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Effect of magnetic activity on the dynamics of equatorial *F* region irregularities

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[1] Two different aspects of the effect of magnetic activity on the dynamics of equatorial spread *F* (ESF) irregularities are studied here using spaced receiver scintillation observations. The first one deals with the question of how magnetic activity affects the generation of ESF irregularities. For this, a parameter designated the "random velocity," which is a measure of random changes in the irregularity drift velocity, is evaluated from the data. In past studies, this parameter has been found to have large values in the early phase of evolution of ESF irregularities during the postsunset period, with a steep decline to a low value by 22 LT. This behavior is attributed to the decline in the height of the *F* region. Therefore, a sudden increase in the "random velocity" in the postmidnight period is attributed to an increase in the height of the *F* region due to the ionospheric zonal electric field turning from westward to eastward due to the effect of magnetic activity, which may also generate fresh irregularities that produce the observed scintillations. This idea has been used to suggest that for two of the magnetically active days considered in the present study the irregularities may be freshly generated in the postmidnight period. The second aspect is the identification of geomagnetically disturbed plasma drifts, which is generally possible only after 22 LT, when the estimated irregularity drift velocities are close to that of the background plasma. The pattern of the estimated drift after 22 LT (3 UT) is found to be well defined for magnetically quiet days with scintillations during a period of a month. This allows the identification of a superimposed westward perturbation in the drift, produced by a disturbance dynamo due to magnetic activity, for all the three events studied here. On 19 February and 1 March 1999, the eastward drift velocities show an identical decrease of about 50 m/s from the undisturbed drift at 0440 UT. On 1 March, the decay phase of the storm sets in later, and the eastward velocity continues to decrease until 0530 UT, turning westward with a maximum decrease of about 80 m/s from the undisturbed drift. On 22 October 1999, which was more disturbed than these two days, the westward perturbation was larger, causing the drift velocity to turn westward around 5 UT and a decrease of nearly 150 m/s from the quiet time drift at 8 UT. The results are in broad agreement with some of the recent empirical models of the evolution, with storm time, of equatorial disturbance dynamo electric fields. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; 2437 Ionosphere: Ionospheric dynamics; 2788 Magnetospheric Physics: Storms and substorms; 2487 Ionosphere: Wave propagation (6934)

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1. Introduction

[2] During periods of enhanced geomagnetic activity, the equatorial ionosphere is known to display highly variable responses to both a prompt penetration of transient magnetospheric electric fields into the low-latitude ionosphere and electric fields generated by the ionospheric disturbance dynamo [*Blanc and Richmond*, 1980]. Changes in the pattern of equatorial *F* region plasma drifts, that may be associated with magnetically disturbed periods, provide sensitive indices of these electric field disturbances. A large database of equatorial *F* region plasma drift velocities,

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derived from radar observations at the Jicamarca Observatory, have been used to model the storm time behavior of the equatorial electric fields and to delineate the contributions from prompt penetration and disturbance dynamo electric fields [*Fejer and Scherliess*, 1997; *Scherliess and Fejer*, 1997]. Variations in the height of the *F* layer and peak electron density changes deduced from ionograms, obtained at low-latitude stations, have shown variable responses of the low-latitude ionosphere to geomagnetic storms [*Sastri et al.*, 2000; *Sobral et al.*, 2001]. The postsunset height of the equatorial *F* region has been identified as one of the most important factors in the generation and evolution of equatorial spread *F* (ESF) [*Kelley and Maruyama*, 1992; *Fejer et al.*, 1999; *Bhattacharyya and Burke*, 2000; *Sobral et al.*, 2001]. Hence, magnetic activity is expected to have a significant effect on the occurrence of spread *F* as discussed in a number of papers [*Fejer et al.*, 1999; *Basu et al.*, 2001a, 2001b; *Huang et al.*, 2001; *Yeh et al.*, 2001].

[3] In the present paper, scintillations on a 244 MHz signal, transmitted from a geostationary satellite and recorded at an equatorial station, are used to study the effect of magnetic activity on two aspects of the dynamics of equatorial *F* region irregularities, which produce scintillations by scattering radio waves. The first one deals with the basic question of how magnetic activity affects the generation of ESF irregularities. In past studies of the effects of magnetic activity on low latitude, nighttime scintillations and irregularity drifts, a distinction between magnetically active and quiet periods has been made on the basis of either the ΣKp or the Ap index for the day [*Bhattacharyya et al.*, 1989; *Pathan and Rao*, 1996]. In another such study [*Valladares et al.*, 1996], hourly occurrence pattern of scintillations on an UHF signal for magnetically quiet and active conditions were determined on the basis of the prevalent Kp index. A value of Kp between 0 and 3o was considered to indicate magnetically quiet conditions, whereas Kp $\geq 3^+$ was considered as an indication of magnetic activity. In all previous studies, except a recent one by *Basu et al.* [2001b], no attempt has been made to distinguish between freshly generated irregularities and irregularities which may have been generated more than 2 hours earlier and subsequently drifted into the path of the recorded radio wave signal. An estimate of the "age" of the irregularities which produce the observed scintillations is essential in an investigation of the association between magnetic activity and generation of ESF irregularities. It has been observed that during magnetically disturbed conditions, an elevated *F* region in the postmidnight period, with altitude of the *F* region peak exceeding 350 km, does not always lead to the generation of irregularities [*Sastri*, 1981], although in most cases it does so [*Sastri*, 1979; *Sastri et al.*, 2000]. This implies that even in the presence of favorable conditions like an eastward electric field, some as yet unidentifiable factors may suppress the generation of fresh irregularities in the postmidnight period. Thus, information about the "age" of the equatorial *F* region irregularities, which produce postmidnight scintillations under magnetically disturbed conditions, may also shed some light on conditions that exist when these irregularities are not freshly generated.

