First in situ observations of equatorial ionospheric bubbles by Indian satellite SROSS-C2 and simultaneous multisatellite scintillations

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[1] The first observation of equatorial ionospheric irregularities by RPA probe of the Indian low Earth orbiting satellite SROSS-C2 is presented in this paper. Amplitude scintillations of medium Earth orbiting Global Positioning System (GPS) satellites and geostationary FLEETSATCOM (244 MHz, 73°E) and INMARSAT (1.5 GHz, 65°E) signals recorded simultaneously at Calcutta (lat: 22.97° N, long: 88.50°E geographic; dip: 32°N) are used for a coordinated study of equatorial *F* region irregularities in the Indian zone. Cases of ionospheric irregularities identified from the SROSS-C2 records obtained during the initial one-and-a-half years since its launch in May 1994 have been analyzed. Some events of in situ ion density irregularities are compared with scintillations simultaneously observed on the transionospheric satellite links. Intense bite-outs of ion density (maximum relative irregularity amplitude $\Delta N/N \sim 65\%$) were detected on one occasion (October 29, 1994) coupled with deep fadings ($S_4 \sim 1$ at VHF, ~ 0.52 at L-band, and ~ 0.69 at GPS L1 frequency) on ground-based satellite links. An estimate of scintillation indices from the observed in situ density deviations compares well with the ground-based measurements. The development of intense equatorial bubbles even on a day like October 29, 1994, under low solar activity conditions, may be attributed to a prompt penetration of magnetospheric electric field equatorwards during the main phase of a magnetic storm in progress [maximum negative excursion of Dst ~ -127 nT at 1600UT (2100MLT) with a dDst/dt rate -37 nT/hr at 1300−1400UT (1800−1900MLT)]. The drift velocity and spatial extent of these irregularities have been estimated from ground-based observations. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; 6979 Radio Science: Space and satellite communication; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; *KEYWORDS:* SROSS-C2, equatorial irregularities and magnetic storm

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1. Introduction

[2] The *F* region of the equatorial ionosphere is characterized by the equatorial anomaly and very intense ionization density irregularities [*Basu and Kelley*, 1979; *Ossakow*, 1979; *Fejer and Kelley*, 1980; *Kelley and McClure*, 1981; *Ossakow*, 1981; *Basu and Basu*, 1981]. While the phenomenon of equatorial anomaly occurs over a large part of the day and extends well into the evening hours, the irregularities in the electron density distribution develop over the magnetic equator in the postsunset hours [*Woodman and LaHoz*, 1976; *Fejer and Kelly*, 1980]. These irregularities, in the form of depletions, manifest as deep bite-outs in the in situ density plots [*Kelley et al.*, 1976; *McClure et al.*, 1977], and cause scintillations in transionospheric satelite links [*Basu and Basu*, 1976; *Basu et al.*, 1983]. Plasma depletions were first observed by the polar orbiting Ogo-6 satellite [*Hanson and Sanatani*, 1973]. *Kil and*

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Heelis [1998a] have reported the global distribution of ionospheric irregularities from the Atmosphere Explorer-E (AE-E) satellite data. *Huang et al.* [2001] examined 2086 cases of equatorial plasma bubbles in the topside ionosphere during the solar maximum 1989–1991. Although India has a long tradition of ionospheric research, no long-term in situ data on *F* region parameters in the Indian longitude sector were available. To fulfill this objective, SROSS-C2 (Stretched Rohini Series Satellite) was launched by the Indian Space Research Organisation (ISRO) in May 1994, with a Retarding Potential Analyzer (RPA) probe on board.

[3] The characteristics and dynamics of the plasma bubbles have been examined from in situ observations by the low Earth orbiting satellite SROSS-C2 (elliptical orbit: 620 × 430 km, orbital inclination: 46°), simultaneously with scintillation measurements of medium Earth orbiting Global Positioning System (GPS) and geostationary FLEETSATCOM (FSC) (244 MHz, 73°E) and INMARSAT (1.5 GHz, 65°E) satellite signals. The in situ probe in SROSS-C2, moving with a velocity of 7.8 km/s, gives an instant snapshot of a section of the sky through which it moves. On the other hand, the scintillation events observed on different geostationary links are caused by irregularities moving across fixed subionospheric points of these satellites, and indicate the nature of drift and extent of the irregularities. The transionospheric signals from the GPS satellites (normally eight to twelve satellite are visible from a low-latitude station), moving with a velocity of 3.9 km/s, pass through different sections of the irregularities at varying look angles, and give a more complete picture of the density structures. This paper presents simultaneous in situ observations of the equatorial *F* region irregularities by the Indian satellite SROSS-C2 for the first time, and corresponding ground-based recordings of amplitude scintillations on GPS and geostationary satellite links.

