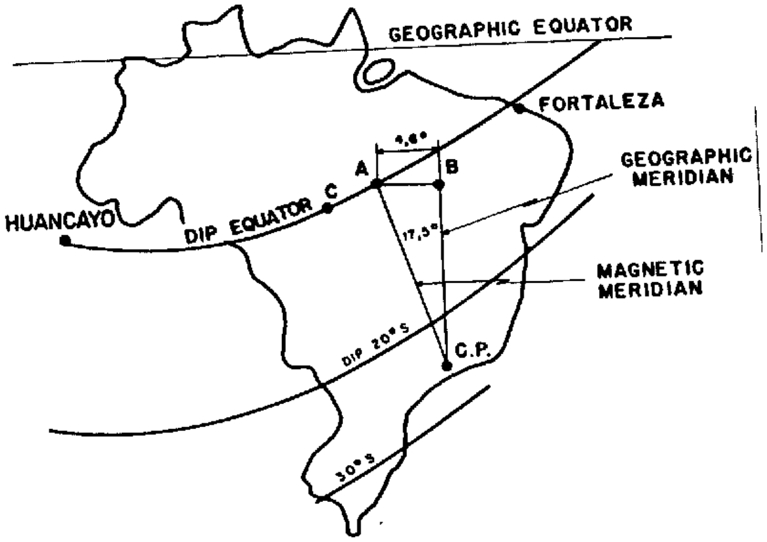
GEOGRAPHIC EQUATOR
FORTALEZA
4,6°
A
B
GEOGRAPHIC MERIDIAN
HUANCAYO
DIP EQUATOR
C
17,5°
MAGNETIC MERIDIAN
DIP 20° S
C.P.
30° S

Fig. 1

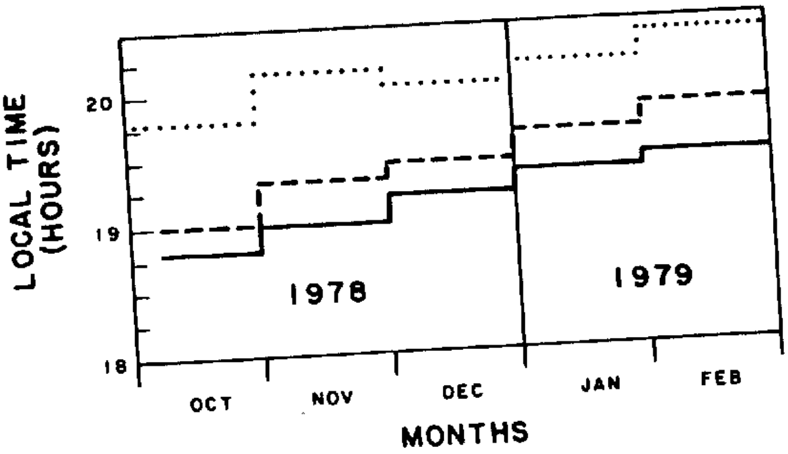

Fig. 2

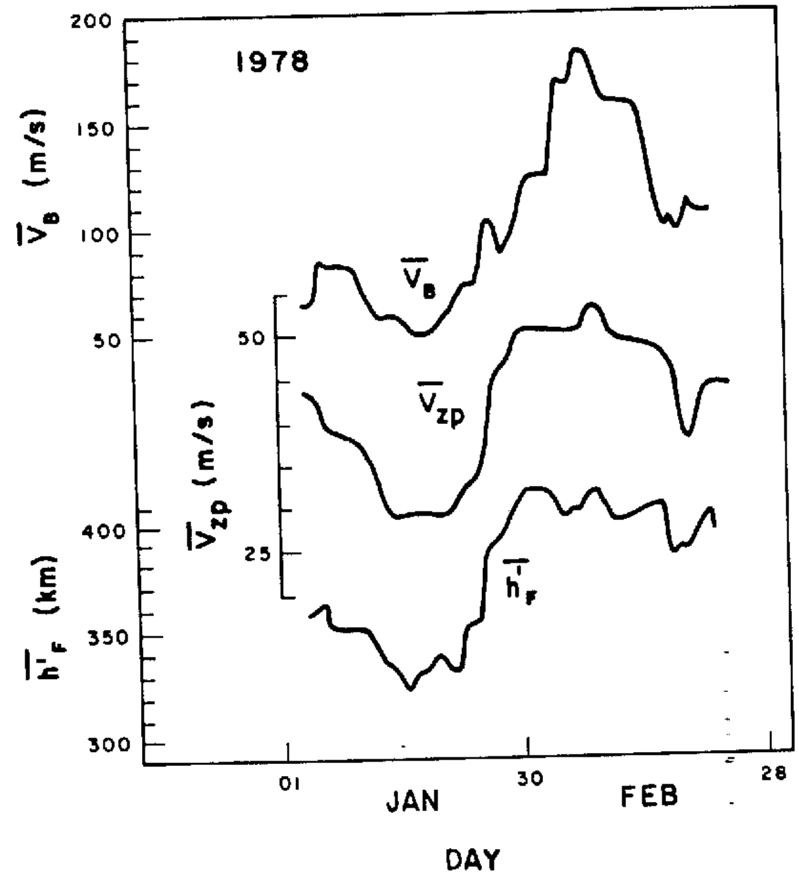
1978
200
150
100
50
$\overline{V}_B$ (m/s)
$\overline{V}_B$
50
25
$\overline{V}_{zp}$ (m/s)
$\overline{V}_{zp}$
400
350
300
$\overline{h'_F}$ (km)
$\overline{h'_F}$
01
30
28
JAN
FEB
DAY

Fig. 3

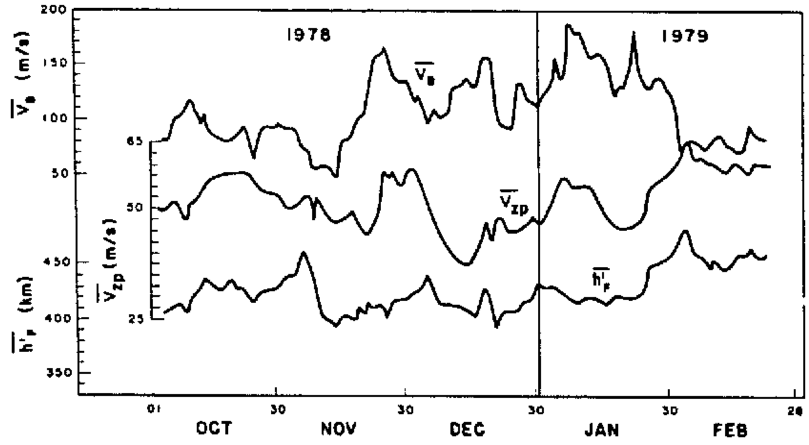
$\overline{V_s}$ (m/s)
200
150
100
50
$\overline{V_{zp}}$ (m/s)
65
50
25
$\overline{h'_F}$ (km)
450
400
350
1978
1979
$\overline{V_s}$
$\overline{V_{zp}}$
$\overline{h'_F}$
01
30
30
30
30
28
OCT
NOV
DEC
JAN
FEB