[4] The second aspect studied here is the effect of magnetic activity on the drift of the irregularities after they have been generated due to nonlinear evolution of the Rayleigh–Taylor (R-T) instability in the postsunset equatorial *F* layer. In initial stages of evolution of the irregularities, their drifts are largely determined by the polarization electric fields associated with the instability, and thus the drifts are highly variable [*Bhattacharyya et al.*, 2001]. After 22 LT, on magnetically quiet days, the irregularity drift approaches the ambient plasma drift, and during these periods, the irregularity drift follows a well-defined pattern over a period of a month with perhaps less day-to-day variability than is to be found in the plasma drifts on days with no ESF. This feature of the drifts allows the emergence of a clear picture of the geomagnetically disturbed drifts.

2. Scintillations and Irregularity Drifts

[5] Intensity scintillations recorded at nighttime, by two spaced receivers with a separation of 187.8 m along a magnetic E-W baseline, at the equatorial station Ancon (11.8°S, 77.2°W, dip latitude 0.9°N), are used to compute the drift speed, V_0, of the ground scintillation pattern at 82 s intervals using a full correlation analysis [*Briggs*, 1984]. It is well known that such an analysis also yields another parameter, V_C, designated the "random" or "characteristic" velocity, which is a measure of the decorrelation between signals recorded by the two receivers. This decorrelation is due to the presence of random variations in the scintillation pattern on the ground brought about by random changes in the irregularities or their drift velocity across the signal path [*Wernik et al*, 1983]. Irregularities produced by the nonlinear evolution of the generalized R-T (GRT) instability in the postsunset equatorial *F* layer would simply convect with the background plasma if the perturbation electric field associated with the instability were negligible. The background plasma drift velocity varies gradually through the night, and in the absence of the irregularity perturbation electric field, the estimated drift velocity would also vary gradually. On the other hand, a fluctuating perturbation electric field associated with the GRT instability would contribute a fluctuating component to the drift velocity of the irregularities thus producing random variations in the drift velocity of the ground scintillation pattern. The full correlation analysis technique used for estimating the drift velocity of the ground scintillation pattern allows for fluctuations in this velocity that give rise to decorrelation of the signals received by the spaced receivers during each interval for which the magnitude V_0 of an average eastward drift velocity is estimated. As noted above, a measure of the decorrelation during each interval is provided by the corresponding value of V_C, which is also estimated from the spaced receiver scintillation data. When there are large fluctuations in the drift velocity, on even a timescale greater than the data interval of 82 s used here, the estimated drift speed V_0 shows large variations. This is generally found to be the situation up to 22 LT for magnetically quiet periods, and the corresponding values of V_C are also found to be high up to 22 LT [*Bhattacharyya et al.*, 2001]. In the estimation of V_0 and V_C from observations, it is assumed that the space–time correlation function of the ground scintillation pattern along the magnetic E-W baseline, is a function of the spatial and temporal lags *x* and *t*, respectively, in the combination $(x - V_0t)^2 + V_C^2t^2$. Theoretical

calculations of the space–time correlation function of the ground scintillation pattern produced by ionospheric irregularities represented as a phase-changing screen, have shown that for both weak as well as saturated scintillations, the parameter V_C may be used as a measure of the width of the random velocity distribution of the irregularities, while V_0 represents an average drift speed of the irregularities, transverse to the signal path [*Wernik et al.*, 1983; *Franke*, 1987]. Thus the irregularity drift speed V may be identified with V_0 plus a fluctuating component, and V_C may be identified with σ_V, the standard deviation of the velocity variations encountered within each data interval.

