Errors in position-fixing by GPS in an environment of strong equatorial scintillations in the Indian zone

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Received 13 November 2002; revised 4 July 2003; accepted 28 July 2003; published 12 February 2004.

[1] The signal-to-noise ratio (SNR) of the L1 (1.6 GHz) transmission from the GPS and GLONASS satellites has been recorded at Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic dip, 17.35°N dip latitude) since 1999 by a stand-alone coarse acquisition (C/A) code Ashtec receiver. The receiver usually tracks 10–15 satellites, sampling different sections of the ionosphere at different look angles from the station. Simultaneously, L-band (1.5 GHz) signals from geostationary INMARSAT (65°E) (350 km subionospheric point: 21.08°N, 86.59°E geographic; 28.74°N magnetic dip, 15.33°N dip latitude) and VHF (244 MHz) from FLEETSATCOM (73°E) (350 km subionospheric point: 21.10°N, 87.25°E geographic; 28.65°N magnetic dip, 15.28°N dip latitude) are also recorded. Calcutta is situated under the northern crest of the equatorial anomaly in the Indian longitude sector. The SNR of many GPS and GLONASS links, particularly in the southern sky and near overhead, has been found to scintillate frequently in between the local sunset and midnight hours. Scintillations of satellite signals near overhead are caused by irregularities in electron density distribution in an environment of high ambient ionization occurring near the crest of the equatorial anomaly. For the links at lower elevation angles in the southern sky, scintillations occur when satellites are viewed "end-on" through the field-aligned plasma bubbles. During periods of intense scintillations, in the high sunspot number years 1999–2002, it has frequently been observed that seven or eight GPS/GLONASS satellite links out of 15 may simultaneously show scintillations in excess of 10 dB. This paper presents an example of the above when the position determined with GPS shows fluctuations to the extent of 11 m in latitude and 8 m in longitude under such an environment. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; 6979 Radio Science: Space and satellite communication; *KEYWORDS:* equatorial scintillation, GPS

Citation: DasGupta, A., S. Ray, A. Paul, P. Banerjee, and A. Bose (2004), Errors in position-fixing by GPS in an environment of strong equatorial scintillations in the Indian zone, *Radio Sci.*, *39*, RS1S30, doi:10.1029/2002RS002822.

1. Introduction

[2] In the absence of selective availability (SA) since May 2000, the major sources of errors in position-fixing by GPS include two important propagation effects: the group delay introduced by the ionospheric total electron content, and ionospheric scintillations caused by small-scale density irregularities. These two effects are particularly severe in the equatorial region. The error due to group delay in this region varies by a factor of 2–3 from solar maximum to minimum as compared with 5–10 in the midlatitudes [see *Mannucci et al.*, 1997, pp. 122 and 124; *Klobuchar and Doherty*, 1998; *Chakraborty et al.*, 1999, Figures 6 and 9] and may be eliminated to some extent by techniques like differential GPS (DGPS) and satellite-based augmentation system (SBAS). Equatorial scintillations have dramatic solar activity dependence, with very little scintillations in the solar minimum years. During the equinoxes of solar maxima, scintillation is

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practically a daily phenomenon. Under extreme conditions of amplitude and phase scintillations, position-fixing by GPS may become impossible. This has drawn considerable attention to the study of scintillations of GPS signals in recent years. This paper presents a study of scintillation and its effects on position-fixing by GPS from a station (Calcutta) situated near the northern crest of the equatorial anomaly in the Indian zone. With geostationary satellites, it has been established that scintillations are most severe at such locations around the anomaly crest [*Aarons et al.*, 1981; *Basu et al.*, 1988].