Fig. 4

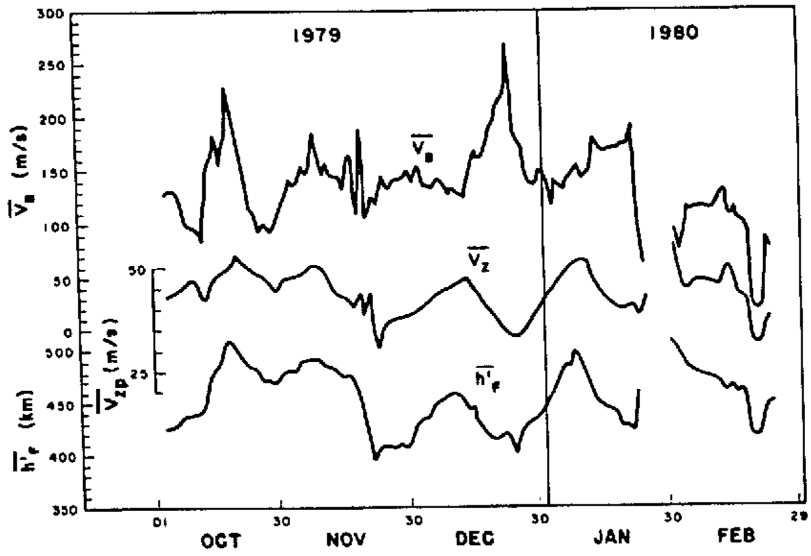
300
250
200
150
100
50
0
500
450
400
350
$\overline{V_B}$ (m/s)
$\overline{h'_F}$ (km)
50
25
$\overline{V_{ZP}}$ (m/s)
1979
1980
$\overline{V_B}$
$\overline{V_Z}$
$\overline{h'_F}$
01
30
30
30
30
29
OCT
NOV
DEC
JAN
FEB

Fig. 5

MFN= 002258
01 SID/SCD
02 2416
03 INPE-2416
04 CEA
05 S
06 as
10 Abdu, Mangalathayil Ali
10 Mediros, Rui Tertuliano
10 Sobral, José Humberto Andrade
10 Bittencourt, José Augusto
12 Spread F plasma bubble vertical rise velocities determined from spaced ionosonde observations

14 000
30 Journal of Geophysical Research
31 88
32 A11
40 En
41 En
42 <E>
58 DAE
59 903108
61 <PI>
64 Nov. <1983>
68 PRE
76 AERONOMIA
83 Systematic time differences in the onsets of spread F events in the ionograms are observed between the magnetic equatorial station Fortaleza (4 degree S, 38 degree W, dip latitude 1.8 degree S) and the low-latitude station Cachoeira Paulista (23 degree S, 45 degree W, dip latitude 14 degree S), two stations in Brazil, located at close-by magnetic meridional planes (actually some 12 degree of magnetic longitude apart). On the assumption, justified from different experimental observations, that the spread F irregularities occur in strongly field-aligned plasma bubbles that extend several degrees on either side of the magnetic equator, and rise up in vertically elongated columns over the magnetic equator, we have related the observed time differences in the onsets of spread F events at the two stations to the plasma bubble vertical rise velocities over the magnetic equator. The vertical rise velocities of the plasma bubble so determined are found to be well within the values measured by VHF radar and satellite techniques, and further show, at times, good correlations with the amplitude of the prereversal peak in the vertical drift velocities and the heights of the evening equatorial F layer. Possible implications of these results are discussed.
87 ionosonda
87 sondas ionosféricas
87 bolhas de plasma
87 propagação F
87 densidade dp plasma
88 ionosonds
88 plasma bubbles
88 spread F
88 plasma density
91 8311

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. A11, PAGES 9197-9204, NOVEMBER 1, 1983

SPREAD F PLASMA BUBBLE VERTICAL RISE VELOCITIES DETERMINED FROM SPACED IONOSONDE OBSERVATIONS

M. A. Abdu, R. T. de Medeiros[1], J. H. A. Sobral, and J. A. Bittencourt

Instituto de Pesquisas Espaciais, Conselho Nacional de
Desenvolvimento Científico e Tecnológico

Abstract. Systematic time differences in the onsets of spread F events in the ionograms are observed between the magnetic equatorial station Fortaleza (4°S, 38°W, dip latitude 1.8°S) and the low-latitude station Cachoeira Paulista (23°S, 45°W, dip latitude 14°S), two stations in Brazil, located at close-by magnetic meridional planes (actually some 12° of magnetic longitude apart). On the assumption, justified from different experimental observations, that the spread F irregularities occur in strongly field-aligned plasma bubbles that extend several degrees on either side of the magnetic equator, and rise up in vertically elongated columns over the magnetic equator, we have related the observed time differences in the onsets of spread F events at the two stations to the plasma bubble vertical rise velocities over the magnetic equator. The vertical rise velocities of the plasma bubble so determined are found to be well within the values measured by VHF radar and satellite techniques, and further show, at times, good correlations with the amplitude of the prereversal peak in the vertical drift velocities and the heights of the evening equatorial F layer. Possible implications of these results are discussed.

Introduction

Equatorial ionospheric spread F irregularities have been investigated using HF ionosondes, VHF radars, satellite beacon scintillation techniques, airglow photometers and in situ measurements from space vehicles. The meter scale size irregularities producing plumes in the VHF backscatter radar maps, the decameter sizes that give rise to the spread F echoes in the ionograms, and the hectometer to kilometer sizes that produce VHF and UHF radio wave scintillation are all known to coexist during, at least, the development phase of an irregularity event [Farley et al., 1970; Woodman and La Hoz, 1976; Morse et al., 1977; Basu et al., 1978; Rastogi and Woodman, 1978; Tsunoda, 1980; Tsunoda and Towle, 1979; Aarons et al., 1980]. Much of our knowledge of the dynamical characteristics of these irregularities has emerged from VHF radar studies. In particular, from measurements using the ALTAIR VHF steerable radar, Tsunoda [1980, 1981] and Tsunoda and Towle [1979] have shown that these irregularities are colocated within plasma density depletions or "bubbles" in the equatorial ionosphere [Hanson and Sanatani, 1973; McClure et al., 1977] that occur strongly aligned along the magnetic flux tubes, extending several degrees to either side of the magnetic equator. Further evidence of the field-aligned characteristics of the bubble and the associated irregularities has been provided from the AE-C ion density measurements [McClure et al., 1977], the observations of 6300-Å and 7774-Å airglow emission patches [Weber et al., 1978, 1980; Moore and Weber, 1981], the all-sky images and scanning measurements of 6300-Å emission [Mendillo and Baumgardner, 1982; Sobral et al., 1980a, b], topside sounder results [Dyson and Benson, 1978], and multistation scintillation measurements [Aarons et al., 1980].