[6] An expression for the standard deviation, σ_V, of the velocity fluctuations has been derived in terms of the standard deviation of density fluctuations associated with the GRT instability [*Bhattacharyya et al.*, 1989]:

$$\sigma_V = \frac{1}{\sqrt{2}} \frac{|E^x_{eff}|}{B_0} \left\langle \left| \frac{n(\vec{\rho})}{N_0} \right|^2 \right\rangle^{1/2} \tag{1}$$

with

$$\frac{E^x_{eff}}{B_0} = \frac{E^x_a}{B_0} + \frac{g}{\nu_i} \tag{2}$$

where E^x_a is the eastward component of the ambient electric field, B_0 is the magnitude of the Earth's magnetic field in the F region at the dip equator, g is the acceleration due to gravity, ν_i is the ion–neutral collision frequency, $n(\vec{\rho})$ is the fluctuation in plasma density and N_0 is the unperturbed background plasma density. In the initial phase of irregularity development, when the F region peak is at a high altitude, the second term in the right-hand side of (2) dominates over the first term, and the value of σ_V increases rapidly with increasing density fluctuation until the ionosphere starts descending with the reversal of the eastward electric field. As the ionosphere descends, there is a steep decline in the value of $|E^x_{eff}|/B_0$ because of the rapid increase in ν_i. This results in σ_V decreasing sharply. If indeed V_C may be identified with σ_V [*Wernik et al.*, 1983; *Bhattacharyya et al.*, 1989], this provides an explanation for the rapid decline in V_C after 21 LT. A dynamic background plasma as well as neutral thermospheric components have been included in a recent computer simulation of the temporal evolution of equatorial F region bubbles [*Retterer*, 1999]. In this simulation, the upward and eastward components of plasma velocities obtained in regions of depleted density or bubbles, displayed large variations in space and time. The ranges spanned respectively by the extrema of the calculated upward/downward and eastward/westward components of plasma velocities in the region of the bubbles, were found to increase rapidly after local sunset, to a peak value, before declining more gradually over a period of 1 hour, following which the extrema moved very close to the ambient plasma drift. On the other hand, the density structures, which represent the bubbles in the simulation, were found to persist long after the velocity structures had been eroded. The simulation results, thus, seem to support the explanation for a rapid decline in V_C given by *Bhattacharyya et al.* [1989]. In the present paper, the parameter V_C is used as a measure of the perturbation electric fields associated with the irregularities, which according to (1) is determined by the fluctuation in plasma density as well as the height of the irregularity layer.

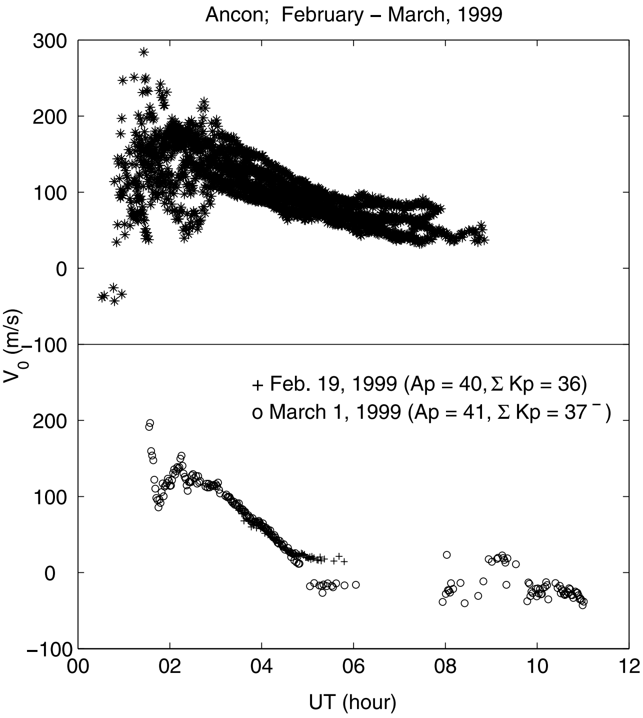

Figure 1. Temporal variation of the magnetic eastward drift speed, V_0, of the ground scintillation pattern at the equatorial station Ancon for 9 days with undisturbed drifts during February 1999 (top) and for two magnetically disturbed days (19 February and 1 March 1999) (bottom). UT ≈ LT + 5 hours.

[7] It should be noted that V_0 has contributions from V_E, the eastward drift and V_Z, the vertical drift of the irregularities, which depend on the orientation of the signal path: $V_0 = V_E - V_Z \tan\theta \sin\phi$ where θ is the zenith angle and ϕ is the azimuth of the signal path measured eastward from the north. For the observations at Ancon, $\theta \approx 28°$, and $\phi \approx 291°$, yielding $V_0 \approx V_E + 0.5V_Z$. Large upward and downward velocities of the irregularities due to polarization electric fields associated with the R-T instability, give rise to large variations in V_0 until 3 UT (22 LT). Hence during this period, it will generally not be possible to identify the effect of geomagnetic activity on the dynamics of the irregularities. However, once these large variations in V_0 die down, and the irregularities start drifting with speeds close to that of the ambient plasma [*Bhattacharyya et al.*, 2001], the effect of magnetic activity may emerge clearly. Data for two equinoctial periods in 1999 have been used in the present study. The first set consists of data from eleven nights in the period 12 February to 1 March 1999, while the second set consists of data from nine nights during the period 13–22 October 1999.

3. Results

3.1. 18 and 19 February 1999

[8] The drifts, V_0, estimated from the first set of data are shown as a function of UT (≈LT + 5 hours) in Figure 1.