2. Data

[3] The signal-to-noise ratios (SNR) of the L1 (1.6 GHz) transmissions from the GPS and GLONASS satellites are being recorded at Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic dip, 17.35°N dip latitude) since 1999 by a stand-alone C/A code Ashtec (model GG24) receiver. Simultaneously, an L-band (1.5 GHz) signal from geostationary INMARSAT (65°E) (350 km subionospheric point: 21.09°N, 86.59°E geographic; 28.74°N magnetic dip, 15.33°N dip latitude) is received regularly with a system consisting of a 3 m dish antenna, preamplifier, and an ICOM wideband communication receiver. VHF (244 MHz) transmission from FLEETSATCOM (73°E) (350 km subionospheric point: 21.10°N, 87.25°E geographic; 28.65°N magnetic dip, 15.28°N dip latitude) is also monitored regularly. The detected outputs are simultaneously recorded on a PC-based data acquisition system and a strip chart recorder. The receivers are calibrated at least once a week by a Hewlett Packard signal generator (model HP8648C) following *Basu and Basu* [1989]. The dynamic range of each receiver is ∼25 dB, and the sampling frequency is 20 Hz. The GPS/GLONASS receiver usually tracks 10–15 satellites, simultaneously sampling different sections of the ionosphere at different look angles from the station. When a satellite signal frequently fades to a level less than a threshold value (SNR = 20 dB in the present case), the receiver ignores the particular satellite for navigation solution. The SNR of the GPS/GLONASS receiver has been calibrated by the manufacturer. The calibration has been found to match that imparted to the L-band geostationary satellite signal receiving system by comparing the scintillation indices of INMARSAT signal and a GPS satellite link traversing the ionosphere near the subionospheric point of INMARSAT. The scintillation index (SI, in decibels) of both geostationary and GPS links has been scaled at 3 min intervals using the third peak method of *Whitney et al.* [1969]. The SI is frequently used in routine scintillation data analysis because of its simplicity. The scintillation index S_4, which is defined as the second moment of the signal intensity over the mean signal level, should, however, be used in studies related to signal statistics. An empirical relationship between S_4 and SI (dB) is given by *Whitney* [1974] and *Secan et al.* [1995].

3. Results

[4] Figures 1 and 2 show the tracks of GPS and GLONASS satellites in polar (elevation-azimuth) plots observed during different hours on the night of 12 February 2001 from Calcutta. The station is located at the center of each plot, and the large circles correspond to 0°, 30°, and 60° elevation angles. The variation of scintillation intensity observed by different GPS and GLONASS satellites is shown with circles of different sizes. The crosses indicate the 350 km subionospheric points of FSC and INMARSAT. The eight polar plots ordered in local time (UT + 6 hours) indicate the evolution of equatorial irregularities causing scintillations. During the early evening hour 1930–2030 LT (1330–1430 UT), the satellite links Sv5, Sv23, and Sv30 showed scintillations in excess of 15 dB. These satellites were located to the southwest of the station. In the next 2 hours (1430–1630 UT or 2030–2230 LT), nearly all the satellites in the zone of reception of the observer were affected by scintillations in excess of 10 dB; two to four links (Sv6, Sv14, Sv21, and Sv30) in the southern sky were severely affected and showed scintillations in excess of 20 dB.

[5] A closer look at Figures 1 and 2 reveals the nature and dynamics of equatorial irregularities. For example, in the 1330–1430 UT interval, the satellite Sv6 moving north to south in the elevation range of 41° to about 67° did not show any scintillations. In the next hour, 1430–1530 UT, initially there were no scintillations till 1445 UT, but scintillations were observed from 1445 UT onward. From 1512 UT, as the satellite approached the latitude of the geostationary INMARSAT, scintillations of more than 25 dB were recorded. Bursts of severe scintillations interspersed with periods of moderate activity persisted until 1757 UT when the satellite set. Continuation of scintillations on Sv6 with its slight eastward movement from 1445 to 1757 UT implies that the satellite either was moving within the same irregularity patch or the irregularities were drifting eastward or both. Similarly, Sv5, which had a more eastward motion, showed no scintillations from 1330 to 1409 UT. Moderate scintillations in the range 15–20 dB were observed from 1409 UT until the setting time at 1503 UT. Examination of the track of Sv5, which moved eastward, also shows the possible eastward movement.