The irregularities are generated in the equatorial ionosphere following the rapid rise of the evening F layer [Farley et al., 1970] associated with the prereversal enhancement in the F region bulk plasma vertical drift [Fejer et al., 1979; Woodman, 1970; Abdu et al., 1983a]. With the resulting large heights, the steep gradient region of the bottomside F layer undergoes conditions propitious for different irregularity generation mechanisms to operate.

The present consensus on the generation mechanism of the plasma bubbles is that they are generated primarily through the Rayleigh-Taylor plasma instability mechanism originally suggested by Dungey [1956] and elaborated by Haerendel [1973] and Balsley et al. [1972], and also by the gradient drift (ExB) instability process [Reid, 1968] operating on ionization perturbations, introduced by a seeding mechanism, at the bottomside electron density gradient region. The steep ionization gradients that develop with the formation of a bubble subsequently provide conditions favorable for secondary plasma instability processes to operate, leading to the generation of smaller and smaller size irregularities, as described by Haerendel [1973]. Begining with the generation and growth phase, the bubble nonlinearly rises up by polarization ExB motion, and also drifts (mostly) westward relative to the ambient ionosphere. The associated velocities (especially the upward component) determined from numerical simulation of the Rayleigh-Taylor mechanism [Scannapieco and Ossakow, 1976; Ossakow et al., 1979] have been found to be in agreement with the velocities observed by VHF radar [Woodman and La Hoz, 1976; Tsunoda, 1980, 1981] and by the retarding potential analyzer on board the AE-C satellite [McClure et al., 1977], which are of the order of 150 m s^{-1} upward and 60 m s^{-1} westward with large variations around these values. From numerical simulation based on the field line integrated quantities of Pedersen conductivity and ion density gradients, Anderson and Haerendel [1979] have shown that the bubble rise velocities are strongly dependent on the F region ambient east-west electric field.

---

[1] Present address: Universidade do Rio Grande do Norte, Natal, Brazil.

Paper number 3A1191.
0148-0227/83/003A-1191$05.00

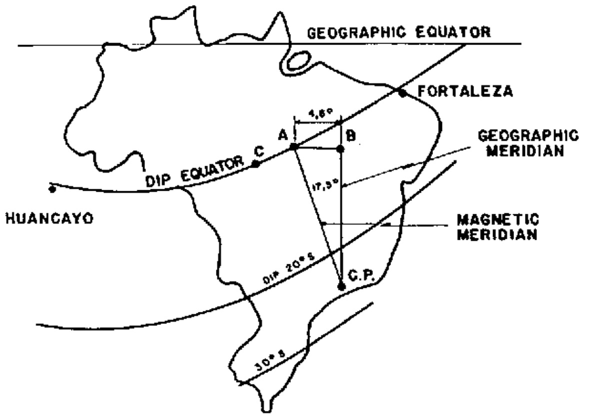

Fig. 1. Locations of the ionosonde stations, Fortaleza and Cachoeira Paulista, relative to the magnetic and geographic equators. Dip latitudes at 20°S and 30°S are shown. Also shown are the geographic and magnetic meridians over Cachoeira Paulista and their intersections with the magnetic equator (see the text for further details).

Radar mapping of the two-dimensional shape of the plasma bubbles in the equatorial plane transverse to the magnetic field has been carried out by Tsunoda [1981] and Tsunoda et al. [1982]. They have shown that the plasma bubbles are vertically elongated depletions that extend upward from the bottomside of the F layer in the form of wedges and have well-defined "head" and "neck" regions. Further, they develop with their axes of depletions tilted somewhat westward of the vertical. The rise velocities were found to vary from 75 to 350 m s^{-1} [Tsunoda, 1981]. As the field-aligned plasma bubble and associated irregularities rise in the equatorial ionosphere, the low-latitude extremities of the bubble should propagate away from the equator in such a way that the upper height limit of the irregularities would define also the latitudinal limit of the irregularity occurrence associated with a given event. Thus the occurrence of spread F events over a low-latitude station in the early hours of the postsunset period could be produced by the poleward passage of the low-latitude footprint of the head region of a developing bubble. Poleward propagating 6300-Å airglow depletion patches observed (especially in the early hours of the postsunset period) over Cachoeira Paulista by meridional scan photometers [Sobral et al., 1980a; Nakamura et al., unpublished manuscript, 1982] were found to be consistent with this picture of the plasma bubble dynamics. (It should be pointed out, however, that the low-latitude spread F observed at later hours of the postsunset period could be caused also by the eastward passages of the neck regions of north-south elongated and westward tilted depletion patches corresponding to the plasma bubble generations that took place at longitudes well westward of that of the ionosonde. These cases will be excluded from consideration here since only the first onsets in the early sunset hours are analyzed).

Therefore, a certain time delay could be expected in the onset of the spread F events over a low-latitude station with respect to that over an equatorial station, located in close-by magnetic meridional planes, in proportion to the time plasma bubbles take to extend upward from the bottomside F region over the magnetic equator to the apex of the field line that meets the subpeak F region over the low-latitude station. Systematic time differences in the local times of the onset of spread F events are observed between the magnetic equatorial station Fortaleza (4°S, 38°W, dip latitude 1.8°S) and the low-latitude station Cachoeira Paulista (23°S, 45°W, dip latitude 14°S). In a comparative study carried out recently of the spread F occurrences at these two stations, Abdu et al. [1983b] have presented evidence that suggested that the spread F irregularities observed over Cachoeira Paulista could indeed be resulting from flux tube extension of the plasma bubbles whose generation could have occurred primarily over the magnetic equator. The following additional points seem to be worth mentioning. During the months of frequent spread F occurrences, namely, equinoctial and southern solstice months, the postsunset spread F onsets on most of the nights occur just before the prereversal maximum in the F layer bulk plasma vertical velocity (usually from 1900 to 1930 local standard time (LST), or 1830 to 1900 LT) [see Abdu et al., 1981a, b]. Further, all the spread F onsets over Cachoeira Paulista were preceded by onsets of spread F at Fortaleza (the time differences varied from a few minutes to a few tens of minutes). Many cases of spread F over Fortaleza were not, however, accompanied by such events over Cachoeira Paulista. We have attributed this latter observation to the possibility that either plasma bubbles did not develop in these cases or the bubble rise velocity was so low that it did not rise to the apex altitude of the magnetic field line before the reversal, to downward, of the F layer bulk plasma velocity (that usually occurs by about 2000 LST).