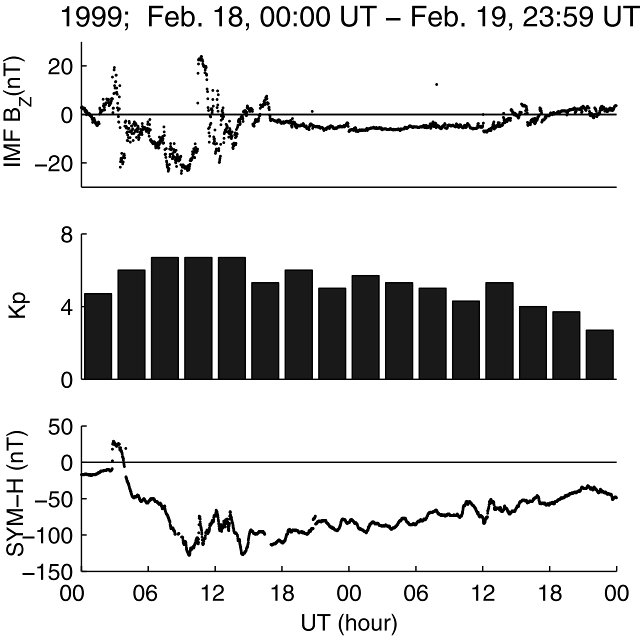

Figure 2. UT variation of the IMF B_Z component, the Kp index, and the SYM-H index for 18 and 19 February 1999.

During the period covered in Figure 1, in terms of UT, 18 and 19 February and 1 March, were the most magnetically disturbed days. Variations in the N-S component B_Z of the interplanetary magnetic field (IMF) measured by the WIND satellite, the 3 hourly Kp index, and the 1 min SYM-H index, for 18 and 19 February, are shown in Figure 2. The evolution with time of these parameters, for 28 February and 1 March, are shown in Figure 3. On 18 February, there was a normal onset of ESF due to growth of the R-T instability in the postsunset period. Strong to moderate scintillations on the 244 MHz signal were recorded at Ancon from 1 UT to 7 UT and the scintillations disappeared at about 8 UT. There was a short-lived perturbation of about 30 m/s in V_0 around 0245 UT, just as the IMF B_Z abruptly turned southward and there was a sudden commencement. However, effects of the magnetic activity on V_0 are not clearly identifiable, because as seen in Figure 1, they fall within the day-to-day variability of V_0 observed during this period. On 19 February, there is no onset of ESF immediately after sunset, but scintillations start just after 3 UT (22 LT). This is seen in the top panel of Figure 4, where the UT variation in the strength of scintillations as measured by the S_4 index, which is the standard deviation of normalized intensity fluctuations, is displayed. After a gradual increase of the S_4 index to a value of 0.9 at 0430 UT, it decreases to noise level by 6 UT. The suggestion that generation of the irregularities, which give rise to these scintillations, may be associated with an eastward electric field produced by the disturbance dynamo, is supported by the fact that there is also a large westward perturbation in the zonal drift superimposed on the normally eastward drift of the background plasma, which caused V_0 to decrease rapidly from about 100 m/s eastward to 20 m/s eastward in a time span of 1.5 hours. This drop in V_0 certainly falls outside the day-to-day variability of V_0 as seen in Figure 1, where the magnetically quiet days in February and March 1999, on which scintillations occurred, show a distinct pattern of variation after 3 UT. *F* region zonal plasma drift perturbations, derived from Jicamarca radar data, which correspond to an extended disturbed period, have indicated a large increase in westward perturbation from 21 to 24 LT, after which the perturbations decrease [*Fejer*, 1997]. It is to be noted that the Jicamarca *F* region zonal plasma drift perturbation shown in Figure 10 of *Fejer* [1997] is the difference between the disturbed plasma drift and a quiet time drift pattern. The disturbed plasma drift on a particular night may still be eastward but much reduced in magnitude due to the superimposition of the westward perturbation on the quiet time pattern, as seems to be the case for 19 February in

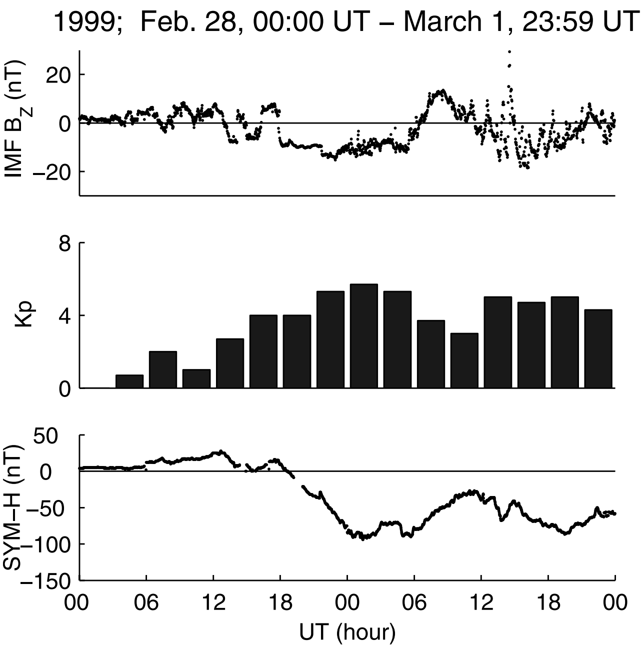

Figure 3. Same as Figure 2, but for 28 February and 1 March 1999.