[6] Observations with geostationary satellites INMARSAT (65°E) and FSC (73°E), however, not included in the figure, showed onset of scintillations at 1429 and 1439 UT, respectively, indicating an eastward drift of the

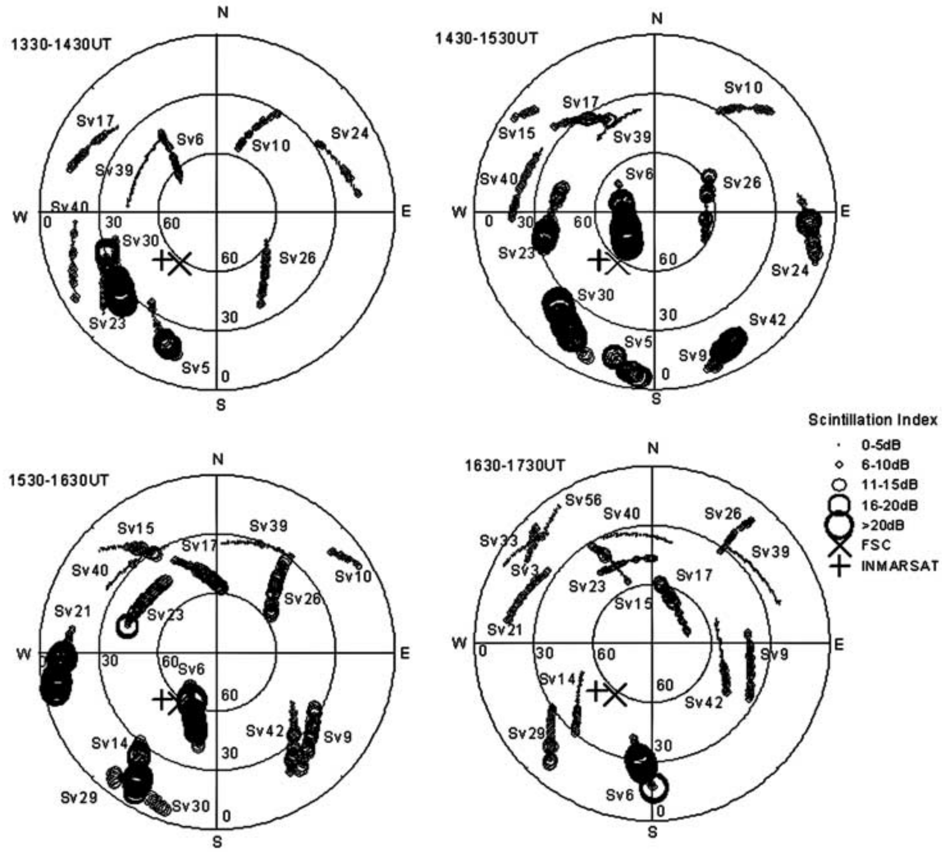

Figure 1. Elevation-azimuth plots of GPS satellite tracks observed from Calcutta during 1330–1730 UT (1930–2330 LT) on 12 February 2001. The superimposed circles show the observed scintillation index (SI) (in decibels).

irregularities, as the 350 km subionospheric point of INMARSAT is more to the west than that of FSC. Three distinct patches of scintillations were observed on FSC during 1439–1614, 1648–1707, and 1907–1937 UT. In the first two cases, scintillations were saturated, whereas SI reached about 11 dB in the third case. On the INMARSAT link, two patches were observed in the time intervals 1429–1605 and 1641–1657 UT. Assuming an eastward drift velocity of 100 m s^{-1}, horizontal east-west extents of the irregularities may be estimated as 576 and 96 km respectively. As mentioned earlier, the scintillation indices of INMARSAT and Sv6 matched quite well when the two links were near one another. Scintillation practically died out during 1630–1830 UT, excepting on the Sv6 link and on all links after 1930 UT. The resurgence of moderate scintillations on the GPS links in the 1830–1930 UT interval corresponded to the third patch observed on the geostationary FSC link.

[7] It may be noted that Sv23 and Sv30 links were very close during the 1330–1430 UT interval, the former moving north and the latter south. Initially Sv23 did not show any scintillations up to 1412 UT, whereas Sv30 had a steady level up to 1406 UT. Moderate to intense scintillations (11–25 dB) were observed during 1412–1627 UT on Sv23 and during 1406–1542 UT on Sv30. From 1430 to 1530 UT, there were practically little scintillations on links Sv10, Sv15, Sv17, Sv39, and Sv40. On the other hand, seven satellites exhibited a scintillation index greater than 15 dB when they were in the southern sky. Satellites Sv23, Sv6, and Sv24 show the latitudinal extent of the equatorial irregularity belt in the Northern Hemisphere in the 1430–1530 UT interval.