In this paper we have analyzed the systematic differences observed in the onset times of spread F at these two stations, in order to deduce the plasma bubble rise velocities that best explain the observed time differences. The analysis is carried out for the months of the more frequent spread F incidence rates, usually the equinoctial and southern solstice months, during the period from January 1978 to February 1980.

Determination of the Plasma Bubble Rise Velocity

In considering the time differences between the onsets of spread F events at Fortaleza and Cachoeira Paulista we should keep in mind that these two stations are located at close magnetic meridional planes. Their locations are shown in Figure 1. The magnetic meridian over Cachoeira Paulista, in fact, passes through point A at the magnetic equator as shown in the figure, which is about 12° westward in longitude from Fortaleza. Based on the considerations presented below, we have assumed that the onset time of the first spread F event on any evening, over the longitudinal range extending from Fortaleza up to point A, and in the vicinity beyond, would be practically the same as those observed over Fortaleza.

The spread F onset usually occurs, as mentioned before, very close to the time of the prereversal peak in the F layer vertical drift in the evening hours [e.g., Woodman, 1970; Farley et

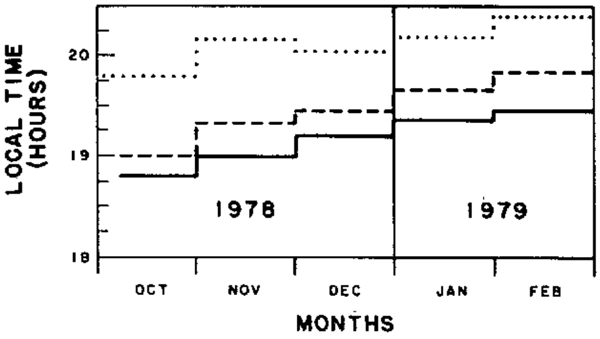

Fig. 2. Monthly mean spread F onset times in local solar times plotted during October 1978 to February 1979, for Fortaleza (solid), Huancayo (dashed), and Cachoeira Paulista (dotted).

al., 1970; Rastogi, 1978, Abdu et al., 1981a; Fejer et al., 1979], and an important factor that determines the times and widths of the prereversal peak in V_z seems to be the magnetic declination angle [Abdu et al., 1981b] which for point A (16°W) is reasonably close to that for Fortaleza (21°W). The monthly average onset times (in local solar time) of range type spread F events read from ionograms over Fortaleza and Huancayo over the magnetic equator, and Cachoeira Paulista over low latitude, are presented in Figure 2 for the period October to February (the months of highest spread F occurrence) during 1978-1979. Similar results hold also for the rest of the periods analyzed here for Fortaleza and Cachoeira Paulista (in the case of Huancayo this point has not been verified). Judging from the onset times at Fortaleza and Huancayo, on the basis of the difference in the magnetic declination angles at these sites, we do not expect any significant difference in the onset times to arise from differences in the vertical rise velocity of the F layer at Fortaleza and the longitude of point A. The other factors such as the F layer base height and its electron density gradient, and the relevant neutral atmosphere parameters, could be assumed to have very similar local time dependence within the longitudes covered by the two places. The spread F occurrence over the Fortaleza site on a given evening could, therefore, be taken as an indication that conditions were conducive to spread F occurrences, in the form of several successive and independent plumes in the neighboring region along the magnetic equator as long as an atmospheric seeding source was present to cause the required initial perturbation in the ambient ionization uniformly in these regions, an assumption that is perfectly justified due, again, to the small longitudinal separation involved. Such seeding sources seem to be present regularly (on all evenings) in the ionosphere over this region as our published results (and unpublished data) on spread F occurrence suggest. For instance, spread F was present in the early hours of the postsunset period on almost all magnetically "quiet" nights of the equinoctial and southern solstice months [Abdu et al., 1981a]. Further, the spread F in 97% of the cases, considered throughout the year, occurred when the Rayleigh-Taylor instability condition determined from ionograms was satisfied, whereas all the cases of nonoccurrences of spread F were found to be accompanied by negative growth rate [Abdu et al., 1982]. The irregularities, causing backscatter plumes, develop as shown by Tsunoda [1981], from the west wall of an altitude-modulated bottomside F layer, presumably caused by a seeding source which might be atmospheric gravity waves [Röttger, 1978] in the presence of an eastward neutral wind [see also Fejer et al., 1981]. Therefore, the precise local times of the postsunset onset of the irregularity patches, over any site along the equator, could vary somewhat from day to day depending upon the phase of the atmospheric wave, in relation to the local onset times of the instability conditions, over that site. Our study of the statistics of the onset times during the spread F season over Fortaleza (see, for example, Figure 2 of Abdu et al. [1981a]) shows that under quiet magnetic conditions the variation in onset times could be reasonably small (of the order of 15-30 min if we consider groups of a few days, so that the mean onset times for such groups could be almost independent of longitude, at least, within the longitude region covered in the present analysis. We are, therefore, justified in assuming that the local time of spread F onset, on an average, over the regions in the vicinity of point A will be practically the same as those over Fortaleza. In other words, we are justified in treating the results of spread F at Fortaleza and Cachoeira Paulista as if these two stations were situated in close-by magnetic meridional planes, especially, for determining the statistical trends, on a few-day basis, of the plasma bubble vertical rise velocities.