2. Data

[4] The ion density values measured by the RPA probe on board the SROSS-C2 during the first eighteen months (May 1994 through December 1995) have been analyzed to study equatorial *F* region irregularities over the Indian longitude sector. Radio transmissions from the geostationary satellites FSC and INMARSAT are routinely recorded at the Haringhata Field Station (HFS) (lat: 22.97° N, long: 88.50° E geographic; dip: 32°N) of the University of Calcutta. This station situated near the northern crest of the equatorial anomaly in the Indian zone offers an excellent platform for studying equatorial ionospheric irregularities. The 400 km subionospheric points of the geostationary satellites (FSC: 20.90° N, 87.10° E; INMARSAT: 20.89°N, 86.35°E) are situated virtually under the northern crest of the equatorial anomaly. 1.6 GHz (L1) signals from the GPS satellites have been recorded at Calcutta since 1994. The orbits of this satellite system are such that normally eight to twelve satellites are visible simultaneously from a low latitude station. These satellites, at the nominal altitude of 20,200 km, slowly drift across the sky of the observer thereby providing both temporal and spatial variations of the irregularity structures to the ground-based observer. The GPS satellites sample different subionospheric points distributed over the observer's sky. A geostationary satellite's subionospheric point is fixed and the temporal variation is mainly caused by the drift of the irregularities across the line of sight. The temporal observations of the GPS signals are contaminated by spatial variations due to the relative motion of the satellites and ionospheric drift.

[5] The carrier amplitudes of the geostationary satellite signals were recorded on a strip-chart recorder (speed: 12 inch/hr, integration time: 0.1 s). The receivers have been calibrated at least once a week following *Basu and Basu* [1989]. The dynamic ranges of the receivers were about 22–25 dB. The output from the C/A code position fixing GPS receiver gives, among a host of other parameters, the carrier-to-noise (CNO) ratios for the satellites tracked at any instant. The output was recorded on a data acquisition system with a sampling interval of 2 s. The intensity of scintillation with geostationary satellite is measured by the S_4 index [*Briggs and Parkin*, 1963], defined as the ratio of the standard deviation of signal intensity fluctuations and the average signal intensity. In the case of GPS, the carrier-to-noise ratio is used instead of the signal intensity.

[6] The RPA measurement by SROSS-C2 has been carried out at a sampling interval of 22 ms which gives a spatial resolution of 170 m, approximately. Although measurements were made throughout the spin cycle of the satellite, data taken only within ±25° of the velocity vector for ion sensors are considered for analysis. Measurements carried out outside the above angle between sensor normal and velocity vector could not be used for ion density calculation as correction for spin modulation could not be applied outside the said limit [*Garg and Das*, 1995]. Thus the ion density plots are not continuous and there is a bunch of points taken within the specified limits and a break for the rest of the spin cycle i.e. for about 80 km in space there are no data points and again a bunch of points with 170 m interval and so on. The relative irregularity amplitude ($\Delta N/N$) has been scaled following the procedure of *Kil and Heelis* [1998a]. The average sample period over which irregularity amplitudes have been computed is 1.39 s that corresponds to a distance of 10.83 km of satellite path length.