[8] Around midnight (1630–1830 UT or 2230–0030 LT), scintillation activity was reduced near overhead, with only two to three satellite links (Sv14, Sv15, Sv17, and Sv29) showing scintillations in the range 11–15 dB. However, in the southernmost part of the sky, at low elevation angles, scintillations in excess of 20 dB even in the late evening hours were recorded with satellite Sv6. In the postmidnight hour (1830–1930 UT

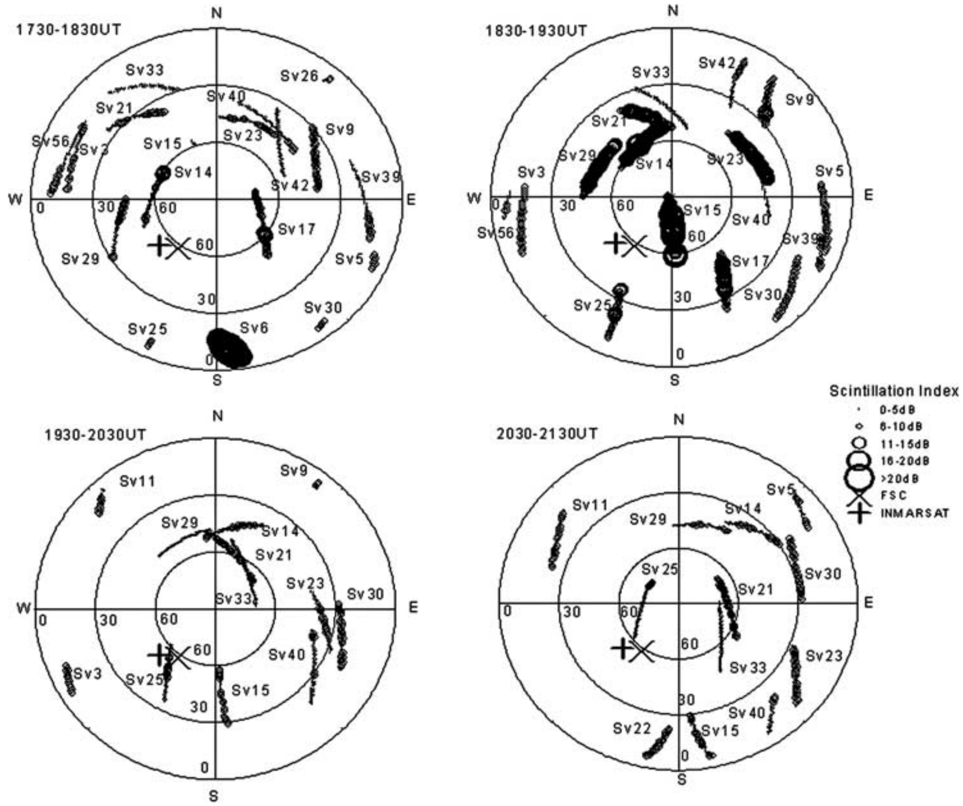

Figure 2. Elevation-azimuth plots of GPS satellite tracks observed from Calcutta during 1730–2130 UT (2330–0330 LT) on 12 February 2001. The superimposed circles show the observed SI (in decibels).

or 0030–0130 LT), weaker irregularities are still present near the anomaly crest causing 11–20 dB scintillations on a number of links (Sv9, Sv14, Sv15, Sv17, Sv21, Sv23, Sv25, and Sv29). After 1930 UT (0130 LT), scintillations became negligible.

[9] In the early evening hours, equatorial irregularities with scale sizes in the range 300–500 m, which cause intense scintillations at L-band, coexist with the irregularities of longer scale lengths (~800–1000 m), causing saturated and fast scintillations at VHF. With the progress of night, however, smaller-scale irregularities decay earlier [*Basu et al.*, 1978], although there may be sufficient power at larger scale sizes to produce scintillations at VHF. Around local midnight, even though the smaller-scale irregularities become weak, the field alignment of the bubbles becomes the dominant factor in controlling the intensity of scintillations at GPS L1 frequency.