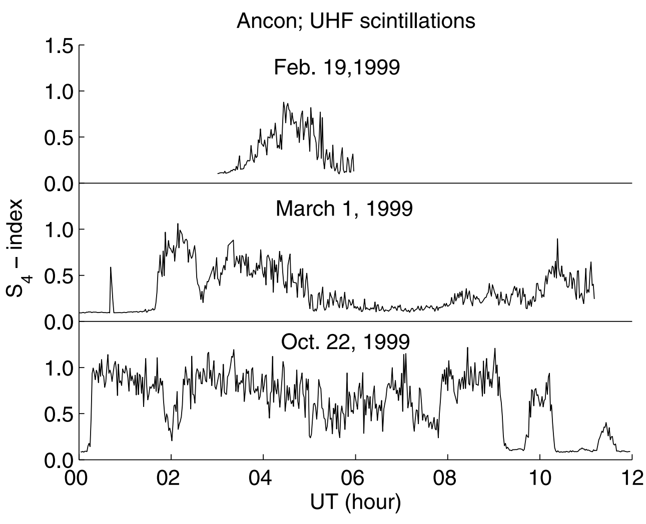

Figure 4. UT variation of the S_4 index derived from intensity scintillations on a 244 MHz signal recorded at Ancon on 19 February, 1 March, and 22 October 1999.

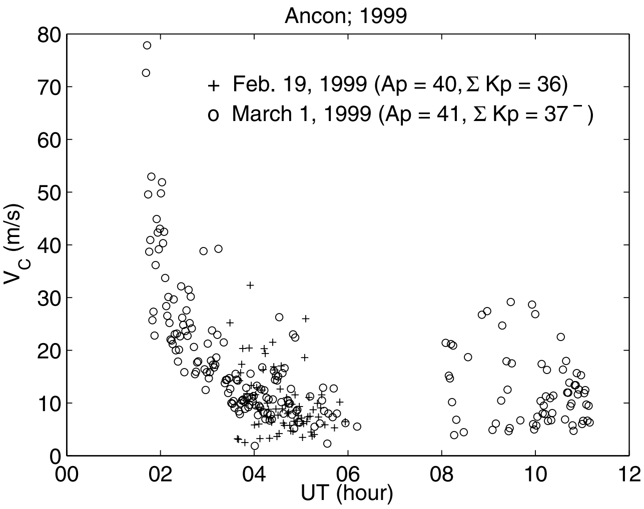

Figure 5. Temporal variation of the parameter V_C estimated from spaced receiver scintillation observations at Ancon for the magnetically disturbed days of 19 February and 1 March 1999.

Figure 1. This figure also shows a leveling off of the westward perturbation drift at 5 UT (0 LT), shortly after which, the irregularities disappear.

3.2. 1 March 1999

[9] Prolonged intense auroral activity, which continued from 14UT on 28 February to 7 UT on 1 March, should have set up a disturbance dynamo, which may have initially inhibited the postsunset occurrence of ESF and scintillations recorded at Ancon on 1 March. However, scintillations started at around 0145 UT and continued until 6 UT. The drift V_0 clearly shows the presence of a westward perturbation drift from 3 to 6 UT due to the disturbance dynamo, as on 19 February. The westward perturbation drift levels off around 5 UT, having attained a larger value than on 19 February, possibly due to the fact that on 19 February, the decay phase of the magnetic storm had started much earlier. The larger westward perturbation on 1 March, superimposed on the quiet time pattern seen in Figure 1, causes the resultant plasma drift to rapidly decrease and become westward before leveling off, whereas on 19 February the resultant plasma drift had, of course, decreased due to the superimposed westward perturbation drift but had remained eastward. An interesting feature of 1 March, seen in Figure 4, is the reappearance of weak scintillations around 0830 UT. Further understanding of what might have happened in the equatorial ionosphere over Ancon at that time, may be gained from Figure 5, where the parameter V_C has been plotted versus UT for both 19 February and 1 March. On the latter night, V_C follows the expected pattern of a sharp decline after 2 UT (21 LT) due to, as explained earlier, the descent of the ionosphere. However, when scintillations start again at 8 UT, V_C has somewhat higher values than it had for comparable S_4 index values between 5 and 6 UT, which would imply comparable levels of density fluctuations. This suggests that there may have been an increase in the height of the *F* layer due to the electric field turning eastward from westward. It is conjectured that the irregularities may be freshly generated as a consequence of the electric field becoming eastward, rather than having been generated a couple of hours earlier and later drifting into the path of the signal. If the irregularities were old, the associated V_C would be expected to have small values observed earlier between 5 and 6 UT. In the past, spaced receiver scintillation observations at the equatorial station Guam, had yielded unusually high values of V_C around midnight and in the postmidnight period of some magnetically disturbed nights [*Bhattacharyya et al.*, 1989]. Those results also support the present suggestion that the scintillations which reappear at 0830 UT on 1 March are due to freshly generated irregularities. This, then, may be an example of the two timescales hypothesis for the evolution of the disturbance dynamo zonal electric fields in the equatorial region, put forward by *Scherliess and Fejer* [1997]. According to this hypothesis, the perturbation of equatorial vertical plasma drifts due to enhanced energy deposition into the high-latitude ionosphere may be described in terms of short-term and long-term components which correspond to time delays of approximately 1–12 and 20–30 hours, respectively. The increase in the amplitude of the disturbance dynamo zonal electric field at 0830 UT may partly be due to the local time dependence of the amplitude of such fields, which shows an increase from local midnight toward dawn.