In the following, we will use definition of the magnetic apex coordinate systems after VanZandt et al. [1972] to describe the parameters used for deriving the plasma bubble rise velocity. The spread F onset time at Cachoeira Paulista corresponds, according to the flux tube extension of the plasma bubble and the associated irregularities, to the time of occurrence of the irregularities at the apex of the field line meeting the base of the F layer (h'F) over Cachoeira Paulista. We shall denote the height of the apex as P_{eq} which could vary, of course, depending upon the h'F over Cachoeira Paulista. It would be of the order of 600 km for an h'F of 250 km which we have found to be the approximate average value in the postsunset hours. Since the irregularities rise in the equatorial ionosphere with an associated eastward (in the corotating frame) velocity, the irregularities that occur at P_{eq} are, in fact, those that had their onset at the base of the F region somewhat westward of point A, namely, over the point marked C in Figure 1. Thus the time required for the irregularities to propagate from their onset region over point C, to P_{eq}, should be the same as the time that elapses between the onset of spread F over point C and that over Cachoeira Paulista (both times being referred to a common reference longitude). We shall denote this elapsed time as Δt. Based on the discussion in the previous paragraph we can assume that the local times of the spread F onset over point C are the same as those over Fortaleza. Thus, we can show that

$$\Delta t = (t_{oCP} - t_{oFz} - T_{\Delta L})/(1 + 2.14 \times 10^{-3} V_x)$$

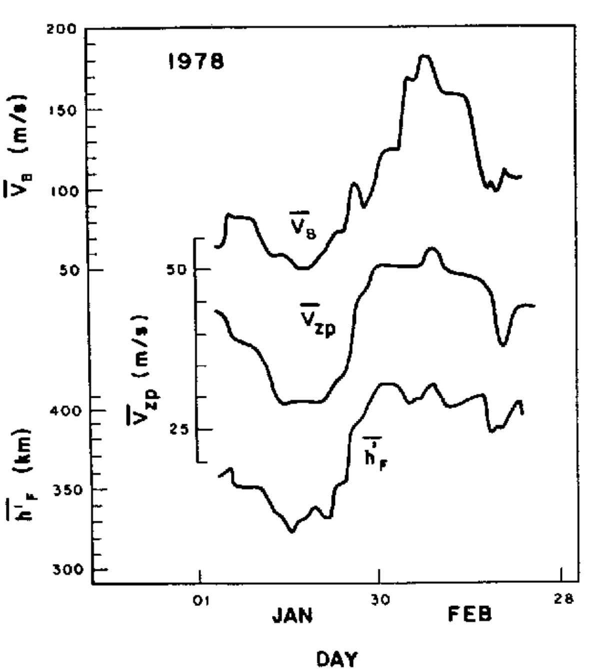

Fig. 3. Ten-day running means of the vertical bubble rise velocity $\overline{V}_B$, for January and February 1978, plotted together with the corresponding running mean values of the amplitudes of the prereversal enhancements in the F layer vertical rise velocities in the evening hours, $\overline{V}_{zp}$, and with those of the heights of the base of the F layer, $\overline{h'F}$.

where t_{oCP} and t_{oFz} are the local solar times of spread F onsets over Cachoeira Paulista and Fortaleza respectively; $T_{\Delta L}$ is the local solar time difference between Cachoeira Paulista and the longitude of A; V_x is the eastward velocity, in meters per second of the plasma bubble; and the factor 2.14 x 10^{-3} represents the change of local time, in seconds, per unit longitudinal distance.

The vertical bubble rise velocity V_B is then determined by knowing the virtual height of the F layer base at the onset of the spread F in the ionograms of Fortaleza, or, over point C (denoted as the height hF_{oe}), at which the bubble begins to be formed with associated vertical growth. The apex height at which the plasma bubble will be located at the end of the time Δt was then determined from the h'F at the onset of the spread F over Cachoeira Paulista with the help of magnetic B-L charts representing the field lines as functions of altitude and latitude, prepared by Harrison et al. [1963]. Thus the vertical rise velocity of the bubble, V_B, will be given by

$$V_B = (P_{eq} - hF_{oe})/\Delta t$$

The value of V_B was calculated for each day during the months of January and February 1978, October 1978 to February 1979, and October 1979 to February 1980, since these are the months when spread F occurred most frequently during the interval considered. In general, the individual V_B values present large scatter, varying from a few meters per second up to a few hundreds of meters per second. Therefore, 10-day running means ($\overline{V}_B$) were calculated during each of these periods and the results for January and February 1978 are presented in Figure 3. These mean values (and even most of the individual values, though not shown here) are well within the bubble vertical velocities obtained previously from different techniques [e.g., Woodman and La Hoz, 1976; McClure et al., 1977; Ossakow et al., 1979; Tsunoda, 1981; Nakamura, 1981]. In Figure 3 we have plotted also 10-day running means of the amplitudes of the prereversal peaks (denotted by $\overline{V}_{zp}$) of the evening F layer vertical velocities calculated as d(h'F)/dt [Bittencourt and Abdu, 1981; Abdu et al., 1981b]. It may be noted that a good degree of correlation between the bubble rise velocities and the bulk plasma velocities is evident in the mean trends of these parameters. The h'F values, obtained from ionograms over Fortaleza, are also plotted in the same figure. The gross characteristics seen in this figure are that the bubble velocity is small (or large) when the $\overline{V}_{zp}$ is small (or large), and both the parameters vary roughly in phase with the $\overline{h'F}$ values. Results for October 1978 to February 1979 and for October 1979 to February 1980 are presented in Figures 4 and 5. The correlation among the three parameters seems to be poor for most of the interval shown in Figure 4. However, trends suggesting varying degrees of positive relationship between $\overline{V}_B$ and the other two parameters are evident in the results presented in Figure 5, during October and a major part of November 1979, and for February 1980. It is interesting to note that during the greater part of the intervals in all these figures (Figure 3, 4, and 5) there seems to be a consistent tendency for a good correlation between variations in $\overline{V}_{zp}$ and $\overline{h'F}$ over Fortaleza.

Discussion

The individual V_B values obtained from the present analysis could have large uncertainty at times, due to the fact that the corresponding Δt was determined from ionosonde observations that were taken simultaneously at both Fortaleza and Cachoeira Paulista, but at 15-min intervals. The onset of a spread F event could have actually taken place before its detection in the ionogram. Thus, Δt values that are close to 15 min could have large errors, whereas the error will decrease for higher Δt values. Consequently, the scatter will be higher for higher V_B values and smaller for smaller V_B values. We have estimated that the individual velocities of the order of 300 m s^{-1} could be in error by as much as 100%, whereas the error would be 10% only for the velocities of the order of 30 m s^{-1}. However, if we assume that the distribution functions of the occurrence of spread F onset times, before their detection in the ionograms, are the same for two stations, the error in Δt is expected to be small when the mean of a large number of values of Δt are considered and hence also in the $\overline{V}_B$ values obtained as the running mean of several points (10 in the present case). Thus, the $\overline{V}_B$ values presented in Figures 3, 4, and 5 seem to be reliable since they fall also within the values for the bubble rise velocities measured by backscatter radar [Woodman and La Hoz, 1976; Tsunoda, 1980, 1981], by satellites [McClure et al., 1977], from airglow photometer techniques [Nakamura et al., (unpublished manuscript); Weber et al., 1980], and those predicted from theoreti-