[10] It was earlier reported from this station that the accuracy of position-fixing by GPS is considerably degraded, indicated by a rise in the position dilution of precision (PDOP) value, during periods of scintillations even in low solar activity years [*Bandyopadhyay et al.*, 1997]. In order to examine the effect of scintillations on navigational accuracy during high sunspot number years, the deviations from the actual position of the station, determined by the GPS receiver, are plotted in Figures 3 and 4 for the hours corresponding to the polar plots of Figures 1 and 2, respectively. The center of each plot gives the position of the station. During periods of intense scintillations (1430–1630 UT), it has been observed that up to eight satellites simultaneously show scintillations in excess of 10 dB. The position values (latitudes and longitudes) show the largest deviation from the mean position during the hour (1530–1630 UT) when the most intense scintillation activity was recorded. The maximum deviation has been observed to be of the order of 11 m in latitude and 8 m in longitude.

[11] Figures 1 and 2 actually represent examples of scintillations, and Figures 3 and 4 represent its corresponding effects on position-fixing during sunspot number maximum years. More or less similar features were recorded on 206 out of 360 days of observations in

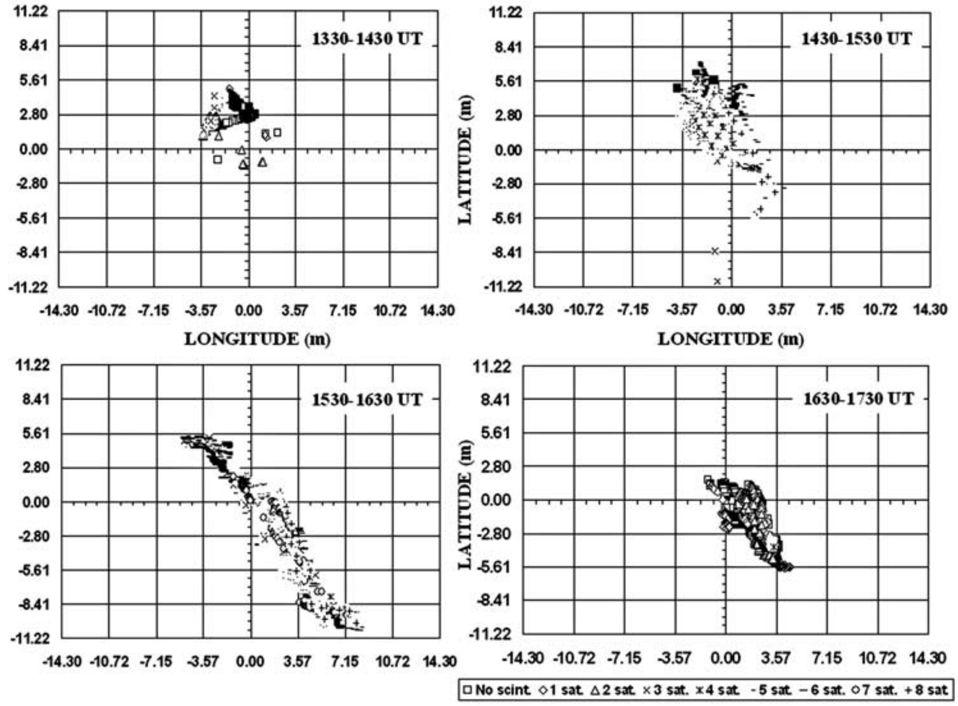

Figure 3. Position deviations of Calcutta observed with GPS during 1330–1730 UT (1930–2330 LT) on 12 February 2001. The legend shows the number of satellites simultaneously exhibiting scintillations in excess of 10 dB corresponding to each position value.

the equinoctial months of 2001–2002 at the present location.

4. Discussions

[12] The observations of GPS signal scintillations from the northern crest of the equatorial anomaly in the Indian zone reveal two distinct regions of very intense scintillations: (1) near the crest of the equatorial anomaly and (2) in the southern sky. The first one is attributed to irregularities in an environment of high ambient electron density near the crest [*Aarons et al.*, 1981], and the latter is attributed to the propagation geometry with respect to the magnetic field line. From a station near the crest of the anomaly, very intense scintillations are observed both on GPS and geostationary links in the postsunset hours. Moderate to intense scintillations are sometimes observed on GPS links even to the north of the station during high sunspot number years. In the late evening hours and around midnight, intense scintillations are observed only on GPS links which are at low elevation angles toward the south, i.e., the satellites which are viewed "end-on" through the field-aligned bubbles. During this local time period, moderate to intense amplitude scintillations are observed on the geostationary VHF FLEETSATCOM link.