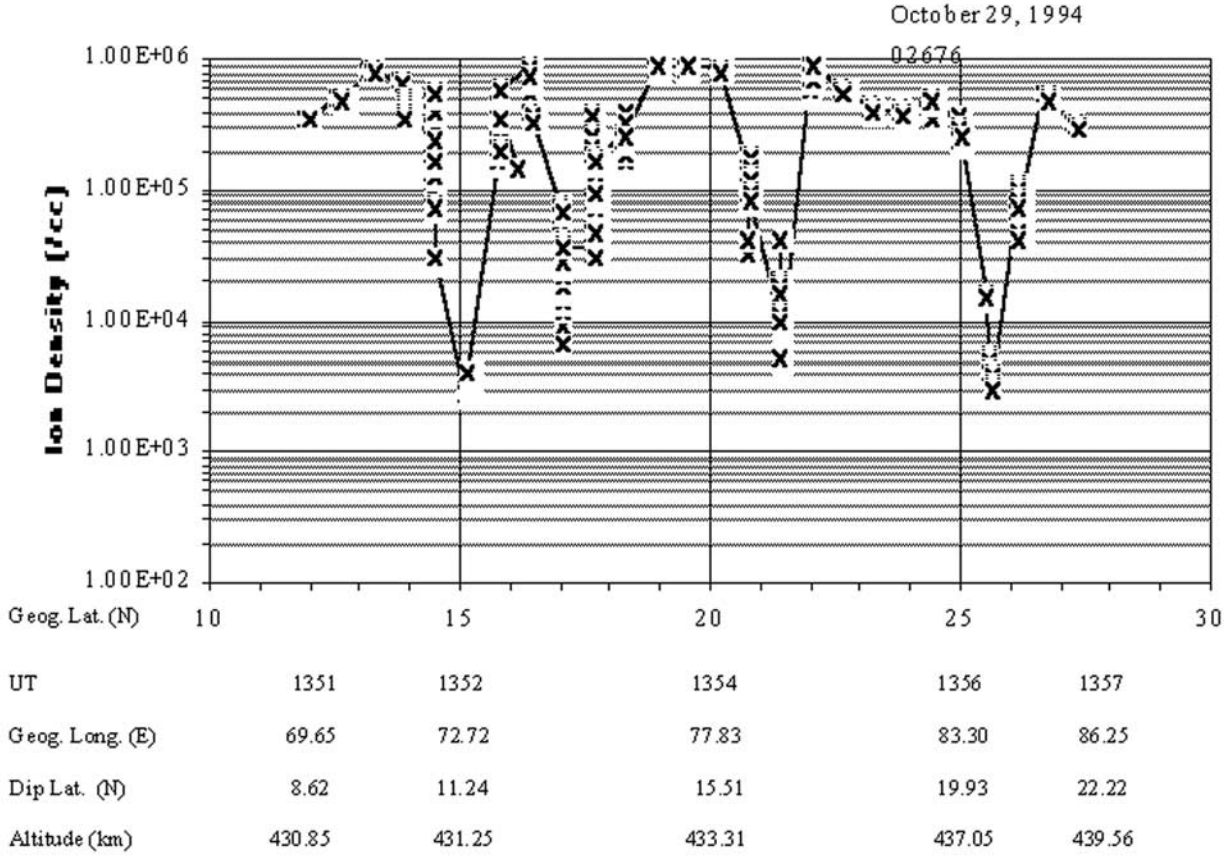

Figure 1. Ion density recorded during Orbit No. 02676 of SROSS-C2 on October 29, 1994.

[7] Ionospheric scintillation in the equatorial *F* region is predominantly a postsunset phenomenon. It is found to increase significantly with the increase in the solar activity level [*Chakraborty et al.*, 1999]. The control is more pronounced at off-equatorial locations around the anomaly crest than at the equator [*DasGupta et al.*, 1981]. Scintillation activity increases dramatically with sunspot number during the equinoxes and December solstice months. This is related to the equatorial ionospheric plasma processes, which become very prominent in the postsunset hours of these seasons. Since the period of interest (October 1994 through December 1995) corresponds to the solar activity minimum (monthly mean sunspot number ranging from 44.0 in October 1994 to 10.0 in December 1995), the number of days on which scintillations were observed and corresponding matches with SROSS-C2 RPA data were found, was very limited. During this time, scintillations were observed on the VHF link (FSC) on 13 nights. From the ion density files of SROSS-C2, containing data at 22 ms interval, only two cases with relative irregularity amplitude ($\Delta N/N$) $\geq$ 5% were identified for which the SROSS transits matched scintillation occurrences in time and location. These orbits are, namely, 02676 on October 29, 1994 and 04925 on March 27, 1995.

3. Results

[8] Figure 1 shows the intense irregular structures in the ion density plot of the SROSS orbit 02676 recorded on October 29, 1994. The duration of the transit was 6 min (1351–1357 UT). A number of intense bite-outs (of about 3 orders of magnitude) of the ion density stretching over the entire recorded pass, occurred over the latitude range 11.92° N (near the magnetic equator) through 27.55° N (beyond the anomaly crest). The corresponding relative irregularity amplitudes ($\Delta N/N$) are shown in Figure 2. The maximum irregularity intensity for this pass was 65%. From this figure, four distinct structures could be identified with breaks in between. The structures became narrow toward the end of the track. Figure 3 shows the variation of scintillation intensity in the postsunset to midnight local time interval on October 29, 1994 observed with FSC, INMARSAT and two GPS satellites, Sv31 and Sv2. The maximum S_4 indices were saturated ($\sim$1.00) at VHF, $\sim$0.52 at L-band and $\sim$0.69 at