3.3. 22 October 1999

[10] The major magnetic storm of 22 October 1999, is a well studied one as far as ionospheric effects at low latitudes are concerned [*Basu et al.*, 2001b; *Yeh et al.*, 2001]. The prompt penetration of an eastward electric field into the equatorial ionosphere around 0 UT when the IMF turned southward helped the growth of R-T instability and strong scintillations on the 244 MHz signal were seen after sunset (Figure 4). In Figure 6, the effect of the disturbance dynamo on the drift V_0 is clearly seen after 2 UT. Here again, a westward perturbation drift is superimposed on the quiet time eastward drift pattern that emerges in Figure 6 for the magnetically quiet days with scintillations in the month of October 1999. This causes the resultant drift to decrease and

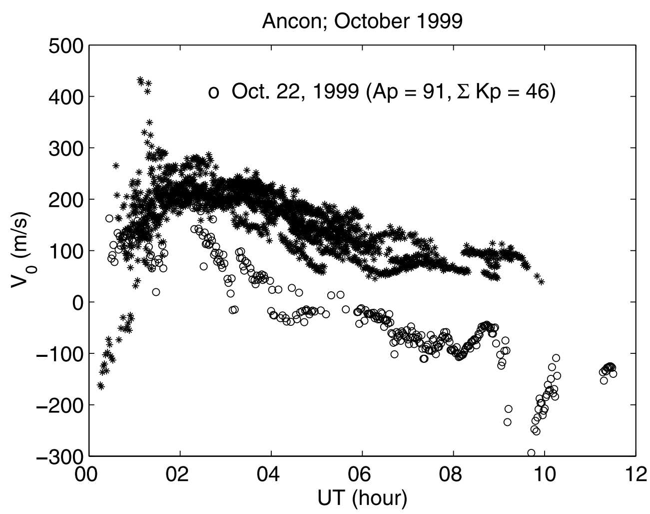

Figure 6. Same as Figure 1, but for 9 days during the period 13–22 October 1999, where results for 22 October 1999, which is magnetically disturbed, are plotted as circles.

turn westward. The very large fluctuation in V_0 encountered between 9 and 10 UT does not seem to be due to a superimposed westward perturbation drift arising from the disturbance dynamo, since the perturbation drift is not expected to change so rapidly. On the other hand, it seems likely that it is due to a polarization electric field associated with freshly generated irregularities as is sometimes observed in the initial phase of equatorial bubble development after sunset. Once again, in support of this idea, variation of V_C with time, for all the nights with scintillation occurrence in October 1999, is displayed in Figure 7. On 22 October, V_C shows a large increase around 9 UT. In situ observations by the ROCSAT satellite around this time, at magnetic latitudes between 20°S and 14°S, in the longitude sector between 275 and 295°E, have shown the presence of enhanced eastward electric fields of 1–2 mV/m in between large amplitude bubbles [*Yeh et al.*, 2001]. This has been attributed to the in-phase contribution of a prompt penetration magnetospheric electric field due to northward turning of the IMF, in addition to an ionospheric disturbance dynamo electric field that is expected to be eastward during the local time period (3–4 LT) under consideration [*Blanc and Richmond*, 1980]. For the night of 22 October, *Basu et al.* [2001b] have also made a strong case for fresh generation of irregularities in this postmidnight period based on the reappearance of L-band scintillations at Ancon, after 8 UT, more than 4 hours after the initial phase of L-band scintillations came to an end at 0330 UT. ROCSAT data have also shown the presence of large irregularity structures near 0850 UT, which intersected the magnetic field lines going through the F region above Ancon [*Basu et al.*, 2001b]. The presence of disturbance dynamo effect is evident from the behavior of V_0 in earlier hours.