[13] The morphology of equatorial scintillations during solar maximum and minimum is well established [*Aarons*, 1982; *Basu et al.*, 1988]. The equatorial *F* region ionosphere possesses two unique features: (1) the equatorial or Appleton anomaly, which is the latitudinal variation of electron density with a trough at the magnetic dip equator and two crests at 15°–20° north and south dip latitudes, and (2) intense irregularities in electron density distribution. The equatorial electric field plays a dominant role in shaping the development of both daytime equatorial anomaly and nighttime density irregularities. The field is eastward during the day and reverses to the west after sunset, around 2100 LT. Before reversal, at the time of sunset, a dramatic increase in the electric field, known as prereversal enhancement, develops at *F* region heights [*Fejer*, 1991]. The effect of prereversal enhancement on the eastward electric field is twofold and has both seasonal and solar activity dependences. The increased electric field causes a redistribution of ionization by a fountain-like effect, thereby increasing the ionization density near the crests at the expense of that at the trough over the magnetic equator. At the anomaly crests, fresh influx of ionization combined with

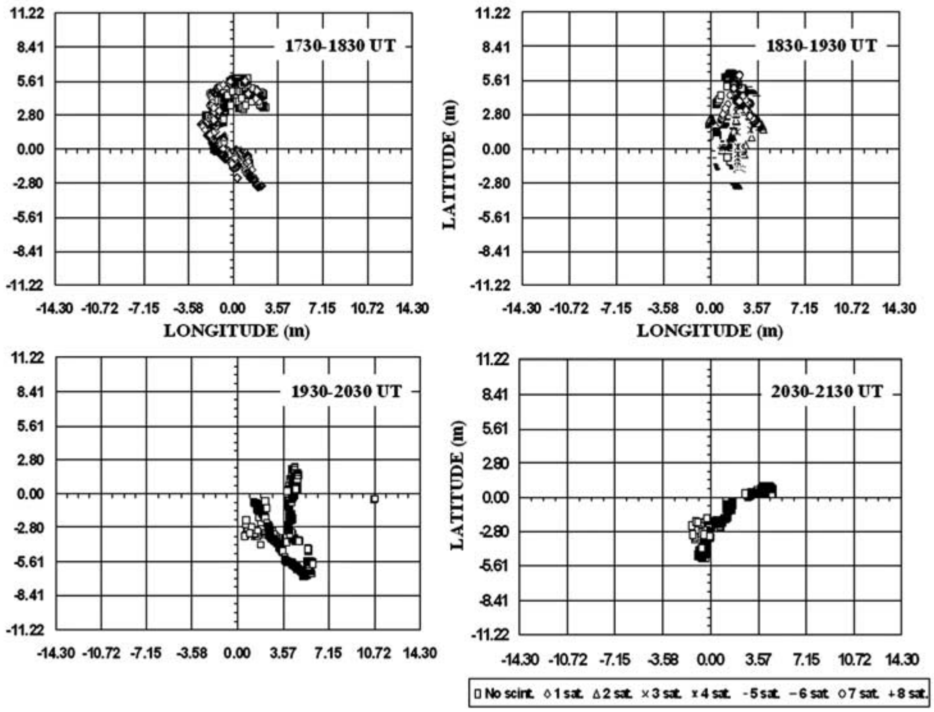

Figure 4. Position deviations of Calcutta observed with GPS during 1730–2130 UT (2330–0330 LT) on 12 February 2001. The legend shows the number of satellites simultaneously exhibiting scintillations in excess of 10 dB corresponding to each position value.