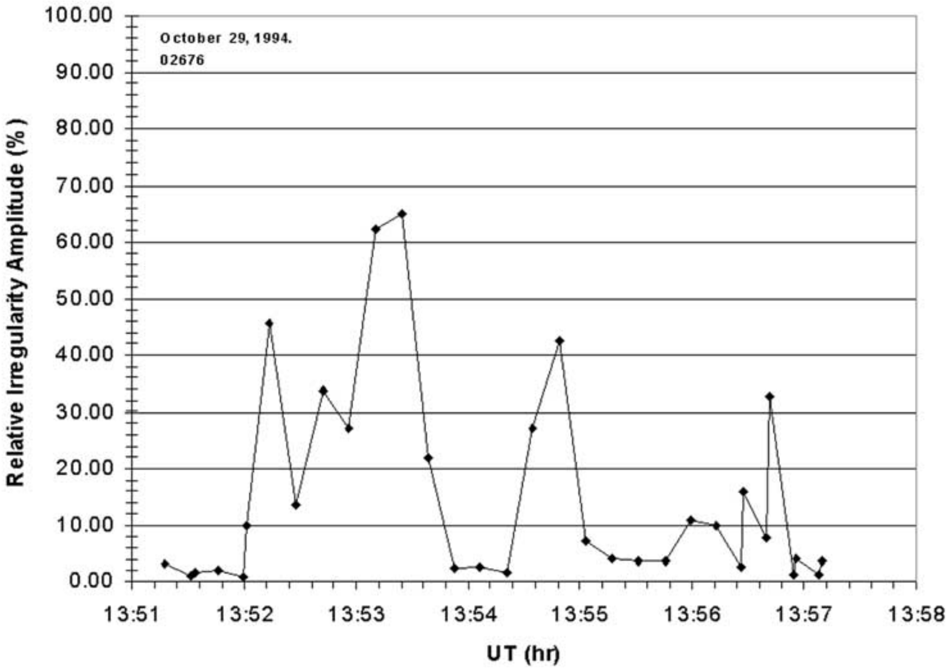

Figure 2. Relative irregularity amplitude ($\Delta N/N$ in%) for Orbit No. 02676 of SROSS-C2.

GPS L1 frequency. From this figure also, four well-defined structures of irregularities could be identified, with clear breaks at L-band and VHF. The 400 km-subionospheric track of Sv31 (1430–1714 UT) was close to the ionospheric penetration point of INMARSAT. A good correspondence of S_4 of INMARSAT and GPS Sv31 may be noted. The onset of scintillations of INMARSAT, FSC and GPS Sv31 in sequence at 1331, 1345 and 1430 UT, respectively indicated an eastward drift velocity of the irregularity patches. The 100 km-ionospheric sunset at the magnetic equator corresponding to the onset of scintillations at 1331 UT in the INMARSAT link and at the beginning of the SROSS-C2 track at 1351 UT are shown by arrow marks.

[9] Figure 4 shows the tracks of SROSS-C2 and two GPS satellites (400 km-subionospheric) superimposed over a map of India. The broad lines indicate portions of the tracks intercepted by ionospheric irregularity clouds. Fluctuations in ion density ($\Delta N/N \geq 5\%$) observed in the SROSS-C2 transit 02676 started at 1352 UT at 71.54° E. Corresponding to this longitude, ionospheric sunset at the magnetic equator occurred at 1339 UT (shown by an arrow in the figure). The subionospheric points of FSC and INMARSAT shown by crosses are separated by about 88 km. From the difference in the onset time of scintillations at 244 MHz and 1.5 GHz, an eastward drift velocity of 105 m/s was estimated. With this eastward velocity, the irregularities reached the subionospheric track of GPS Sv31 around the noted time. SROSS-C2 moving toward northeast, with a velocity of about 7.8 km/s, gave an instant snapshot of the ionosphere through which it traveled. The irregularity cloud encountered by this satellite at the onset (1351 UT, 70° E) had the westernmost location, whereas the track ended at a longitude east of the above (1357 UT, 86° E). As the irregularities drifted eastward, the easternmost structures affected the transionospheric links of INMARSAT, FSC and GPS Sv31 in succession. The second patch of scintillation, starting at 1700 UT corresponded to irregularities encountered by SROSS at the beginning of its transit. The narrow section of scintillations on GPS Sv2 as shown in Figure 3 may be attributed to its northern location (dip latitude ~ 19.5° N) and local time (after 2230 hrs). The INMARSAT link showed less intense scintillations around this time. The total duration of scintillations on the INMARSAT link was about two hours (1331–1528 UT). From the estimated value of drift velocity (105 m/s), the east-west extent of the patch was calculated to be about 750 km. Scintillations at 1.5 GHz for about two hours at a stretch are normally rare at this location. The presence of three distinct patches may be an indication of the ionospheric plumes breaking into streams at higher off-equatorial latitudes.