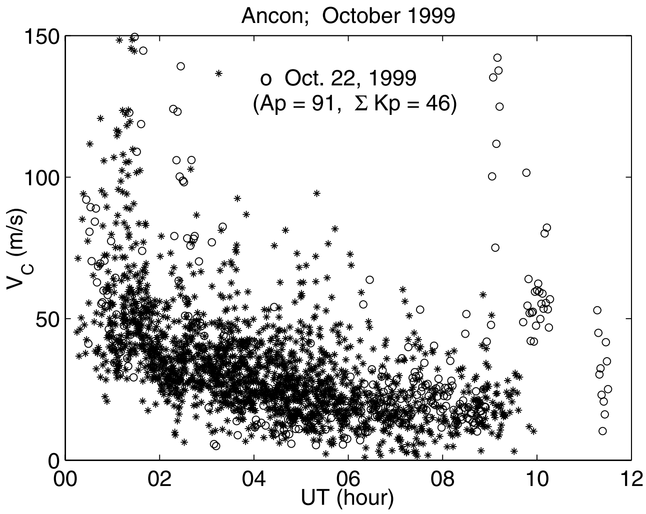

Figure 7. Same as Figure 5, but for 9 days during the period 13–22 October 1999, where results for 22 October 1999, which is magnetically disturbed, are plotted as circles.

4. Summary

[11] In this paper, the drift speed of the ground scintillation pattern, resulting from the vertical and zonal drifts of the irregularities which give rise to the scintillations, is estimated from spaced receiver scintillation observations and used in a study of the effect of magnetic activity on the dynamics of equatorial F region irregularities. Generally, it is difficult to distinguish the effects of geomagnetic storms on the equatorial ionosphere from the large day-to-day variability of the quiet time equatorial ionosphere. However, on those magnetically quiet days which are characterized by the occurrence of ESF and scintillations in an equatorial region, the ionosphere in that region is likely to show less variability because conditions favorable for the occurrence of ESF impose some constraints on the behavior of the ionosphere. Consequently, the day-to-day variations in the irregularity drift speeds estimated from scintillation observations on magnetically quiet days during a month is small once the fluctuating polarization electric field associated with the postsunset GRT instability becomes sufficiently weak. This is found to happen after 22 LT, and hence longer-lived perturbation drifts produced by a disturbance dynamo during magnetically disturbed periods are clearly identifiable after 22 LT. The polarization electric field associated with the GRT instability causes the irregularities to move up or down through the ambient plasma in the initial stages of their evolution. The variability in V_0 due to the polarization electric fields associated with freshly generated irregularities, may, in fact, be useful in gauging the "age" of the irregularities. A measure of this variability is provided by the parameter V_C which is also estimated from spaced receiver scintillation observations. This parameter provides studies such as the present one, with a tool to identify the role of magnetic activity in the generation of fresh irregularities in the postmidnight period due to reversal of the background electric field from westward to eastward. An encounter of the radio waves with such freshly generated irregularities, which may be traced to either a short-lived prompt penetration of a transient magnetospheric electric field or to longer-lived ionospheric disturbance dynamo effect, or an in-phase combination of these two, is likely to give rise to larger values of V_C, than would be obtained in the absence of irregularity polarization electric fields.

[12] It must be noted that the ionospheric disturbance dynamo-produced changes in V_0 are mostly due to zonal perturbation drifts of the equatorial ionospheric plasma, because the contribution of a vertical perturbation drift of the ionosphere to V_0 is usually small. Observation of such perturbed drifts obtained from scintillation data during magnetically active periods has been reported earlier by *Valladares et al.* [1996]. However, the generation of fresh irregularities after 22 LT is an indication that an eastward perturbation electric field is acting on the ionosphere at the time, and there is an upward perturbation drift. In order to reach this conclusion, it is imperative that freshly generated irregularities be distinguished from those which have been generated a couple of hours before they drift into the path of the signal. There have been numerous studies in the past of a possible relationship between magnetic activity and occurrence of ESF, based solely on the occurrence of scintillations, which did not take into consideration the "age" of the irregularities that produced the scintillations. In the present study, an attempt has been made to address this problem. On the basis of the hypothesis presented here regarding the "age" of the irregularities, an example may be

seen of the presence of two timescales in the temporal evolution of equatorial disturbance dynamo zonal electric fields, on 1 March 1999. The disturbance dynamo did not produce an eastward electric field during a time period of about 2 hours, from 6 to 8 UT on 1 March 1999, which occurred after 16 hours of auroral activity. The fresh occurrence of weak to moderate scintillations at about 0830 UT indicate an eastward disturbance electric field which may be conjectured to be due to the dynamo action of storm-driven composition/conductivity effects [*Fuller-Rowell et al.*, 1997] at a time when magnetic activity had come down as seen in the Kp indices shown in Figure 3. This would be in agreement with the hypothesis put forward by *Scherliess and Fejer* [1997]. However, as noted at the end of section 3.2, increase in the amplitude of the disturbance dynamo zonal electric field at this time may partly be due to the local time dependence of the amplitude of such fields, which indicates an increase from midnight toward dawn.