the neutral wind counteracts the normal decay of ionization and produces a secondary peak or a ledge in the ionization distribution [*Anderson and Klobuchar*, 1983; *DasGupta et al.*, 1985; *Huang et al.*, 1989]. Further, the prereversal enhancement of the eastward electric field raises the *F* layer at the magnetic equator to high altitudes, where recombination effects are negligible and conditions favorable for the generation of irregularities may be obtained [*Haerendel*, 1974; *Woodman and LaHoz*, 1976]. Through the Rayleigh-Taylor mechanism, the irregularities then develop into plasma-depleted bubbles and are upwelled to the topside of the ionosphere. The polarization electric field within the bubbles is higher, and as a result, the bubbles rise to the topside at a velocity much greater than the ambient *F* region plasma drift [*Anderson and Haerendel*, 1979]. Steep gradients on the edges of the depletions [*Haerendel*, 1974; *Costa and Kelley*, 1978] help to generate small-scale irregularities as the bubbles rise to great heights, sometimes exceeding 1000 km above the magnetic equator. These are widely recognized as plumes on radar backscatter maps [*Woodman and LaHoz*, 1976]. The bubbles extended in altitude map down along the magnetic field line to anomaly locations of about 15°N and 15°S magnetic latitudes. The above effect is most pronounced during the equinoctial months of sunspot number maximum years. Persistence of high ambient ionization and injection of equatorial irregularities result in severe scintillation effects near the anomaly crest in the postsunset period. The intensity of scintillation is primarily controlled by the irregularity amplitude ΔN. A higher background ionization density N implies a larger integrated density deviation and hence intense scintillations [*Aarons et al.*, 1981]. The events of *F* region height rise at the magnetic equator, the persistence of high ambient ionization, and the occurrence of intense scintillations near the anomaly latitudes are all associated phenomena.

[14] Topside sounder [*Lockwood and Nelms*, 1964; *King et al.*, 1967] and in situ observations have established that the equatorial anomaly is not confined to the height of maximum ionization only; it also extends to the topside. The separation between the crests decreases with increasing altitude, and the locus of the crest lies on a field line. A higher apex implies a more developed anomaly due to an enhanced electric field. *Basu et al.* [2002] have suggested from in situ measurements of the polar orbiting DMSP satellites that the latitudinal variation of plasma density at 840 km measured at 1800 LT is associated with scintillation occurrence on the same

evening. Scintillations have been observed at the longitude of DMSP transit on evenings corresponding to which the latitudinal variation of electron density at satellite altitude 840 km is flat-topped, indicating an enhancement of electric field before reversal. For days on which the ion density at the level of the satellite falls off on both sides of the magnetic equator, the anomaly may be taken as not well developed and scintillations are absent.

[15] Examining the DMSP in situ data for the day under study, 12 February 2001, it was observed that the latitudinal variation of total ion density measured by the spacecraft F12 during 1411–1421 UT (2011–2021 LT) at the altitude range of 840.8–842.7 km in 87.29°E–79.03°E longitude exhibited a flat top over the magnetic equator. The flat top extended up to 3.28°N magnetic latitude (11.35°N geographic latitude). The field line with apex at 840 km above the magnetic equator maps down to 18°N magnetic latitude (23.8°N geographic latitude) at the mean ionospheric height 350 km. In other words, the northern crest of the anomaly on this particular occasion extended beyond the above latitude. GPS observations with satellites Sv23, Sv6, and Sv24 during 1430–1530 UT are in agreement with the latitudinal extent obtained from DMSP data.

[16] It is shown that the accuracy of position-fixing becomes worse during periods of intense scintillations on a number of GPS links. During sunspot number maximum years, when the incidence of intense scintillations is very frequent, the observed deviations are a regular feature at the present location. Whether this is due to nonavailability of satellites suitable for navigation solution or to differing group delays introduced by the equatorial bubbles on different satellite links is yet to be established.

[17] **Acknowledgments.** This research has been sponsored in part by the Ministry of Information Technology (MIT), Government of India, the Indian Space Research Organization (ISRO), and the University Grants Commission (UGC) through research projects. The authors gratefully acknowledge the Center for Space Sciences at the University of Texas at Dallas and the U.S. Air Force for providing the DMSP thermal plasma data via the Web site http://cindispace.utdallas.edu/DMSP/. The authors thank the referees for pointing out some inaccuracies in the original manuscript and for helpful comments.

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