[10] The presence of intense equatorial plasma bubbles causing severe and extensive scintillations on October 29, 1994, was rather unusual, for a year close to the minimum phase of solar activity. An examination of the magnetic

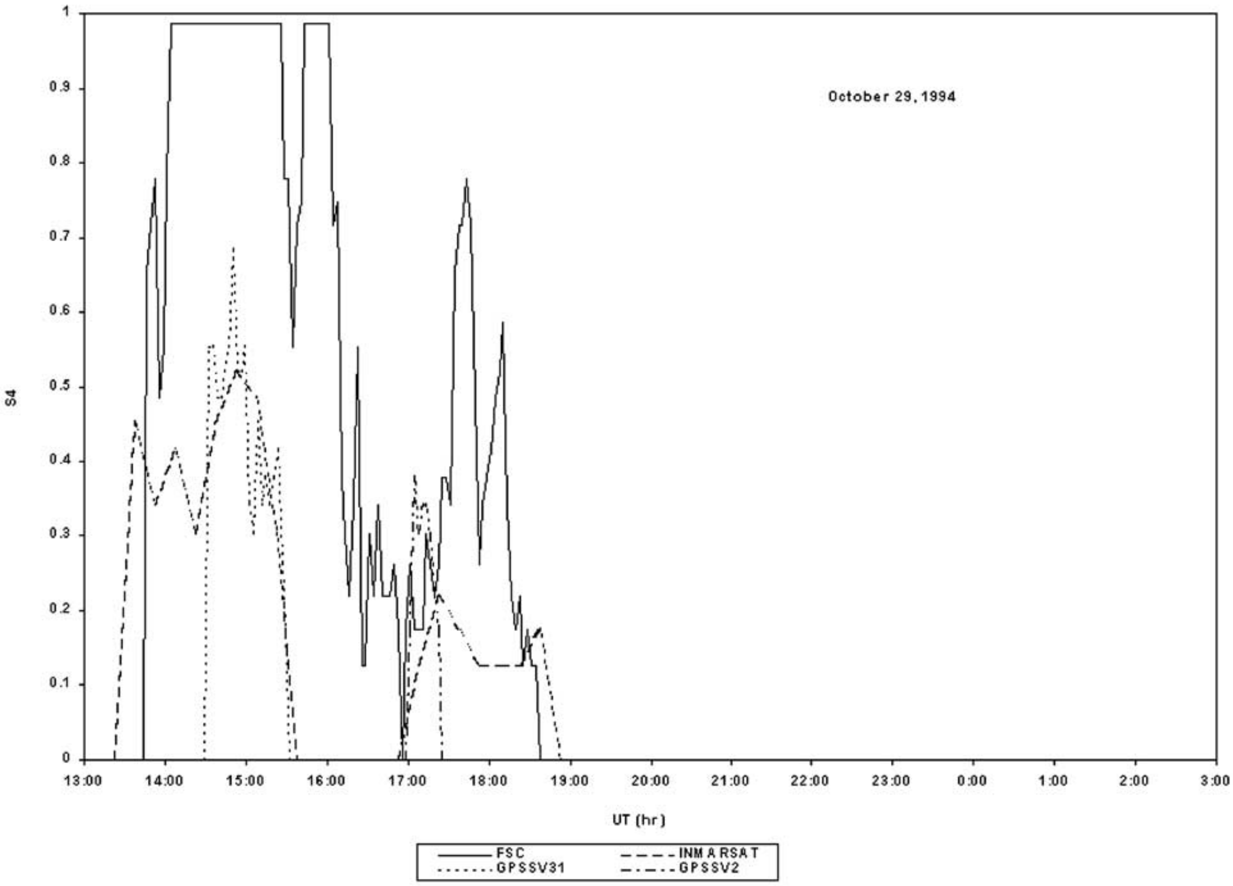

Figure 3. Variation of scintillation index (S_4) for FSC, INMARSAT, GPS Sv31 and Sv2 observed during the night of October 29, 1994 at Haringhata Field Station.