[13] **Acknowledgments.** The work at the Air Force Research Laboratory was partially supported by AFOSR Task 2311AS.

References

Basu, S., et al., Response of the equatorial ionosphere in the South Atlantic region to the great magnetic storm of July 15, 2000, *Geophys. Res. Lett.*, *28*, 3577–3580, 2001a.

Basu, Su., et al., Ionospheric effects of major magnetic storms during the international space weather period of September and October 1999: GPS observations, VHF/UHF scintillations and in-situ density structures at middle and equatorial latitudes, *J. Geophys. Res.*, *106*, 30,389–30,413, 2001b.

Bhattacharyya, A., and W. J. Burke, A transmission line analogy for the development of equatorial ionospheric bubbles, *J. Geophys. Res.*, *105*, 24,941–24,950, 2000.

Bhattacharyya, A., S. J. Franke, and K. C. Yeh, Characteristic velocity of equatorial F-region irregularities determined from spaced receiver scintillation data, *J. Geophys. Res.*, *94*, 11,959–11,969, 1989.

Bhattacharyya, A., et al., Dynamics of equatorial F region irregularities from spaced receiver scintillation observations, *Geophys. Res. Lett.*, *28*, 119–122, 2001.

Blanc, M., and A. D. Richmond, The ionospheric disturbance dynamo, *J. Geophys. Res.*, *85*, 1669–1688, 1980.

Briggs, B. H., The analysis of spaced sensor records by correlation techniques, in *Middle Atmosphere Program, Handbook for MAP*, vol. 13, edited by R. A. Vincent, pp. 166–186, published for ICSU SCOSTEP, 1984.

Fejer, B. G., The electrodynamics of the low-latitude ionosphere: Recent results and future challenges, *J. Atmos. Sol. Terr. Phys.*, *59*, 1465–1482, 1997.

Fejer, B. G., and L. Scherliess, Empirical models of storm time equatorial zonal electric fields, *J. Geophys. Res.*, *102*, 24,047–24,056, 1997.

Fejer, B. G., E. R. De Paula, and L. Scherliess, Effects of vertical plasma drift velocity on the generation and evolution of equatorial spread F, *J. Geophys. Res.*, *104*, 19,859–19,869, 1999.

Franke, S. J., The space–time correlation function of scintillation due to a deep random phase screen, *Radio Sci.*, *22*, 643–654, 1987.

Fuller-Rowell, T. J., et al., How does the thermosphere and ionosphere react to a geomagnetic storm? in *Magnetic Storms, AGU Monogr.*, vol. 98, edited by B. T. Tsurutani et al., pp. 203–225, AGU, Washington, D. C., 1997.

Huang, C. Y., et al., DMSP observations of equatorial plasma bubbles in the topside ionosphere near solar maximum, *J. Geophys. Res.*, *106*, 8131–8142, 2001.

Kelley, M. C., and T. Maruyama, A diagnostic model for equatorial spread F, 2, The effect of magnetic activity, *J. Geophys. Res.*, *97*, 1271–1277, 1992.

Pathan, B. M., and D. R. K. Rao, Seasonal and solar cycle association of zonal drifts of ionospheric plasma irregularities in the Indian equatorial region, *Ann. Geophys.*, *14*, 297–303, 1996.

Retterer, J. M., Theoretical model for fast equatorial bubbles, in *Proceedings of Ionospheric Effects Symposium*, pp. 688–691, Alexandria, Va., 1999.

Sastri, J. H., Occurrence of equatorial spread F during post-midnight period, *Curr. Sci.*, *48*, 12–13, 1979.

Sastri, J. H., Post-midnight occurrence of equatorial spread F, *Indian J. Radio Space Phys.*, *10*, 113–114, 1981.

Sastri, J. H., et al., Ionospheric storm of early November 1993 in the Indian equatorial region, *J. Geophys. Res.*, *105*, 18,443–18,455, 2000.

Scherliess, L., and B. G. Fejer, Storm time dependence of equatorial disturbance dynamo zonal electric fields, *J. Geophys. Res.*, *102*, 24,037–24,046, 1997.

Sobral, J. H. A., et al., Responses of the low-latitude ionosphere to very intense geomagnetic storms, *J. Atmos. Sol. Terr. Phys.*, *63*, 965–974, 2001.

Valladares, C. E., et al., The multi-instrumented studies of equatorial thermosphere aeronomy scintillation system: Climatology of zonal drifts, *J. Geophys. Res.*, *101*, 26,839–26,850, 1996.

Wernik, A. W., C. H. Liu, and K. C. Yeh, Modeling of spaced-receiver scintillation measurements, *Radio Sci.*, *18*, 743–763, 1983.

Yeh, H. C., S. Y. Su, and R. A. Heelis, Storm time plasma irregularities in the pre-dawn hours observed by the low-latitude ROCSAT-1 satellite at 600 km altitude, *Geophys. Res. Lett.*, *28*, 685–688, 2001.

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