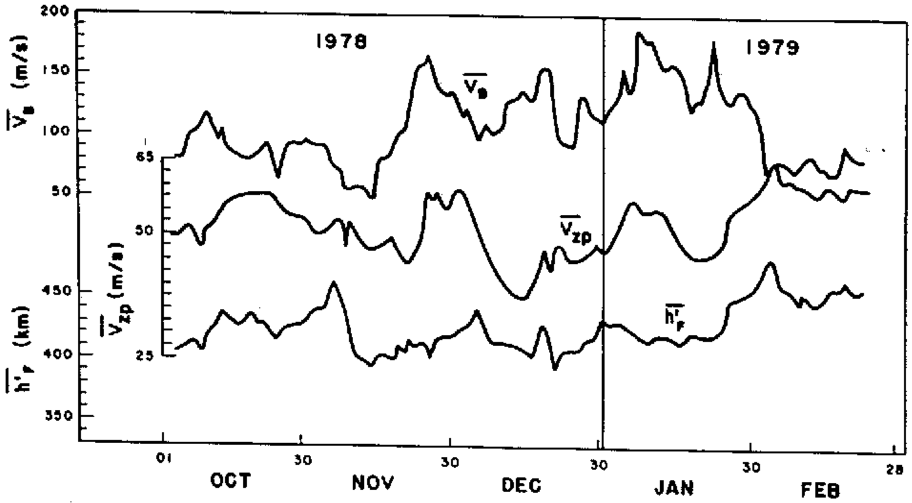

Fig. 4. Same parameters as in Figure 3, plotted for October, November, and December 1978 and for January and February 1979.

cal modeling [Ossakow et al., 1979; Anderson and Haerendel, 1979]. Another possible error could be due to variations in the eastward velocity, V_x, which we have taken as 100 m s^{-1} in all our calculations. A 100% change in V_x could introduce about 20% error in the individual V_B values. Another source of systematic error that could cause significant scatter in the individual values mentioned above is related to the fact that the ionosondes are so widely separated that they are not monitoring the progress of individual bubbles but only the first appearance of any bubble-induced signature at the two locations. For reasons mentioned before, the error due to this factor should be insignificant in the mean trends, obtained by taking the running means, of the bubble velocities.

In analyzing the relationship between $\overline{V}_B$ and $\overline{V}_{zp}$ we should consider the diverse factors that control the plasma bubble generation and its subsequent vertical growth velocities. From theoretical modeling, taking into account field line-integrated plasma properties, Anderson and Haerendel [1979] showed that the bubble rise velocities are in general always small (or large) when the F region ambient electric field or the $\underset{\sim}{E}\times\underset{\sim}{B}$ vertical drift velocity is small (or large). Our results in Figure 3 and in parts of Figures 4 and 5, showing a positive relationship between $\overline{V}_B$ and $\overline{V}_{zp}$, are in good agreement with these results of Anderson and Haerendel [1979]. VHF radar measurements by Tsunoda [1981] has shown a decrease in the plume rise velocity toward the end of a bubble development phase which might be caused by a similar decrease in the bulk plasma vertical motion at those times. The bubble generation and vertical growth, according to the Rayleigh-Taylor mechanism, depend also upon the presence of an initial perturbation in the ionization, ion-neutral collision frequency, and the ionization gradient at the base of the F layer. Two-dimensional simulation of the collisional Rayleigh-Taylor mechanism by Ossakow et al. [1979] has shown strong dependence of the ionization depletion in the bubble, and consequently of the bubble rise velocity, on the height of the F layer (arising from the upward decrease in the ion-neutral collision frequency), which is in agreement with the positive relationship between $\overline{V}_B$ and $\overline{h'F}$ observed in parts of the present results. If the degree of the depletion in the bubble is a measure of the spread F irregularity strength, then the recent results [Abdu et al., 1983a], showing a positive correlation between V_{zp} and range type spread F indices in the postsunset hours, seem to be complementary evidence supporting the positive relationship between $\overline{V}_B$ and $\overline{V}_{zp}$ obtained from the present analysis. The in-phase variations in $\overline{V}_B$, $\overline{V}_{zp}$, and $\overline{h'F}$, present in part of our results, in fact, suggest that the east-west F region ambient electric field influences the bubble rise velocity in two ways: (1) through polarization changes resulting from the difference in the conductivity between the bubble and nearby regions, in the presence of the ambient electric field [Anderson and Haerendel, 1979], and (2) through changes in the ion-neutral collision frequency at F layer heights [Ossakow et al., 1979] when variations in these heights are produced by the ambient electric field.

The good degree of correlation that is present among $\overline{V}_B$, $\overline{V}_{zp}$, and $\overline{h'F}$, though restricted to some periods only, could be explained as due to the dominating influence of the F region ambient east-west electric field in the bubble development phase. The absence of any significant correlation seen on many other occasions, therefore, seems to warrant a discussion in terms of the other different parameters that also control, or influence, the bubble development. It should be noted that the dominating influence of an F region ambient electric field could be identified through a positive correlation between $\overline{V}_B$ and $\overline{V}_{zp}$ only because variations in the other controlling factors were not sufficient to mask this influence. One of the most important of these factors seems to be the amplitude of the initial perturbations in the ambient ionization upon which the instability processes operate. Two-dimensional numerical simulation of the collisional Rayleigh-Taylor instability mechanism, of the type carried out by Ossakow et al. [1979], has been used by Nakamura [1981] to study the bubble height and rise velocity characteristics as a function of the amplitude of the initial perturbations, and

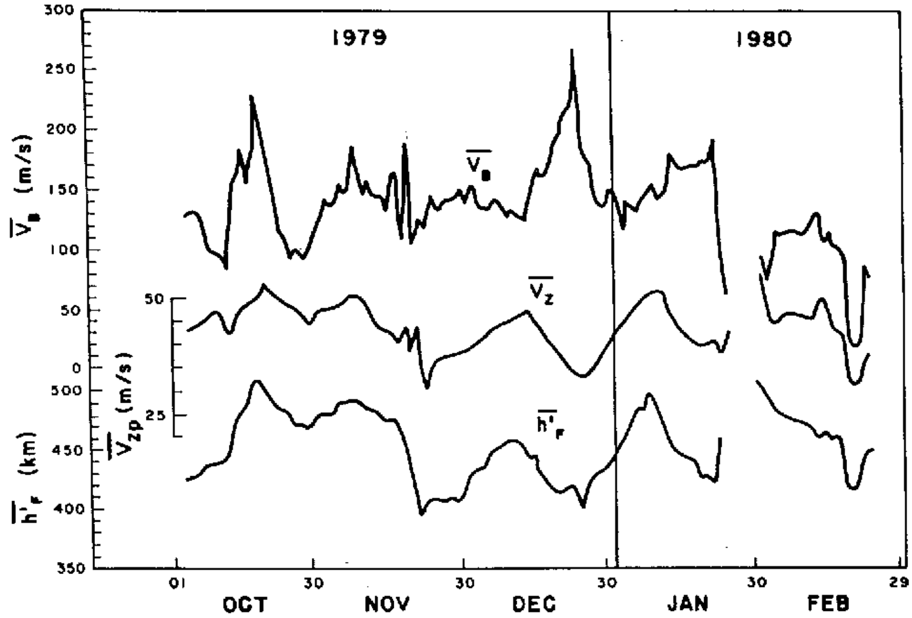

Fig. 5. Same parameters as in Figure 3 and 4, plotted for October, November, and December 1979 and for January and February 1980.