data shows that a geomagnetic storm was in progress on this day. Figure 5a shows the variation of Dst index on October 29, 1994. Figure 5b plots hourly rate of change of Dst. The maximum dDst/dt during the main phase of the storm occurred between 1300–1400 UT (1800–1900 MLT) and attained a value −37 nT/hr. This storm had two minima: initially the Dst value dipped to −106 nT at 1200 UT (1700 MLT) which was less intense than the final one, −127 nT at 1600 UT (2100 MLT). The main phase of the storm was from 1100–1600 UT (1600–2100 MLT). The intense fluctuations in ion-density observed by SROSS-C2 started at 1352 UT, shown by the vertical line in Figure 5a. Scintillation onset in geostationary INMARSAT and FSC links at 1331 and 1345 UT respectively occurred during the main phase of the storm. The phenomena observed by in situ and ground-based scintillation measurements were similar to the cases of intense plasma bubbles during the main phases of geomagnetic storms of March 19–29, 1991 reported by *Huang et al.* [2001, Figure 6b] and that of October 21–22, 1999 by *Basu et al.* [2001, Figure 11]. *Huang et al.* [2001] used plasma density measurements from DMSP satellites and *Basu et al.* [2001] utilized a global coverage of data from GPS International Geodynamic Service (IGS) network, Republic of China Satellite-1 (ROCSAT-1) and in situ measurements of density, electric field and particle precipitation from DMSP satellites. The storms reported in these papers were more severe in nature and occurred during high solar activity years.

[11] During our period of interest, October 1994 to December 1995, the only other transit (04925) exhibiting ion density fluctuations ($\Delta N/N \geq 5\%$) occurred in the early morning hours (0026–0033 UT) of March 27, 1995. Two distinct bite-outs were observed around 0029 and 0030 UT. The corresponding relative irregularity amplitudes ($\Delta N/N$) also exhibited two notches around the noted time with a maximum value of 8% at 0030 UT. Sunrise at the corresponding longitude (69.94° E) occurred at 0031 UT, and hence the irregularity intensity was much less. Extensive scintillations observed on the FSC, INMARSAT and GPS links in the premidnight hours of March 26/27, 1995 lasted well into

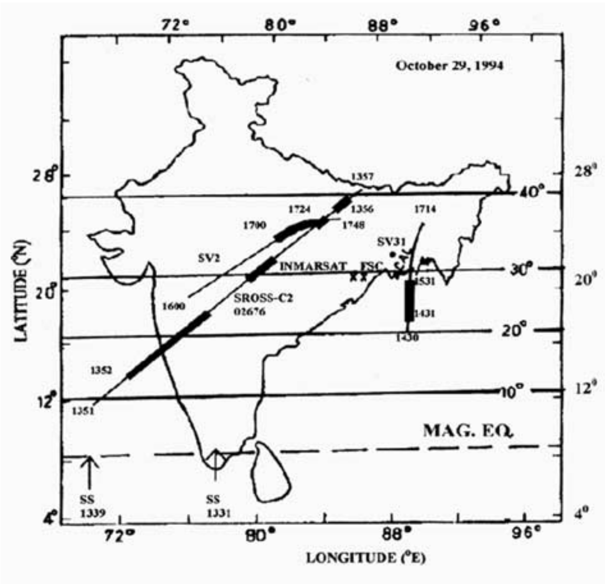

Figure 4. Tracks of SROSS-C2 Orbit No. 02676 (Mean Ht.: 433 km) and GPS Sv31 and Sv2 (400 km-subionospheric) observed on October 29, 1994 superimposed over a map of India. The magnetic equator and the dip contours are also shown on the grid. Crosses show the 400 km-subionospheric points of FSC and INMARSAT from Haringhata. The bold portions of the tracks indicate scintillations [$S_4 \geq 0.17$] on GPS links and irregularities [$\Delta N/N \geq 5\%$] observed by SROSS-C2.

the early morning hours only on the VHF FSC link. It is well known that during the developmental phase in the postsunset hours, irregularities of different scale sizes producing VHF and microwave scintillations coexist, but with the progress of night, the meter scale irregularities rapidly decay while the km-scale irregularities persist [*Basu and Basu*, 1976]. Thus, scintillations at L-band (INMARSAT, GPS Sv9 and Sv23) were confined to local premidnight hours. The patch of scintillation on the FSC link after 2300 UT was weak [$S_4 \leq 0.17$] and had been caused by the weak km-scale irregularities still left over in the postsunrise hours.