the results show strong dependence between them. In a typical calculation [Nakamura, 1981], an initial perturbation of 1% of the ambient ion density gave rise to a bubble vertical velocity of 60 m s^{-1} at a height of 340 km, whereas an initial perturbation of 10% resulted in a velocity of 170 m s^{-1} at a height of 400 km, at the end of 700 s from the onset of the instability process in both cases. Therefore, variabilities in the factors that determine the amplitude of the initial perturbations, such as possibly a gravity wave spectrum that could be regularly present in the evening equatorial ionosphere [Röttger, 1978; Booker, 1979], should be sufficient to mask any possible dependence of the plasma bubble rise velocity on the F region ambient electric field. Variations in the ionization gradient scale length at the F layer base, variations in eastward neutral winds, and changes in the ion-neutral collision frequency (caused by magnetic activity, for example) are the other factors that could contribute to ambiguous relationships of $\overline{V}_B$ with $\overline{V}_{zp}$ and $\overline{h'F}$. Detailed investigation into these different problems is beyond the scope of the present work, which has as its main purpose to demonstrate that reasonable estimates of the plasma bubble rise velocities in the equatorial ionosphere could be achieved from simultaneous observations of spread F events by spaced ionosondes located, preferably, along or in the vicinity of a common magnetic meridional plane, covering the magnetic equator and low latitudes.

Conclusions

We have analyzed the systematic differences in times of the first onsets of the range type spread F, in the postsunset period, observed over the equatorial station, Fortaleza, and over the low-latitude station, Cachoeira Paulista, to determine the equatorial plasma bubble rise velocities. The derivation of the individual velocities, as referred to a selected bubble event, has involved some assumptions about the physical and dynamical bubble characteristics that are realistic and based on the well-known results from VHF radar observations, airglow, and satellite measurements, widely cited above, and on the comparative studies of spread F statistics over the two stations, carried out by us recently.

The irregularities giving rise to range type spread F in the ionograms have their onset usually in the early hours of the postsunset period. They constitute part of the wide spectrum of the irregularities, from meter to kilometer sizes, that are generated during an equatorial plasma bubble event. The generation of the bubble and the associated irregularities occur simultaneously along magnetic flux tube, extending several degrees to either side of the equator. The depleted regions rise up over the equator in elongated columns extending upward from the bottomside F layer in the form of westward tilted wedges as described by Tsunoda et al. [1982]. The field line footprint of the "head" region of the bubble, during its resulting poleward motion, causes spread F events over low-latitude sites, which could account for (at least) the first spread F events occurring in the early sunset period over low latitude. If a spread F event in the equatorial ionosphere is not associated with a growing bubble event, then, according to this picture, no spread F will be observed over low-latitude sites.

Hence, the time delay observed in the onsets of spread F events was attributed to the time that a plasma bubble takes, from its development at the bottomside F layer, to rise up to the apex of the magnetic field line linking the low-latitude F layer base. The rise velocity of a selected bubble, derived in this way, has significant dispersion due, mainly, to the longitudinal separation of the two stations and to some extent to the 15-min time resolution used in the measurement. The dispersion in the derived velocities from these factors is, however, significantly reduced in the running means of the velocities, as evident from the excellent agreement obtained with the bubble rise velocities determined from several other different techniques (cited before), and from the very good correlation observed, on may occasions, with the prereversal peak in the F layer bulk plasma vertical drift. The latter point also corroborates the theoretically expected dependence of the bubble rise velocity on the ambient F region electric field shown by Anderson and Haerendel [1979]. Possible causes for not observing such a correlation on many other occasions have been discussed. Better precision and confidence in the individual bubble velocities could be achieved from observations taken with better time resolution, say every 1 to 5 min, and from operating the ionosondes closer to a common magnetic meridional plane than is done at present. Such studies are being planned for the near future.

Acknowledgments. The authors wish to thank B. G. Fejer for his helpful comments on the original manuscript. This work was partially supported by the Fundo Nacional de Desenvolvimento Científico e Tecnológico under contract FINEP-537/CT.

The Editor thanks J. P. McClure, R. T. Tsunoda, and another referee for their assistance in evaluating this paper.

References

Aarons, J., J. P. Mullen, J. R. Koster, R. F. da Silva, J. R. Medeiros, R. T. Medeiros, A. Bushpy, J. Pantoja, J. Lanai, and M. R. Paulson, Seasonal and geomagnetic control of equatorial scintillations in two longitudinal sectors, J. Atmos. Terr. Phys., 42, 861-866, 1980.

Abdu, M. A., I. S. Batista, and J. A. Bittencourt, Some characteristics of spread F at the magnetic equatorial station Fortaleza, J. Geophys. Res., 86, 6836-6842, 1981a.

Abdu, M. A., J. A. Bittencourt, and I. S. Batista, Magnetic declination control of the equatorial F region dynamo electric field development and spread F, J. Geophys. Res., 86, 11,443-11,446, 1981b.

Abdu, M. A., R. T. de Medeiros, and J. H. A. Sobral, Equatorial spread F instability conditions as determined from ionograms, Geophys. Res. Lett., 9, 692-695, 1982.

Abdu, M. A., R. T. de Medeiros, J. A. Bittencourt, and I. S. Batista, Vertical ionization drift velocities and range type spread F in the evening equatorial ionosphere, J. Geophys. Res., 88, 399-402, 1983a.

Abdu, M. A., R. T. de Medeiros, and Y. Nakamura, Latitudinal and magnetic flux tube extension of the equatorial spread F irregularities, J. Geophys. Res., 88, 4861-4868, 1983b.

Anderson, D. N., and G. Haerendel, The motion of depleted plasma regions in the equatorial ionosphere, J. Geophys. Res., 84, 4251-4256, 1979.

Balsley, B. B., G. Haerendel, and R. A. Greenwald, Equatorial spread F: Recent observations and a new interpretation, J. Geophys. Res., 77, 5625-5628, 1972.

Basu, S., J. Aarons, J. P. McClure, and M. D. Cousins, On the coexistence of kilometer and meter-scale irregularities in the nighttime equatorial F-region, J. Geophys. Res., 83, 4219-4226, 1978.

Bittencourt, J. A., and M. A. Abdu, A theoretical comparison between apparent and real vertical ionization drift velocities in the equatorial F region, J. Geophys. Res., 86, 2451-2454, 1981.

Booker, H. G., The role of acoustic gravity waves in the generation of spread F ionospheric scintillations, J. Atmos. Terr. Phys., 41, 501-515, 1979.

Dungey, J. W., Convective diffusion in the equatorial F-region, J. Atmos. Terr. Phys., 9, 304-310, 1956.

Dyson, P. L., and R. I. Benson, Topside sounder observation of equatorial bubbles, Geophys. Res. Lett., 5, 795-798, 1978.

Farley, D. T., B. B. Balsley, R. F. Woodman, and J. P. McClure, Equatorial spread F: implications on VHF radar observations. J. Geophys. Res., 75, 7199-7216, 1970.

Fejer, B. G., D. T. Farley, R. F. Woodman, and C. Calderon, Dependence of equatorial F region vertical drifts on season and solar cycle, J. Geophys. Res., 84, 5792-5796, 1979.

Fejer, B. G., D. T. Farley, C. A. Gonzalez, R. F. Woodman, and C. Calderon, F region east-west drifts at Jicamarca, J. Geophys. Res., 86, 215-218, 1981.

Haerendel, G., Theory of equatorial spread F, report, Max-Planck Inst. für Phys. und Astrophys., Munich, 1973.

Hanson, W. B., and S. Sanatani, Large Ni gradients below the equatorial F_2 peak. J. Geophys. Res., 78, 1167-1173, 1973.

Harrison, R. E., K. W. Hubbard, F. L. Keller, and J. I. Vette, Plots of constant B and constant L for various longitudes, Rep. TDR-169(3510)-TR 4, Aerospace Corp., El Segundo, Calif., 1963.

McClure, J. P., W. B. Hanson, and J. F. Hoffman, Plasma bubbles and irregularities in the equatorial ionosphere, J. Geophys. Res., 82, 2650-2656, 1977.

Mendillo, M., and J. Baumgardner, Airglow characteristics of equatorial plasma depletions, J. Geophys. Res., 87, 7641-7652, 1982.

Moore, J. G., and E. J. Weber, OI 6300 and 7774 Å airglow measurements of equatorial plasma depletions, J. Atmos. Terr. Phys., 43, 851-858, 1981.

Morse, F. A., B. C. Edgar, H. C. Koons, C. J. Rita, W. J. Heikkila, J. H. Hoffman, B. A. Tinsley, J. D. Winnigham, A. B. Christensen, R. F. Woodman, J. Pomalaza, and N. R. Teixeira, Equion: An equatorial ionospheric irregularity experimental, J. Geophys. Res., 82, 578-592, 1977.

Nakamura, Y., Irregularidades ionosféricas em baixas latitudes no setor americano, doctoral thesis, INPE-2243-TDL/065, Inst. de Pesquisas Espaciais, São José dos Campos, Brazil, 1981.

Ossakow, S. L., S. T. Zalesak, B. E. McDonald, and P. K. Chaturvedi, Nonlinear equatorial spread F: Dependence on altitude of the peak and bottomside electron density gradient scale length, J. Geophys. Res., 84, 17-29, 1979.

Rastogi, R. G., On the equatorial spread F, Proc. Indian Acad. Sci., Sect. A, 87, 115-131, 1978.

Rastogi, R. G., and R. F. Woodman, VHF radio wave scattering due to range and frequency types of

equatorial spread F, J. Atmos. Terr. Phys., 40, 485-491, 1978.
Reid, G. C., The formation of small-scale irregularities in the ionosphere, J. Geophys. Res., 73, 1627-1640, 1968.
Röttger, J., Drifting patches of equatorial spread F irregularities: Experimental support for the spatial resonance mechanism in the ionosphere, J. Atmos. Terr. Phys., 40, 1093-1102, 1978.
Scannapieco, A. J., and S. L. Ossakow, Nonlinear equatorial spread F, Geophys. Res. Lett., 3, 451-454, 1976.
Sobral, J. H. A., M. A. Abdu, and I. S. Batista, Airglow studies on the ionosphere dynamics over low latitude in Brazil, Ann. Geophys., 36, 199-204, 1980a.
Sobral, J. H. A., M. A. Abdu, C. J. Zamlutti, and I. S. Batista, Association between plasma bubble irregularities and airglow disturbances over Brazilian low latitudes, Geophys. Res. Lett., 7, 980-982, 1980b.
Tsunoda, R. T., Magnetic field aligned characteristics of plasma bubbles in the nighttime equatorial ionosphere, J. Atmos. Terr. Phys., 42, 743-752, 1980.
Tsunoda, R. T., Time evolution and dynamics of equatorial backscatter plumes, 1, Growth phase, J. Geophys. Res., 86, 139-149, 1981.
Tsunoda, R. T., and D. M. Towle, On the spatial relationship of 1-meter equatorial spread F irregularities and depletions in total electron content, Geophys. Res. Lett., 6, 873-876, 1979.
Tsunoda, R. T., R. C. Livingston, J. P. McClure, and W. B. Hanson, Equatorial plasma bubbles: Vertical elongated wedges from the bottomside F layer, J. Geophys. Res., 87, 9171-9180, 1982.
VanZandt, T. E., W. L. Clark, and J. M. Warnock, Magnetic apex coordinates: A magnetic coordinate system for the ionospheric F_2 layer, J. Geophys. Res., 77, 2406-2411, 1972.
Weber, E. J., J. Buchau, R. H. Eather, and S. B. Mende, North-south aligned equatorial airglow depletions, J. Geophys. Res., 83, 712-716, 1978.
Weber, E. J., J. Buchau, and J. G. Moore, airborne studies of equatorial F layer ionosphere irregularities, J. Geophys. Res., 85, 4631-4641, 1980.
Woodman, R. F., Vertical drift velocities and east-west electric fields at the magnetic equator, J. Geophys. Res., 75, 6249-6259, 1970.
Woodman, R. F., and C. La Hoz, Radar observations of F region equatorial irregularities, J. Geophys. Res., 81, 5447-5466, 1976.

M. A. Abdu, J. A. Bittencourt, R. T. de Medeiros, and J. H. A. Sobral, INPE, C. P. 515, 12200 São José dos Campos, SP, Brasil.

(Received June 4, 1982;
revised November 30, 1982;
accepted July 15, 1983.)