4. Discussion

[12] This paper presents a study of equatorial ionospheric irregularities with the first Indian RPA probe on board the satellite SROSS-C2, and simultaneous scintillation observations of GPS and geostationary satellite transmissions. From the coordinated observations of in situ measurements and scintillations, an explosive development of equatorial plasma bubble and its streaming into narrow patches at off-equatorial locations even during a low solar activity period is illustrated. On the night of October 29, 1994, the bite-outs in the in situ density plots are correlated with deep fadings in different transionospheric radio links. The depletions shown in the plots of ion density have been quantified in terms of the commonly used parameter, relative irregularity amplitude ($\Delta N/N$ in%). The drift velocity and the horizontal extent of the irregularities determined from the onset time differences of the ground-based observations have been found to be about 105 m/s eastward and 750 km, respectively.

[13] The sequences of events recorded by the LEO SROSS-C2 (orbital inclination: 46°) in the ascending orbit 02676 west of the station, and the transionospheric radio links are in reverse order. As a result, the observed structures show the effects of temporal and spatial variations. The first cloud of irregularities observed by SROSS-C2 occurs immediately after sunset near the magnetic equator. On the contrary, the last patch observed by SROSS is relatively narrow and occurs around 40° N dip. This patch causes scintillations on INMARSAT, FSC and GPS signals in succession in the postsunset hours.

[14] The SROSS-C2 satellite moving with a velocity of 7.8 km/s samples the in situ ion density at 22 ms intervals. This gives a minimum irregularity scale of 342 m. It is known that strong amplitude scintillations occur when the Fresnel dimension of a propagating radio wave is of the order of the irregularity scale in the ionosphere [*Briggs and Parkin*, 1963]. For the geostationary INMARSAT ($\lambda = 0.2$ m) the Fresnel dimension comes out to be 317 m. Since this value is close to the minimum irregularity scale size detected by SROSS, it is assumed that the density depletion ($\Delta N = 2.32 \times 10^{10}$ electrons/m^3) measured by the in situ probe at 1357 UT near the subionospheric longitude of INMARSAT (86.35° E) causes the first patch of scintillation on the geostationary link. The small patch encountered last by the in situ probe, around 40° N dip at 430 km altitude, maps up along the geomagnetic field lines to an altitude of 1150 km at the magnetic equator. The bubble intercepts geostationary satellite ray paths from the ground station over a length of about 500 km if the base of the bubble is taken to be around 400 km. Assuming the power spectra of the intermediate scale irregularity structures to follow a power law with spectral index $n = -3.2$ [*Kil and Heelis*, 1998b], the perturbation magnitude in the VHF range ($\lambda = 1.23$ m) is obtained as 6.6×10^{12} electrons/m^3. With these density depletions, the estimated S_4 values are found to be $\sim$1.02 at 244 MHz and 0.46 at 1.5 GHz, using the phase screen model of *Rino* [1979]. These values compare well with the observed S_4 from ground-based scintillation measurements considering the many assumptions involved in computation.

[15] It takes about three hours for the initial SROSS-C2 bite-outs to drift eastward across the subionospheric points of the geostationary satellites. In this time interval, the strength of the irregularities is eroded, more so at smaller scale sizes. The scintillation patterns seen by the satellite radio links between 1330 and 1700 UT are caused

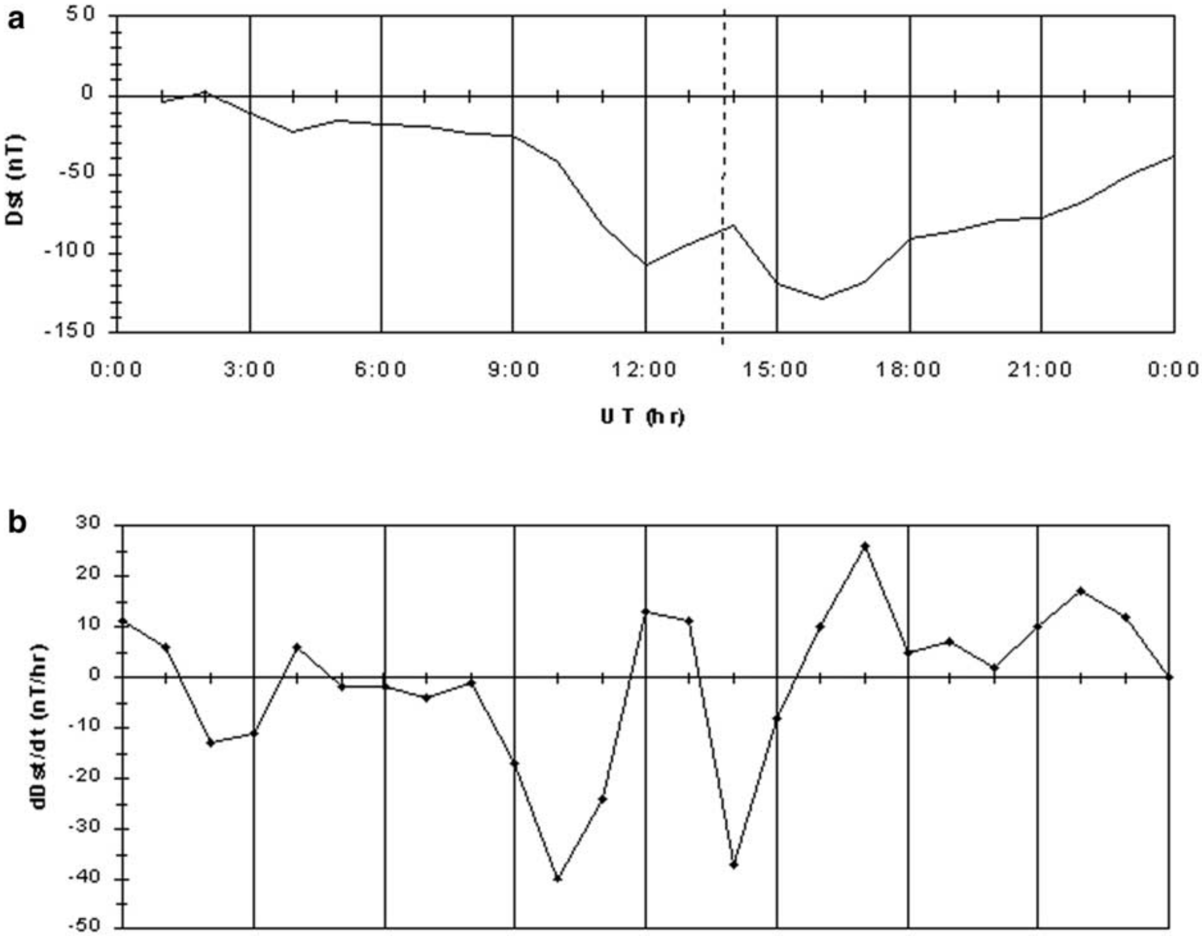

Figure 5. (a) Variation of hourly Dst index in nT on October 29, 1994. The dotted vertical line shows the onset of ion-density fluctuations in the orbit 02676 of SROSS-C2. (b) Variation of dDst/dt in nT/hr on the same day as Figure 5a.

by the irregularities seen last by SROSS. The relatively longer duration of scintillations on the transionospheric satellite links may be attributed to the location of the subionospheric points in between the magnetic equator and the equatorial anomaly crest ($\sim 25^\circ - 30^\circ$ N dip). This picture is consistent with airglow observations where dark bands of electron density bite-outs appear over an extensive area in proximity to the magnetic equator. The dark band streams out into narrower patches to off-equatorial sky [*Weber et al.*, 1980; *Aarons et al.*, 1999]. There is a sharp transition of the ambient ionization level beyond the equatorial anomaly crest. As a result, under diffusive equilibrium, the clouds of irregularities should develop into narrower and weaker striations.

[16] As mentioned earlier, the explosive development of intense equatorial bubbles in the postsunset hours during the main phase of a magnetic storm has been attributed to prompt penetration of the magnetospheric electric field to the magnetic equator. *Basu et al.* [2001] have recently shown that equatorial irregularities develop in the longitude sector where 1800–2100 MLT correspond to the UT of maximum dDst/dt. *Senior and Blanc* [1984] had suggested this earlier from model computations. *Wygant et al.* [1998] reports a case of earthward penetration of the magnetospheric large scale electric field in the MLT sector 1800–2100 hrs during the main phase of the geomagnetic storm of March 24, 1991. The dDst/dt, which is a measure of the net current injection rate ranged up to -50 nT/hr. In the present case, the maximum dDst/dt value during the main phase was -37 nT/hr in the time sector 1300–1400 UT (1800–1900 MLT). The observations of *Basu et al.* [2001] and *Wygant et al.* [1998] correspond to sunspot number maximum conditions. Whether the criteria required for

penetration of electric field at lower solar activity levels have to be relaxed is yet to be established.

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